An ICT Architecture for the Neighbourhood Area Network in the Smart Grid

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy
In the Faculty of Engineering and Physical Sciences

2015

Zoya Pourmirza

School of Computer Science
With them the Seed of Wisdom did I sow,
And with my own hand labour'd it to grow:
And this was all the Harvest that I reap'd---
"I came like Water, and like Wind I go."

Poet: Omar Khayyam (1048 –1131)
Rendered into English Verse by Edward Fitzgerald (1809–1883)
# List of Contents

List of Contents ......................................................................................................................... 3  
List of Figures ............................................................................................................................ 8  
List of Tables .............................................................................................................................. 12  
Abstract ..................................................................................................................................... 13  
Declaration ................................................................................................................................. 15  
Copyright Statement .................................................................................................................. 16  
Acknowledgments ...................................................................................................................... 17  
Chapter 1. Introduction .............................................................................................................. 18  
  1.1 Smart Grid Overview ........................................................................................................ 18  
  1.2 Overview of the Problem Domain .................................................................................... 20  
   1.2.1 Primary Problem: ICT for the Neighbourhood Area Network (NAN) Level ............... 20  
   1.2.2 Solution to the Primary Problem ................................................................................. 21  
   1.2.3 Secondary Problem: Energy Efficient Design for the ICT Network ......................... 22  
   1.2.4 Solutions to the Secondary Problem ......................................................................... 22  
  1.3 Project Description ............................................................................................................ 24  
  1.4 The Research Aims and Objectives .................................................................................. 28  
  1.5 Research Methodology .................................................................................................... 29  
  1.6 Research Contributions .................................................................................................... 31  
   1.6.1 Thesis Contributions .................................................................................................... 31
## List of Contents

1.6.2 Contributions to the Smart Grid Community ........................................... 32

1.7 Thesis Structure ......................................................................................... 34

Chapter 2. Background and Literature Review .................................................. 35

2.1 Introduction ............................................................................................ 35

2.2 Background on Distributed Systems ......................................................... 35

2.2.1 Types of Networks ........................................................................... 36

2.2.2 Distributed System Topologies ......................................................... 38

2.3 Literature Review on the Smart Grid ......................................................... 41

2.3.1 Introduction ...................................................................................... 41

2.3.2 Smart Grid Topology ........................................................................ 42

2.3.3 Smart Grid Communication Requirements ....................................... 43

2.3.4 Related Work .................................................................................... 48

2.3.5 Summary ........................................................................................... 55

2.4 Literature Review on the Energy Aware Topology of a Wireless Sensor Network ............................................................................................................. 56

2.4.1 Introduction ...................................................................................... 56

2.4.2 General Wireless Sensor Networks ................................................ 57

2.4.3 Energy Efficient Wireless Sensor Networks .................................. 59

2.4.4 Related Work ................................................................................... 62

2.4.5 Summary ........................................................................................... 68

2.5 Literature Review on Data Reduction ......................................................... 68

2.5.1 Introduction ...................................................................................... 68

2.5.2 Energy Efficient Data Transmission Techniques ................................ 69

2.5.3 Data Reduction Techniques .............................................................. 70

2.5.4 Lossless Data Reduction Techniques ............................................. 71

2.5.5 Related work .................................................................................... 73

2.5.6 Summary ........................................................................................... 81
Chapter 3. ICT Architecture for the NAN in the Smart Grid........................................83

3.1 Introduction.....................................................................................................................83

3.2 Background Knowledge...............................................................................................84

3.3 The Proposed ICT Architecture for the NAN in the Smart Grid .......................86

3.4 Implementation of the ICT Architecture on the University Campus ............90

3.5 Sensor Network Applications in the Smart Grid.....................................................96

3.6 Summary .......................................................................................................................97


4.1 Introduction.....................................................................................................................99

4.2 Application of the WSN for the Second Layer of the Architecture ..........100

4.3 Energy-Aware Topology for the Wireless Sensor Network..........................101

4.3.1 Network Model and Assumptions........................................................................101

4.3.2 Energy Model...........................................................................................................104

4.3.3 Energy Consumption Analysis.............................................................................106

4.4 Discussion....................................................................................................................112

4.5 Evaluation ....................................................................................................................118

4.5.1 Comparing Direct Communication with Cluster-Based Communication in a Wireless Sensor Network.................................................................................118

4.5.2 Validation of the Behaviour of the Total Energy Consumption in a Wireless Sensor Network..........................................................................................120

4.5.3 Analysis of Other Works.........................................................................................122

4.6 Summary .......................................................................................................................124

Chapter 5. A Data Reduction Algorithm for the Smart Grid.................................126

5.1 Introduction.....................................................................................................................126

5.2 Proposed Data Reduction Algorithm .......................................................................128

5.2.1 Design Considerations for DRACO.................................................................128

5.2.2 Design of DRACO ...............................................................................................128
<table>
<thead>
<tr>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2.3</td>
</tr>
<tr>
<td>5.3</td>
</tr>
<tr>
<td>5.3.1</td>
</tr>
<tr>
<td>5.3.2</td>
</tr>
<tr>
<td>5.3.3</td>
</tr>
<tr>
<td>5.3.4</td>
</tr>
<tr>
<td>5.4</td>
</tr>
<tr>
<td>5.4.1</td>
</tr>
<tr>
<td>5.4.2</td>
</tr>
<tr>
<td>5.5</td>
</tr>
</tbody>
</table>

Chapter 6. Architectural Considerations and Evaluation of the Proposed ICT Architecture | 149 |
| 6.1     | Introduction                                          | 149 |
| 6.2     | Architectural Styles                                   | 150 |
| 6.3     | Architectural Principles                               | 153 |
| 6.4     | Evaluation of the Design of the ICT Architecture       | 158 |
| 6.5     | Summary                                               | 162 |

Chapter 7. Conclusion and Future Work | 164 |
| 7.1     | Conclusion                                            | 164 |
| 7.1.1   | ICT Architecture for the NAN level                     | 164 |
| 7.1.2   | Energy Aware Topology                                  | 165 |
| 7.1.3   | Data Reduction                                        | 167 |
| 7.1.4   | Summary                                               | 168 |
| 7.2     | Future Work                                           | 168 |

Appendix A. Extension to the Query Processing System | 172 |
Appendix B. Data to Knowledge (Visualisation Tool) | 175 |
B.1 Literature Review on Visualisation for Smart Grids ........................................ 175

B.1.1 Introduction ........................................................................................................ 175

B.1.2 Other Geographically Based Visualisation Tools .............................................. 175

B.1.3 Visualisation Tools for Smart Grids .................................................................. 176

B.1.4 Summary ............................................................................................................ 182

B.2 Data to Knowledge (Developed Visualisation Tool) ............................................. 183

B.2.1 Developed Visualisation Tool ........................................................................... 184

B.2.2 Requirements ..................................................................................................... 185

B.2.3 Software Architecture ....................................................................................... 187

B.2.4 Analysis and Design ......................................................................................... 190

B.2.4.1 Use Case Diagram .......................................................................................... 190

B.2.4.2 Data Flow Diagram ......................................................................................... 191

B.2.5 Evaluation .......................................................................................................... 193

B.2.5.1 A Walkthrough of the Implemented Visualisation Tool .................................. 194

B.2.5.2 Qualitative Evaluation of the Design of our Visualisation Tool Architecture ........................................................................................................... 205

B.2.5.3 Identifying Emergency Scenarios .................................................................... 207

B.2.6 Summary ............................................................................................................ 210

References ................................................................................................................. 213

Total word count: 65,803
List of Figures

Figure 1.1: A Smart Grid Network. ................................................................. 19
Figure 1.2: Monitored attributes during an hour at a substation in the University of Manchester (Voltage phase A). ................................................................. 25
Figure 1.3: Monitored attributes during an hour at a substation in the University of Manchester (Current phase A). ................................................................. 26
Figure 1.4: Monitored attributes during an hour at a substation in the University of Manchester (Frequency). ................................................................. 26
Figure 1.5: Monitored attributes during an hour at a substation in the University of Manchester (Total active power). ................................................................. 27
Figure 1.6: Monitored attributes during an hour at a substation in the University of Manchester (Total power factor). ................................................................. 27
Figure 2.1: Centralised topology. ................................................................. 38
Figure 2.2: Ring topology. ................................................................. 39
Figure 2.3: Hierarchical topology. ................................................................. 39
Figure 2.4: Decentralised topology. ................................................................. 40
Figure 2.5: A holarchy system comprising holons (Negeri and Baken, 2012). .......... 50
Figure 2.6: A Smart Grid communication network (Al-Omar et al., 2012). .......... 51
Figure 2.7: The communication architecture used by López et al. (2012). .......... 52
Figure 2.8: Information architecture for the Smart Grid (Chen et al., 2013). .......... 53
Figure 2.9: Communication architecture for the Smart Grid (Hammoudeh et al., 2013). .............................................................................................................. 55
Figure 2.10: Diagram of a wireless sensor node (Saini et al., 2010). .......... 58
Figure 2.11: Efficient data transmission. ................................................................. 71
Figure 2.12: Generating the common base (Aquino et al., 2008). .......... 77
Figure 2.13: The compression and decompression process (Aquino et al., 2008) .......... 78
Figure 2.14: In-network compression (Kimura and Latifi, 2005) .......................... 79
Figure 3.1: An abstract view of the proposed ICT architecture .............................. 88
Figure 3.2: An abstract view of the designed software architecture ...................... 89
Figure 3.3: Proposed ICT architecture ............................................................... 91
Figure 3.4: Monitoring system at the substations ............................................... 94
Figure 4.1: 16 WSNs comprising 4 base stations .............................................. 102
Figure 4.2: Energy for L=9 m. .................................................................. 110
Figure 4.3: Energy for L=90 m. ................................................................ 111
Figure 4.4: Average total energy when z is equal to 2, 5 and 10 for L=9 m .......... 112
Figure 4.5: Average total energy when z is equal to 1, 2, 5 and 10 for L=90 m ...... 112
Figure 4.6: The effect of clustering size, location and shape on total energy consumption in a 90m×90m network ......................................................... 114
Figure 4.7: 6 CHs. .................................................................................. 115
Figure 4.8: 6 CHs. .................................................................................. 115
Figure 4.9: 8 CHs. .................................................................................. 116
Figure 4.10: 10 CHs. ............................................................................. 116
Figure 4.11: 12 CHs. ............................................................................. 117
Figure 4.12: 14 CHs. ............................................................................. 117
Figure 4.13: 16 CHs. ............................................................................. 118
Figure 4.14: Normalised energy for L=9 m (z=2) ......................................... 119
Figure 4.15: Normalised energy for L=90 m (z=2) ....................................... 120
Figure 4.16: Optimal number of clusters (Heinzelman et al., 2002) ............... 121
Figure 4.17: Optimal number of clusters (Gu et al., 2010) .............................. 121
Figure 4.18: Optimal number of clusters (Tuah et al., 2012) ......................... 122
Figure 5.1: The data reduction procedure ....................................................... 129
Figure 5.2: Effect of DRACO on simulated data .............................................. 136
Figure 5.3: 24 hours of compressed voltage data ............................................ 137
Figure 5.4: 24 hours of compressed current data ............................................ 138
Figure 5.5: 24 Hours of compressed frequency data ....................................... 138
Figure 5.6: Data acquisition rate evaluation ..................................................... 139
Figure 5.7: Total Active Power (top figure) and the corresponding bit-rate (bottom figure) .......................................................... 141
List of Figures

Figure 5.8: Comparison with other data reduction algorithms. .............................................. 145
Figure 6.1: Abstract view of layered system ....................................................................... 151
Figure 6.2: Abstract view of a component-based system within a layered architecture. .................................................................................................................. 152
Figure A.1: Result of a sample query. .................................................................................. 174
Figure B.1: Visualisation framework for power system monitoring by Bo et al. (2012). ................................................................................................................................. 180
Figure B.2: Enterprise GIS architecture for visualising the Smart Grid by Datta and Mohanty (2013) ............................................................................................................ 181
Figure B.3: 3-layered information display frame by Liu et al. (2013) ................................. 182
Figure B.4: Software Architecture for the ICT infrastructure of the Neighbourhood Area Network ....................................................................................................................... 189
Figure B.5: Use Case Diagram ............................................................................................ 191
Figure B.6: Data Flow Diagram .......................................................................................... 193
Figure B.7: Interface of the main page of the visualisation tool ......................................... 195
Figure B.8: Interface of the terrain view of the University of Manchester campus ......... 196
Figure B.9: Interface of the satellite view of the University of Manchester campus... 197
Figure B.10: The user has selected cRIO number 2 (which is located at the University of Manchester museum) from the right panel. Its location and related information are shown on the map. ........................................................................................................ 198
Figure B.11: The user has selected cRIO number 1 which results in opening another page, as is shown in this picture. Now the user can choose to view the schematic view of cRIO number 1, or return to the main page. ............................................................. 198
Figure B.12: The user has selected to view the schematic view of cRIO number 1. .... 199
Figure B.13: The user has selected the drop markers to locate all the cRIO devices on the map. ......................................................................................................................... 199
Figure B.14: The user has selected the Kilburn-meters from the main page which result in opening this page. Now the user is asked to enter her/his credentials. .................... 200
Figure B.15: The user has entered the correct credentials which results in opening this page. This page shows data that are extracted from the selected smart meter. The over threshold data are highlighted. ......................................................................................... 200
Figure B.16: The user has selected to view data which belongs to the period of one week from 21st November 2012 to 28th November 2012. The result of real data captured from the Kilburn-meters are shown on the graph.

Figure B.17: The user has checked the off-peak period against the calendar and realised that it was the weekend which results in low usage.

Figure B.18: The user has received a text message regarding the over threshold data of the area being monitored.

Figure B.19: The user has received a web service reporting the over threshold data.

Figure B.20: The backup database storing data for the past one week.

Figure B.21: The user has run the simulation tool on another machine to generate the simulated data.

Figure B.22: Results of simulated data on another machine.

Figure B.23: The user has entered correct information through ODBC in order to connect to the machine upon which the simulation is running.

Figure B.24: The user has extracted simulated data from the simulation tool on another machine and viewed it on the visualisation tool.

Figure B.25: The persistence layer is down.

Figure B.26: Using text messaging for alerting users.
List of Tables

Table 2.1: Comparing the evaluation parameters for different distributed system topologies. .......................................................... 40
Table 4.1: Energy models used in our analysis. ................................. 107
Table 4.2: Parameters used in our analysis. ........................................ 108
Table 5.1: The transmitter side (DRACO-1). ........................................ 131
Table 5.2: The receiver side (DRACO-1). ........................................ 131
Table 5.3: The transmitter side (DRACO-2). ........................................ 132
Table 5.4: The receiver side (DRACO-2). ........................................ 132
Table 5.5: The transmitter side. ...................................................... 134
Table 5.6: The receiver side. ...................................................... 134
Table 5.7: Compression efficiency of different data reduction algorithms. ............ 146
Table 5.8: Execution time of different data reduction algorithms. .................. 147
Table B.1: Summary of functionalities of visualisation tools. ...................... 183
Table B.2: Qualitative comparison between our prototype visualisation tool and other existing prototypes. ................................................ 194
In planning for future electricity supplies certain issues will need to be considered such as increased energy usage, urbanisation, reduction in personnel, global warming and the conservation of natural resources. As the result, some countries have investigated the transformation of their existing power grid to the so-called Smart Grid. The Smart Grid has three main characteristics which are, to some degree, antagonistic. These characteristics are the provision of good power quality, energy cost reduction and improvement in the reliability of the grid. The need to ensure that they can be accomplished together demands much richer Information and Communications Technology (ICT) networks than the current systems available.

In this research we have identified the gap in the current proposals for the ICT of the power grid. We have designed and developed an ICT architecture for the neighbourhood sub-Grid level of the electrical network, where monitoring at this level is very underdeveloped because most current grids are controlled centrally and the response of the neighbourhood area is not generally monitored or actively controlled. Our designed ICT architecture, which is based on established architectural principles, can incorporate data from heterogeneous sources. This layered architecture provides both the sensors that can directly measure the electrical activity of the network (e.g. voltage) and also the sensors that measure the environment (e.g. temperature) since these provide information that can be used to anticipate demand and improve control actions. Additionally, we have designed a visualisation tool as an interface for a grid operators to facilitate a better comprehension of the behaviour of the neighbourhood level of the Smart Grid.

Since we have noticed that energy aware ICT is a prerequisite for an efficient Smart Grid, we have utilised two different approaches to tackle this issue. The first approach was to utilise a cluster-based communication technique for the second layer of the architecture,
which comprises Wireless Sensor Networks, where energy limitation is the major problem. Accordingly, we have analysed the energy-aware topology for wireless sensor networks embedded in the mentioned layer. We provide evidence that the proposed topology will bring energy efficiency to the communication network of the Smart Grid. The second approach was to develop a data reduction algorithm to reduce the volume of data prior to data transmission. We demonstrated that our developed data reduction is suitable for Smart Grid applications which can keep the integrity and quality of data.

Finally, the work presented in this thesis is based on a real project that is being implemented in the medium voltage power network of the University of Manchester where power grid instrumentation, real data and professionals in the field are available. Since the project is long-term and the environmental sensor networks in particular are not currently installed we have evaluated some of our predictions via simulation. However, where the instrumentation was available, we were able to compare our predictions and our simulations with actual experimental results.
Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
Copyright Statement

i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trademarks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://www.campus.manchester.ac.uk/medialibrary/policies/intellectual-property.pdf), in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on presentation of Theses.
Acknowledgments

These four years of research have felt to me like a journey. A long, but definitely enlightening, journey. I would like to take this opportunity to say special thanks to my supervisor, Dr. John M. Brooke, for his supervision, valuable guidance, counsel, continuous support, patience and encouragement throughout the course of my PhD research. Also, I wish to acknowledge Professor Ian Cotton from the School of Electrical and Electronic Engineering for all technical guidance, discussions, feedback, and valuable suggestions. Additionally, I would like to thank Mr. Peter R. Green, senior lecturer in the School of Electrical and Electronic Engineering for his valuable discussions and feedback.

Further thanks go to the Faculty of Engineering and Physical Sciences and the School of Computer Science for their generous offer of partial funding which was essential for my PhD research.

Thanks are expressed to all the student members of room 1.17 and the friends that I have made in Manchester for their care and support and for providing a stimulating environment.

Giant thanks go to my dear fiancé Ashkan for his love, understanding and encouragement. A very big thanks to my dear brother Shaya for caring so much and making me laugh even if I did not feel like it. Further thanks to my dear Hamid, Nilou, Anna and Khosrow for making this journey more pleasant for me.

I would also like to express my sincere thanks and appreciation to my loving parents Roza and Amir for their moral and financial support and encouragement throughout my life. Their utmost love, selfless care, trust and patience were all that kept me going. Finally, I would like to dedicate this thesis to my parents who made all this possible for me; without them I would not be what I am now.
Chapter 1. Introduction

1.1 Smart Grid Overview

In recent years the conventional electrical grid has faced difficulties due to issues such as the energy crisis and environmental degradation (Daoud and Fernando, 2011). Consideration of these issues has led to the birth of the Smart Grid. The term ‘Smart Grid’ (Gallagher, 2009) generally refers to an advanced electricity grid for the 21st century that incorporates digital computing, communication technologies and services for power-delivery systems. The main drivers of Smart Grids are (Datta and Mohanty, 2013) the reduction of greenhouse gases, customer price signals, the integration of renewable energy sources, supply shortfalls, peak-load management, loss reduction and, finally, rapid technical developments (e.g. in equipment and materials).

According to the US Department of Energy (DOE) (Miller et al., 2008) the desirable characteristics of the Smart Grid have been identified as: self-healing, consumer friendly, reliable with good power quality, and resistant to cyber-attack. It should also be able to accommodate all storage and generation options and facilitate new services and markets. The Smart Grid proposes to accomplish the above-mentioned goals by incorporating Information and Communication Technology (ICT) in the power network to bring more intelligence into the Grid. Intelligence here addresses the ability to monitor and control a range of industrial appliances and functional components to optimise energy generation and consumption (Kayastha et al., 2012). Thus ICT networks are considered as enablers for the modernisation of power grids which can create new energy markets and decentralise control of the grid. Additionally, they can improve the quality, efficiency and reliability of power grids.
As shown in Figure 1.1, the Smart Grid is considered as an integration of a power network and an ICT network. The power network, responsible for transmitting electricity from generation points to the clients, consists of three networks: generation, transmission and distribution. The ICT network, responsible for providing communication between different sectors in the power network by using digital technology, has three networks. These networks are known as the wide area network (WAN), the neighbourhood area network (NAN) and the home area network (HAN). The focus of this thesis is on the NAN level of the Smart Grid. In a traditional grid there is only a power network and the whole system lacks thorough monitoring of the state throughout the grid. Power grids are complex networks and represent a huge investment in physical infrastructure (which contains diverse components from cables and wires to transformers and towers). Sensors and computers were implemented centrally in this network many years ago; however nowadays these sensors are not ideal. Therefore, ICTs, which comprise new sensor networks, computational units, and various communication technologies, are now one of the key players in this domain. The ICT networks can operate at different levels, for example, to enable user appliance communication and automated meter readings in a HAN or to enable substation automation, asset health monitoring and mobile workforce management in a NAN and a WAN. Since Smart Grids are an emerging topic of research, many types of expertise from various fields have to be combined to meet the needs of such networks.

Figure 1.1: A Smart Grid Network.
1.2 Overview of the Problem Domain

In this section we\(^1\) will discuss the identified problem domains and the solutions used for resolving these problems in this thesis.

1.2.1 Primary Problem: ICT for the Neighbourhood Area Network (NAN) Level

In the near future, a large amount of electricity will be generated by decentralised micro-generators such as solar panels. These micro-generators could be placed in a close vicinity to the consumption areas, such as in buildings or close to neighbourhoods, which will be valuable in reducing the consumption of primary sources of energy (e.g. oil and gas) and in reducing emissions of CO\(_2\). Some of these micro-generators can transport their excess energy to the electricity network. These new additions to the power grid necessitate more monitoring and control of the grid which could be achieved through appropriate ICT networks. Moreover, the emergence of storage devices, such as electric cars, will impose new challenges for the grid which can be dealt with through future ICT networks. This means that the distribution level of the network, for example in a NAN, is no longer passive with respect to its transmission network but is dynamic and requires sophisticated monitoring and control.

On the other hand, current electricity grids are hierarchical structures with different levels, from the transmission level operating at very high voltages right down to neighbourhood and home levels of the distribution grid, with much lower voltages. A whole network of electricity sub-stations mediates these voltage step-downs via transformers that operate on electromechanical principles which are only subjected to occasional testing and maintenance. These components are thus not controllable in the sense that the processors and processor boards in a data centre are controllable. They are, moreover, located in fixed geographical locations and would be very expensive to replace. This is in contrast to the ease by which processors and processor boards can be slotted in and out of a large cluster in a data centre, or PCs can be moved or replaced in an office.

\(^1\) The author of this thesis is the sole author and the sole contributor to this thesis. However, the author has decided to use the word “we” throughout the thesis, since using “we” is common practice in scientific literature and can be used to refer to a generic third person.
means that the design used for ICT networks in electrical grids are different from those applying to general ICT networks.

In terms of Smart Grid ICT networks, this means that their data processing and automatic control strategies have to be adapted to a power transmission network that was not designed to be monitored and controlled in this way. The main exception is the home area network (HAN) level, where the increasing use of consumer devices equipped with microprocessors and the increasing ubiquity of home area wireless networks that can be powered from the electricity mains, means that they are starting to resemble the distributed networks commonly studied in ICT research.

In this research we have identified a lack in having an appropriate ICT architecture for the NAN level of the Smart Grid. This ICT architecture can be valuable for the monitoring and control of an electricity grid. As an example, it enables an understanding of the behaviour of electricity consumption, production, transportation and storage. Ultimately, the envisaged ICT architecture can lead to a better control of these issues and offer a more reliable power grid compared to a blind NAN level of a grid which is all that exists at the current time.

1.2.2 Solution to the Primary Problem

In this thesis we have investigated Smart Grid architecture above the home level. A key focus of this research is to design an ICT architecture at the NAN level of the Smart Grid in order to enable monitoring of the interaction between environmental variables and the electrical behaviour of the network. Rather than relying on historical records to extrapolate a “typical” diurnal pattern, we wish to monitor these interactions in real-time. This means integrating information from sensors placed in the environment, both within buildings and also outdoors, with sensors that are directly connected to the power network to monitor electrical variables (e.g. voltage, current and frequency). The ICT architecture for the Neighbourhood Area Network (NAN) level of the Smart Grid must be a distributed ICT architecture since the NAN is geographically distributed over distances to the order of thousands of metres. The primary purpose of the ICT network is to gather data and transmit it to appropriate control points. This architecture has integrated information-gathering sub-networks, such as WSNs, alongside networks of smart electrical meters and sensors monitoring the power network itself.
In this research we have been able to deploy our architectural proposals in a real sub-Grid which serves a university campus. This has the characteristics of very varied energy use and has considerable variations throughout the day and throughout the year (e.g. during academic vacations). This makes it a rich test bed for the Smart Grid research.

1.2.3 Secondary Problem: Energy Efficient Design for the ICT Network

Having studied, and conducted experiments in the real environment, we have identified that energy awareness is one of the prerequisites of an efficient ICT in the Smart Grid. The sensors deployed in the test bed cannot, for some parts of it, be powered from the electrical network but must derive power by other means, e.g. from batteries or solar cells. The key constraints of such wireless sensor devices deployed in the Smart Grid are due to their limited resources such as memory, battery and processing power. The battery technology used in a wireless sensor network (WSN) has a slower development rate than both the sensor device technology and the processor technology (Miao et al., 2009), thus minimisation of power consumption per unit of data collected and transmitted is the key architectural driver for a section of our ICT architecture which deals with WSNs.

In terms of the sensors deployed directly in the power network, it is sometimes possible to power them from the power network itself. However, using wired communication instead of wireless for these sensors is not always possible, or may be prohibitively expensive to enact. This is because the network components such as sub-stations and transformers are not accessible, both in terms of location and in the way they are enclosed, to easily wire them into a data network. Where such sensors can be powered from the power grid and can also be connected to wired data transmission networks, this offers some advantages. However, even in the wired case, energy efficiency is still important for reasons of cost (economical considerations) and reduction of CO₂ emissions (environmental considerations). Thus our ICT architectural design at the NAN level, which is prompted by this need, has to be as energy aware as possible and must be able to integrate both wired and wireless networks.

1.2.4 Solutions to the Secondary Problem

It is known from the literature that cluster-based networks, which are derived from the concept of locality, are generally more energy efficient than the centralised ones in terms of communication energy consumption (Heinzelman et al, 2000). We have divided a
Chapter 1

Introduction

Our NAN is the medium voltage power network of the University of Manchester campus. The university possesses its own distribution grid and it intends to provide a better understanding of the behaviour of this electrical grid at the sub-Grid level by finding out when fluctuations start, under what conditions, and what factors might influence them. In order to comprehend the characteristics of this level of the Smart Grid we have to monitor the behaviour of the grid with high frequency and accuracy. Consequently our system requires the DRACO to be a lossless method. Therefore, rather than anticipating when the network is going to change and adapting the rate of sampling, we monitor the grid all the time at high frequency. The focus of this part of our research is to use the wide NAN into several smaller NANs (called NAN1, NAN2, NAN3 …) resembling the clusters in the cluster-based networks. The two parameters, which most affect the communication energy consumption in a network, are data transmission distance and the number of transmitted bits. Therefore, in order to tackle the energy efficiency problem and enhance energy-awareness in our architecture we have followed two approaches. The first approach was to also apply cluster-based communication within each of these smaller NANs. The second layer of our proposed ICT architecture comprises WSNs for environmental monitoring; each of these WSNs has been divided into clusters to offer energy efficiency. We have analysed the energy-aware topology of such a network and thus, have examined the shape and location of these clusters with regards to their position in the network. The second approach was to apply data reduction on the collected data in order to reduce the number of transmitted bits. Therefore, we investigated developing a data reduction algorithm within an ICT architecture at the NAN level of the Smart Grid and experimented on the simulation data as well as real world data. Our proposed data reduction shows a reasonably good compression efficiency. However, this compression efficiency depends on the behaviour and characteristics of data. Our data reduction algorithm, which will be introduced later in this thesis, is called DRACO “Data Reduction Algorithm for COrelated data”. We will describe the algorithm itself and we will show how it can be incorporated into an ICT network for the NAN level of the Smart Grid. We will also present an evaluation of DRACO within this environment. We consider a key strength of our approach to be that we have not only designed this architecture and integrated DRACO within it, but we have actually deployed a working realisation of the architecture within a working NAN sub-Grid. Thus our evaluation is carried out not only in the computing laboratory but also in a realistic working environment.

Our NAN is the medium voltage power network of the University of Manchester campus. The university possesses its own distribution grid and it intends to provide a better understanding of the behaviour of this electrical grid at the sub-Grid level by finding out when fluctuations start, under what conditions, and what factors might influence them. In order to comprehend the characteristics of this level of the Smart Grid we have to monitor the behaviour of the grid with high frequency and accuracy. Consequently our system requires the DRACO to be a lossless method. Therefore, rather than anticipating when the network is going to change and adapting the rate of sampling, we monitor the grid all the time at high frequency. The focus of this part of our research is to use the
DRACO to extract data at a high data sampling rate and transmit the essential information, rather than sending all the data. This will provide energy efficiency and ease of data communication in our ICT architecture.

As well as the energy efficiency problem, the exponential increase in the number of monitoring devices in the Smart Grid will lead to an explosion in the volume of data. Recent evidence (McNamara and Meynardi, 2010; Allalouf et al., 2011; IBM, 2012) has confirmed the data volume problem in the Smart Grid. As we are not yet prepared to manage such a volume of data, we have to start developing new methods and techniques to ease the transmission and storage of such data. Thus our proposed ICT architecture could be a starting point for solving this problem.

To summarise, in this research we have designed an ICT architecture\(^2\) which has both a communication aspect and a software aspect. In this thesis we emphasis the communication side particularly the energy aware aspect of communication. However, as we expect that this architecture will be developed in the future, other aspects, such as control features, will become important; thus we have developed a software tool as a proof of concept which can be improved in the future, according to future need.

At the time we started this project in 2010, the concept of the Smart Grid was at its infancy stage; it was a vague subject and there were far fewer investigations and thus results at that time. Our research was one of the early researches in this area. However, in recent years, a growing body of researchers have been investigating diverse areas of the Smart Grid. Now that the foundations are being laid, and more and more investigations are being carried out by researchers, it is hoped that a modernised reliable grid will be achieved which can offer economic and environmental benefits in the near future.

### 1.3 Project Description

This project is part of a collaboration project between the School of Computer Science and the School of Electrical and Electronic Engineering in the University of Manchester led by Professor Ian Cotton. This research relates to the first phase of this mentioned

\(^2\) In this thesis we describe our architecture as an ICT architecture as it is the precise description of such an architecture. However, some other researchers refer to this purely as a communication architecture. Therefore in the literature review chapter we will use the term communication architecture when it is used by the authors themselves.
Project concerning the creation of a communication and monitoring architecture for the Smart Grid test bed provided in the University of Manchester. The University of Manchester owns a unique facility in the Manchester city centre. This test bed comprises of 6.6kV high voltage network owned by the University of Manchester which is fed from the primary substation on Upper Brook Street. A number of monitoring devices are provided and placed in this test bed. Additionally, real equipment, real data and professionals in this field are available which are valuable for validating our design decisions. As an example the substations are equipped with Compact RIO (cRIO) devices, monitoring attributes such as voltage, current, frequency, total active power, and total power factor. The substations with one transformer are supplied with a single cRIO, while the substations with two transformers are implemented with two cRIOs. These devices provide data with high frequency and high accuracy with three different phases for voltage and current. Currently cRIOs are running at frequency of 1 Hz. Figures 1.2-1.6 demonstrated the behaviour of these attributes over period of roughly one hour from 16:52 to 17:49 on 25th April 2013. As depicted below the variations amongst some attributes are low such as total power factor, frequency, and voltage, while some other attributes have higher variations during an hour. These monitored attributes can be used for applications such as fault identification in the system, or power quality analysis.

Figure 1.2: Monitored attributes during an hour at a substation in the University of Manchester (Voltage phase A).
Figure 1.3: Monitored attributes during an hour at a substation in the University of Manchester (Current phase A).

Figure 1.4: Monitored attributes during an hour at a substation in the University of Manchester (Frequency).
Figure 1.5: Monitored attributes during an hour at a substation in the University of Manchester (Total active power).

Figure 1.6: Monitored attributes during an hour at a substation in the University of Manchester (Total power factor).
Frequent meetings with power grid professionals led us to refine our designed architecture and detailed design decisions until the point where it met the professionals’ expectations. This project enabled us to check our ICT architectural design against a real environment whose challenges are different from a simulated environment. Our designed visualisation tool and designed data reduction algorithm are at the stage of going live on the campus. Since this part of the grid has not been instrumented before, no real deployment or measurement were provided (and much less information is available below 33kV), therefore, our research is quite novel since it will deliver the collected data from this level of the grid to the experts and will demonstrate what is happening in the lower voltage network that will, consequently, offer better control over the grid.

1.4 The Research Aims and Objectives

The primary aim of this research is to develop an ICT architecture for the neighbourhood area of the Smart Grid which enables collecting and monitoring data at this level of the grid.

The secondary aim of this research is to enhance communication energy awareness within the designed ICT architecture to fit within the potential energy savings of the Smart Grid.

Based on these mentioned aims, the objectives of this research are as follows:

1. To review the state-of-the-art for ICT in Smart Grids.
2. To investigate the design of an ICT architecture which could meet the needs of the Smart Grid at the NAN level, and which could cope with future developments.
3. To review the literature on the two selected approaches for providing energy awareness to the designed ICT architecture.
4. To investigate an approach for providing an energy aware topology for the layer of the ICT architecture that comprises WSNs.
5. To investigate a practical approach for developing a data reduction algorithm in order to reduce the volume of data prior to data transmission. This data reduction
is informed by measurements from a real power network on the University of Manchester campus.

This project was limited by a number of constraints during the design and implementation process. The first limitation was the lack of literature or previous work in this area. Additionally, since this was a collaboration project it was limited by requirements of Electrical Engineers. During the experimentations of the ideas that were developed during the course of this project we had no control on the sensor side, the given data, and the software embedded in our sensor devices.

1.5 Research Methodology

In this research, in order to develop an ICT architecture incorporating energy awareness considerations for the NAN level of the Smart Grid we have used a number of different methodologies, namely, architectural design approaches, software design approaches, algorithm design approaches, experimental investigations, simulation tools, and an application of analytic methods. In this research we have conducted a thorough literature review of four diverse topics which ultimately led to the creation of our research. Each of these literature reviews are related to a specific chapter within this thesis. We have also utilised a number of different programming languages and technologies such as MATLAB, ASPX, CSS, JavaScript, and tools such as MATLAB, Visual Studio and TinyDB to implement and realise our designs. Additionally, our data collection method was divided into two approaches; the first approach was to exploit real data collected from real instrumentation within our test bed (which is a part of an actual working power grid), and the second approach was to generate simulated data where real instrumentations were not available.

Chapter three, which is the core of this research, is an experimental investigation that proposes how to design an ICT architecture at NAN level of the Smart Grid. In this chapter we have taken the principles established for architectural design in different domains and have adopted them and applied them in a real situation, for designing an ICT architecture in a real-life scenario. This is a particularly important investigation, especially at this stage, because most of the studies in the literature are based on simulations or they
are purely suggestions and ideas for future development. However, in order to move forward in this area of research we have commenced implementing and testing these ideas in real situations, getting real results and analysing these results. Accordingly, we have taken this research further and have implemented the important parts of our designed ICT architecture in a real working electrical grid. Additionally, we have designed and implemented a software tool as a proof of concept to represent how data can be collected, visualised and turned into useful knowledge at this level of the grid. This tool has been discussed in the Appendix B.

After the architectural design phase of our research, in order to enhance the energy awareness within the system, we have investigated two approaches using different methodologies. Since data transmission distance and the volume of transmitted data are the two most influential parameters on the total energy consumption of the communication system in our ICT architecture, we have investigated each of these issues in a separate chapter within this thesis. Accordingly, in the first approach, we utilised the concept of cluster-based communication instead of direct communication for a layer of the architecture where energy limitation is a determining factor in the design. This approach utilised numerical analysis and simulation and is discussed in chapter four. In the second approach, we designed and developed a data reduction algorithm suitable for NAN level of the Smart Grid. In this approach we used synthesized data and also experimental data collected from the instrumentation of the electrical grid; thus we were able to evaluate our design ideas and realisation in the real environment rather than in a simulated environment only. This approach has been discussed in chapter five.

Finally, all these various approaches fit together to create an energy aware ICT architecture for monitoring and collecting data from the distribution network of an electrical grid, which has remained unexplored until now.
1.6 Research Contributions

This research offers theoretical contributions as well as practical contributions. In this section we will firstly present the main contributions of this thesis and then we will present the contributions made to the Smart Grid community via a number of publications which have been produced as an outcome of this research.

1.6.1 Thesis Contributions

The contributions of this work are:

- Identifying the gap in current proposals for the communication network of the Smart Grid which, until now, had lacked an ICT architecture for the NAN level.

- Proposing and designing an ICT architecture for the NAN in the Smart Grid which can incorporate data from heterogeneous sources. This architecture has been designed based on established architectural principles. It enables electrical engineers to analyse a part of an electrical grid which has remained unexplored until now.

- Implementing the important aspects of the proposed ICT architecture in the real environment. This implementation is unique and provides the basis for future analysis and development of the grid.

- After the identification of the general gap in current studies, we have narrowed down our research and have identified a more specific gap in this area, namely, a lack of energy awareness in the communication system of the NAN which has to fit within the prospective energy saving of Smart Grids.

- Analysing an energy aware topology for the area of the NAN which mainly comprises battery operated devices with wireless communication. We have discussed that the suggested topology dissipates less energy.

- Developing a practical data reduction algorithm suitable for correlated data to be collected from the NAN level of the grid. This data reduction has been tested on real data rather than synthesized data and it has been proved that it can reduce the amount of transmitted data with a generally good compression rate.
1.6.2 Contributions to the Smart Grid Community

In addition to the above key contributions, 9 main publications were presented to the Smart Grid community during the course of this PhD. In addition to these 9 main publications, 5 invited presentations were also presented to other parties. These works are as follows:

**Book chapter:**


**Peer-reviewed journal papers**: 3:


**Peer-reviewed conference papers:**


---

3 Additionally, two more journal papers each concerning one chapter of our work is in the process of submission.


**Extended abstracts and invited presentations:**


2. Poster presentation for research symposium in the School of Computer Science in the University of Manchester, November 2011.


4. Oral presentation in a research symposium in The school of Computer Science in the University of Manchester, October 2012.


**Summer schools attended:**

1. Summer school: CICADA, 2011, Manchester, UK


1.7 Thesis Structure

This thesis is structured as follow:

Chapter 2 provides the background and surveys the available studies relating to this research. It has been divided into four main sections. Each of these sections relates to one of the chapters of this thesis. The second section discusses the background to the research. The third section reviews the literature on ICT networks in Smart Grids. The fourth section reviews the literature on providing energy aware topology for WSNs. And finally the fifth section reviews studies on data reduction techniques.

Chapter 3 presents the background of this work. It then proposes an ICT architecture for the NAN level of the Smart Grid and discusses this ICT architecture in terms of its five layers and its implementation. It also presents the applications of sensor networks in the Smart Grid.

Chapter 4 discusses the influence of topology on energy consumption in WSNs. It analyses the total energy consumption in a cluster-based WSN. It evaluates the proposed cluster-based WSNs in terms of providing evidence that cluster-based communication in WSNs is more energy efficient than direct communication in WSNs. Additionally, it validates the behaviour of energy consumption within our WSNs and provides a critical analysis of previous work in this area.

Chapter 5 describes the data reduction algorithm developed for the NAN level of the Smart Grid. It discusses this algorithm in terms of its principles, design and implementation. It evaluates the proposed algorithm by testing its compression during a 24 hour period. It evaluates the effect of changing the frequency of data acquisition. Finally, it analyses the effect of different bit-rate on the proposed algorithm.

Chapter 6 presents the architectural styles and principles we have used in the design of such our ICT architecture for the NAN level of the Grid. It then evaluates the design of our proposed ICT architecture according to a number of parameters identified for the evaluation of an architecture.

Finally, chapter 7 concludes this research and suggests relevant topics for future research.
Chapter 2. Background and Literature Review

2.1 Introduction

In this chapter firstly we will present a brief overview of the background to this work, then we will discuss three diverse literature reviews, each relating to one of the chapters in this thesis. Section 2.2 provides an overview of the background research. Section 2.3 which relates to chapter 3 discusses the available literature on the ICT network for the Smart Grid. Section 2.4 which relates to chapter 4, reviews the literature concerning providing an energy awareness for a WSN topology. Section 2.5 which relates to chapter 5, looks at studies on data reduction techniques.

2.2 Background on Distributed Systems

In this section we will briefly present the history of distributed systems, the types and topologies of such systems.

Distributed systems can be defined as a network of computers in which communication and coordination of their actions can be achieved through passing messages (Coulouris et al., 2012). In this system a remote user can be connected to remote resources which can be spatially distributed throughout a room, a building, a country, or a continent. These resources should appear as a coherent system to the user. A famous example of such system is the Internet in which users can use resources in a consistent manner without knowing where the data and resources are hosted or created.
The distributed systems’ concept refers back to the idea presented by Lickliders in 1960 (Licklider, 1960) which envisioned cooperative interaction between men and computers in order to enable decision-making and control of complicated situations. This idea came into practice by the creation of the world’s first packet switching network called ARPANET (Advanced Research Projects Agency Network) by the US Department of Defence. ARPANET became publicly available in 1970. The initial ARPANET comprised four nodes in which messages were exchanged between computers embedded in a wide area network. With the aim of sharing information and resources, ARPANET further led to the creation of academic networks. In 1989, Tim Berners-Lee submitted a proposal (Berners-Lee, 1989) discussing the linking and sharing of information over the internet. This proposal eventually became the World Wide Web (www). Finally, in 1993, Mosaic became the first popular web browser which enabled texts and images to be on the same page; this helped the web to flourish as the main source of information and resource sharing in today’s lives.

In order to design a distributed system, factors such as types of network and network topologies should be considered. This will be discussed in the following subsections.

2.2.1 Types of Networks

The fundamental requirement of individual computers communicating through a network is the availability of wired or wireless media. Taking on board issues such as network scale, bandwidth usage, and privacy, different types of computer networks can be realised. The most common types of computer networks which supports distributed systems are as follows (Coulouris et al., 2012): Local Area Network (LAN), Metropolitan Area Network (MAN) and Wide Area Network (WAN).

Local Area Network (LAN)

LANs are usually distributed over a relatively shorter distance than MANs and WANs. They enable communication between computers over a range of up to 2km via twisted pair copper wires, coaxial cables, or fibre optics with a relatively high speed. A LAN is appropriate for the type of network which offers networking services to areas such as a home, an organisation, or a university campus. A segment of a LAN is the part of the

---

4 All the bandwidth and transmission distance values in this section are taken from Coulouris et al.’s (2012) fifth edition. However these values might be different from reference to reference.
network that has many computers attached, which directly communicate to it; this can serve a floor of a building or a department. However, a large LAN can comprise many segments connected by hubs or switches. The typical available bandwidth for LAN is between 10Mbps to 10Gbps.

Wireless LANs (WLANs) enable communication between computers without the wired infrastructure in a LAN. WLANs mainly use IEEE 802.11 standard (WiFi) which provide bandwidth up to 100Mbps to cover up to 1.5km.

One sub-category of a LAN is a Personal Area Network (PAN) where a number of personal digital devices are connected together by low cost, low energy technologies such as Bluetooth.

**Metropolitan Area Network (MAN)**

MANs are typically distributed over longer distances than LANs and over shorter distance than WANs, for example, to cover a city or town. MANs are owned by large companies and governmental organisations such as ISPs (Internet Service Providers) or telecommunication operators. They use high bandwidth communication media such as copper and fibre optics. A MAN data transmission range is between 2km to 50km with a bandwidth range of 1Mbps to 600Mbps.

Wireless MANs (WMANs), which are alternatives to wired MANs, mainly use IEEE 802.16 standard (WiMAX) which provides a bandwidth up to 20Mbps and a distance coverage of up to 50km.

**Wide Area Network (WAN)**

A WAN is typically used to provide communication between computers which are geographically distributed over a large distance such as worldwide (e.g. the Internet). WANs are usually owned by a group of organisations cooperating to provide services. WANs have higher latency compared to MANs and LANs which depend on the route which is chosen to convey data and the traffic load on the different network segments that the data traverse. The available bandwidth for WAN is currently up to 600Mbps.

Wireless WANs (WWANs) use technologies such as the GSM (Global System for Mobile communication) standard for providing communication between mobile phone networks. These mobile phone networks can cover a whole country or continent via utilising
cellular radio connections with relatively lower bandwidths up to 33kbps. However, the third generation (3G) of mobile phone networks offer bandwidths up to 14.4Mbps while stationary, and up to 348Kbps in a moving vehicle such as a car. Additionally, fourth generation (4G) provides data rates up to 100Mbps.

2.2.2 Distributed System Topologies

The topology of distributed systems defines the arrangement of the components in the network and describes how these components should interact with each other. The basic distributed system topologies are such as centralised, ring, hierarchical and decentralised. In this section we will briefly discuss each of these topologies. Additionally, the effectiveness of these topologies can be evaluated against a number of parameters which will also be discussed below (Minar, 2002).

Centralised Topology

Centralised systems are the ones where all the data and services are concentrated in a central node which makes it fairly easy to manage and make secure. The other advantages of the centralised system are its simplicity and the fact that it offers information coherency, whereas the potential single point of failure is its main disadvantage, and its scalability potentials are not clear. Extensibility in this type of topology is hard to achieve because new resources can only be added to the central node. Figure 2.1 depicts a centralised topology network. Examples of centralised systems are typical web servers, and database servers.

![Centralised topology](image)

Figure 2.1: Centralised topology.

Ring Topology

Ring topologies (see Figure 2.2) are the ones where a cluster of nodes are arranged in a ring, whereby each individual node connects to the two neighbouring nodes to create a
continuous path which represents a distributed system for resource sharing. In this topology each node can perform an identical function. It is assumed that, in ring topology, nodes are near each other and that the whole network has a single owner. Ring topology networks are manageable, scalable, coherent, fault tolerant and relatively secure. However, they are not extensible as they are owned by a single owner and the user requires the permission of the network owner to add resources. An example of this topology is a cluster of machines used for load balancing, whereby state information is shared between the nodes.

![Figure 2.2: Ring topology.](image)

**Hierarchical Topology**

Hierarchical topologies (see Figure 2.3) are the ones that have a tree structure, such that each node is connected to several other nodes and each of these nodes are connected to a number of different nodes, and so on. This is a common topology in large organisations. Hierarchical systems are, to some extent, coherent, extensible and partially manageable. However, the root can be considered as a single point of failure and hierarchical systems are more difficult to be made secure. Additionally, they have a good degree of scalability.

![Figure 2.3: Hierarchical topology.](image)
Decentralised Topology

Decentralised topologies (see Figure 2.4) are the ones where each node is responsible for providing some services and there is no single node which provides all the services. In this topology, nodes can communicate to each other through other nodes in the network which act as a relay, and can be a service provider, or a consumer or both. Although offering information coherency, managing and securing this topology is difficult. It is extensible and scalable and a single point of failure has been avoided in these networks.

A summary of the network topologies and evaluation parameters discussed above is presented in Table 2.1 (Minar, 2002). It is not possible to identify which topology is the best in all circumstances, as each of these topologies has its own advantages and disadvantages. For example, while centralised systems are easier to manage, decentralised systems are more extensible and prevent single points of failure. Therefore, depending on the desired application of the network, one should choose which topology to select, or use a hybrid of these topologies.

Table 2.1: Comparing the evaluation parameters for different distributed system topologies.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Centralised</th>
<th>Ring</th>
<th>Hierarchal</th>
<th>Decentralised</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manageability</td>
<td>✓</td>
<td>✓</td>
<td>partially</td>
<td>✗</td>
</tr>
<tr>
<td>Information Coherence</td>
<td>✓</td>
<td>✓</td>
<td>partially</td>
<td>✗</td>
</tr>
<tr>
<td>Extensibility</td>
<td>✗</td>
<td>✗</td>
<td>partially</td>
<td>✓</td>
</tr>
<tr>
<td>Fault-Tolerant</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Security</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Scalability</td>
<td>?</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
2.3 Literature Review on the Smart Grid

2.3.1 Introduction

As discussed earlier, smart electrical grids are called Smart Grids. Other terms used for the Smart Grid within the literature are a smart power grid, a future grid and an intelligent grid. The Smart Grid can be viewed as resembling the internet (Daoud and Fernando, 2011). Instead of uploading and downloading data, customers upload and download electricity. Rather than using a modem representing the data usage, customers have smart meters indicating the amount of electricity they have used or generated and, accordingly, the price incurred.

As mentioned earlier, the Smart Grid is the integration of a power network and an ICT network to meet the future requirement for energy. A power grid, responsible for transmitting energy from generation point to the customers, consists of three layers: generation, transmission and distribution. Similarly, the current proposal for an ICT network, responsible for collecting and routing data between different sectors in power grid, has three layers; Wide Area Network (WAN), Neighbourhood Area Network (NAN) and Home Area Network (HAN) (Rong et al., 2011). The WAN covers the generation, transmission and distribution network of the power grid. The NAN and HAN covers the rest of the distribution grid ending in the consumers’ premises.

Until now most research has focused on monitoring and controlling at the WAN and HAN levels. By contrast, we have particularly investigated monitoring the NAN and we describe, in this study, how it is being implemented in a test bed of monitoring devices installed in a 6.6 kV sub-Grid on a university campus. Until now it has not been understood how a NAN functions as a grid, thus NANs have been and are controlled from higher levels. Our research aims to provide such monitoring architecture at the NAN level of the grid. Thus in this thesis we have proposed an ICT network to provide these functions. The ICT architecture should enable the collecting, routing and monitoring of data (Daoud and Fernando, 2011). It should encompass the networking aspects of the NAN and consider energy awareness issues in such a system, since energy awareness have been identified as one of the major considerations of the communication system. In this section we will study the current proposal for the topology of the Smart Grid, and
the communication requirements of this system. Then we will investigate the existing proposals for the Smart Grid communication architecture.

2.3.2 Smart Grid Topology

Traditional electrical grids comprise electricity generation plants, transmission and distribution substations, and consumers (Rengaraju et al., 2012). These grids carry power from a limited number of central generators to a large number of end users. In contrast, the Smart Grid carries both power and data in a two-way direction to construct an advanced energy grid. One of the aims of the traditional power grid was to reduce the investment in power generation, transmission and distribution in order to minimise the cost of energy for the customers. Currently, total power generation capacity is higher than peak total power usage which has removed the need for measures to limit consumption at the end users’ side. However, in future the increase in population and usage will lead to greater power consumption and an unstable demand with spikes which will result in overloads and blackouts in the power grid. Thus it is becoming more important to invest in information gathering and processing functionality which can be added over the traditional power grid to balance generation and consumption. This has led to the birth of Smart Grids. This added functionality over power grids necessitates having a communication network in order to carry data between the different elements of the grid (Rengaraju et al., 2012).

Since the communication network of the Smart Grid is a huge network, it has been generally divided into three sub-networks by various researchers, based on their geographic area and applications. Each of these sub-networks encompasses a number of sensing devices, a few substations and control centres. For example, Daoud and Fernando (2011) divided the communication network into the following three sub-networks: core, distribution and access networks. The core network is in charge of connecting the centralised control centres to the substations and the distribution network. In case of a critical situation, such as power consumption exceeding the peak load, the control centres are responsible for taking preventive action. In normal cases they are responsible for analysing power consumption and billing. The distribution network of the communication network is in charge of establishing connections between the sensing devices on the grid and the core network to convey data that are collected by these devices to the databases and
computational units in the control centres. It is responsible for monitoring power consumption and provides a balance between power consumption and generation. Finally, the access network of the communication network is in charge of establishing connections between homes and offices to the sensing devices and transmitting the data collected at this level to the distribution network. It is responsible for monitoring end users’ power consumption and generation, and also the behaviour of the end users in order to inform the grid of any rise or fall in demand.

In another example, Kumar P et al. (2011) classified the Smart Grid communication network into the three sub-networks of Wide Area Network (WAN), Neighbourhood Area Network (NAN) and Home Area Network (HAN). WAN is considered as the communication path between the grid operator and the concentrators. The concentrators are responsible for collecting data from meters and field devices. They are usually located in streets in order to gather data from homes and buildings nearby. NAN is considered as the communication path between the concentrators and the energy meters which link customers to the grid. Finally, HAN is considered as the communication network between in-home devices.

Each of these networks can be implemented using different communication technologies. The use of various communication technologies, such as wired and wireless, has been suggested by various researchers such as Daoud and Fernando (2011). However, the faster pace of change in wireless technologies compared with changes in utility infrastructure is a challenging issue. Accordingly, in this project we have focused on the NAN and designed an Information and Communication Technology (ICT) architecture at an abstract level, independent of the choice of any particular communication technology, for this specific area of the Smart Grid. In the next section, we discuss the communication requirements of such networks.

2.3.3 Smart Grid Communication Requirements

The communication network in the Smart Grid is responsible for carrying information about the grid and for facilitating communication between the various elements of the grid in order to deliver energy more efficiently and to enable end users to manage their energy consumption. In this section firstly we will discuss some of the requirements for such a communication network that have been identified by existing research. Then we
will present a number of issues which should be considered in order to meet the communication requirements.

Research published by Rohjans et al. (2012) has discussed the requirements for the ICT architecture in the Smart Grid. This study was published after we had completed the design of our ICT architecture for the NAN, but our designed architecture meets a number of requirements specified by this research. The authors divided the requirements of the Smart Grid ICT infrastructure into two types, namely, non-functional requirements and architectural requirements. Non-functional requirements address the overall system while architectural requirements address the characteristics of the basic element of the system. Moreover, non-functional requirements address the performance issues whereas architectural requirements address the design decisions.

Accordingly, Rohjans et al. (2012) have classified the non-functional requirements of the ICT network for the Smart Grid into seven main classes which are: performance, space, dependability, security, environmental, operational and developmental. Subsequently, a number of requirements have been introduced within each class to meet the goals of the Smart Grid.

The first class of requirements is performance. The desired requirements in this class include supporting various values of latency and bandwidth, and supporting different frequencies of exchanging data. Some of the requirements in this class have also been identified by other researchers.

The second class of requirements is space considerations. This class necessitates managing a huge amount of data collected from millions of monitoring devices. We have considered this issue by decentralising the data storage, such that each area is responsible for managing the data related to that area.

The third class of requirements is dependability. This class demands the extensibility of the architecture to be able to incorporate the idea of multi-utilities (gas, water, heat). In the design of our architecture we have already considered the incorporation of gas, water and heat meters.

The fourth class of requirements is security. This class demands that only authorised users have access to the data and that no data can be modified without permission. It also
Requires consistency between the original and backup data. Although, the concept of security is out of the scope of this research, we have provided for only authorised users to access the data collected from the field.

The fifth class of requirements is consideration of the immediate environment of the infrastructure. This class requires the integration of different types of data, such as internal and external data, and it affects reliability and redundancy issues. An example of this class could be the temperature in the data centres, which is external data. Temperature can affect the reliability of the ICT infrastructure, as high temperatures can cause component failure; this is where redundancy for the components is required. Consideration of the environment affects the ICT network and the electricity network differently. In the electricity grid, temperature, which is also considered as external data, has a different impact. Temperature in an electricity grid can change the way people use electricity, for example, in high or low temperatures people start using cooling or heating systems which will, in turn, affect the electricity grid.

The sixth class of requirements is operational considerations. This class is concerned with monitoring, controlling functionality and the location of the devices in terms of geography. It also addresses the need for controlling, not only a single device, but also as a group of devices. In the design of our architecture we support both monitoring and control functionalities in different layers of the architecture. We also have provided a geographical information system interface which locates the monitoring devices and represents their data. Also, we consider controlling a single device, as well as a group of devices, by adopting the concept of clustering in our design.

Finally, the seventh class of requirements concerns developmental considerations. This class is mostly concerned with implementation issues such as enabling the tracing and auditing of exchanged information.

In addition to the seven classes of non-functional requirements, Rohjans et al. (2012) have introduced architectural requirements. Although many of the requirements specified are related to the implementation of an architecture, there are some others that relate to the design of the architecture. Accordingly, the architectural requirements of the system are as follows: supporting decentralised systems and providing capability to analyse and process data collected from the field. This includes considerations of: wired and wireless communication, two-way communication, alarm handling, fail-safe scenarios,
and changes of topology. Finally, consideration of the concept of layering and loosely coupled components within the ICT architecture of the Smart Grid are some of the architectural requirements pointed out by the above-mentioned research. Our designed communication architecture is a decentralised layered system, with loosely coupled components, that offers analysis and processing of data collected from the test bed. It can also utilise a hybrid communication technology. Moreover, an alarm system has already been implemented in the architecture and a number of failure scenarios have been considered. The details of these requirements are discussed in chapter 6.

In addition to the requirements discussed above, Daoud and Fernando (2011) have identified reliability and availability as another requirement of the system. The reliability and availability of the communication structure depends on implementation issues such as the choice of communication technology, as well as design issues. For example, wired communication technologies with improved bandwidth, high reliability and security are costly, whereas wireless technologies with limited bandwidth and less security are easier to deploy and are less costly. Therefore, in order to balance the reliability and availability of a communication system with cost considerations, a hybrid communication technology using both wired and wireless technologies has been suggested.

The other requirement of the communication infrastructure within the Smart Grid, which has also been identified by Daoud and Fernando (2011), is the scalability of the system. This network should be scalable enough to integrate new functionalities, sensing devices and renewable energy resources which might be added to the communication network of the Smart Grid in future. We have discussed scalability considerations in our designed communication architecture in chapter 6.

Bouhafs et al. (2012) have identified a number of challenges and issues that need to be considered in order to satisfy the communication requirements of a Smart Grid. One of these challenges is the migration from a centralised communication approach to a more distributed approach. The control system of the traditional power grid is a centralised system which encompasses control devices, namely, master and slave remote terminal units (RTUs). These slave RTUs are located within remote sections of the grid and periodically transmit their measurements to the master RTU which, in return, transmits control commands to the slave RTUs. However, to make the Smart Grid a reality, the control
system of such a network should become more distributed in order to provide functionalities that are not available in the existing system (Bouhafs et al., 2012). Accordingly, our designed ICT architecture is a combination of the centralised and distributed approaches.

Another issue which should be considered in order to overcome these network challenges and meet the Smart Grid requirements is a consideration of the communication network management. Smart Grid networks are responsible for collecting and transmitting large volumes of data which requires the efficient transmission of data between control devices and control centres. This can be achieved through managing such networks effectively. Bandwidth and latency are examples of network management parameters. Accordingly, high bandwidth and low latency are required for such systems. High bandwidth is required to enable the transmission of large volumes of data between different elements of the grid. The solution to this issue would be either to upgrade the communication media (e.g. fibre optics, radio waves) as well as the communication technologies (e.g. 3G, WiMAX, etc.) or to store data in substations and exchange only appropriate and relevant data among the various units (Bouhafs et al., 2012). Our designed communication architecture is independent of communication media or technology, thus it can be realised via a number of different media and technologies. Hence, to alleviate bandwidth considerations, we have extended the approach of storing data in local storage within each neighbourhood area, and only small portions of data are conveyed.

Latency is another parameter that should be considered for managing the communication grid more effectively. Latency is the time data takes to be transmitted from one location to another location in a network. Different applications in the Smart Grid will have different latency requirements. For example, less stringent latency is required for system wide controls while lower latency is required for local analysis (Daoud and Fernando, 2011).

The final challenge in such a network which has been identified by Bouhafs et al. (2012) is extending the communication to the whole electricity grid including end user homes and the neighbourhood area. Generally, these areas necessitate lower reliability and connectivity requirements such as bandwidth and latency (Bouhafs et al., 2012).
To summarise, the communication requirements for the Smart Grid as discussed in this section are ones identified by other researchers. However, in addition to these requirements, we have identified the energy awareness requirement for the communication infrastructure in the Smart Grid. Energy awareness is important both for wired and wireless communications. In general, it is important for wired communications due to factors such as potential economic benefits and environmental impacts (Bianzino et al., 2012). In wireless communication, energy awareness is important because wireless devices have power limitations. We will discuss this requirement in more detail and how we have tackled this issue later on in this thesis.

2.3.4 Related Work

The purpose of this section is to review the literature on proposed ICT architectures of Smart Grids. Surveys such as those conducted by Wang et al. (2011), Yan et al. (2013) and Safdar et al. (2013) have studied the communication infrastructures of Smart Grids, the importance of such communication infrastructures, their challenges and requirements, and the available communication technology. However, they have not discussed the architectural design and principles for such networks.

Other investigations, such as Singh et al. (2013) and Salvadori et al. (2013) have proposed communication architectures for Smart Grids. In the former paper, the authors have proposed a two-tier communication architecture in which two different communication channels are used between smart meters and control centres based on normal or emergency scenarios. In latter paper, the authors have proposed a hybrid network architecture for industrial, commercial and residential sections of the Smart Grid by integrating a wired infrastructure, WSN and Power-line Communication (PLC) (Salvadori et al., 2013). However, our architectural design is independent of the communication technology used.

Moreover, researchers have proposed different techniques for providing communication in Smart Grids. As such a study in 2013 (Fan et al., 2013) has proposed a cloud computing architecture for the overall Smart Grid network. This architecture is at the proposal stage. Another study has discussed the design of a client server architecture for the Smart Grid using TCP/IP for information transmission (Ali et al., 2012).
Additionally, a very recent study (Nabati et al., 2015) has proposed an energy-efficient architecture for Smart Grids. They have considered a WSN architecture for Smart Grids in which energy limitation is the main issue. Accordingly, they have proposed a hierarchical routing protocol to decrease energy consumption. In this research the authors simply considered a WSN for the whole grid and tested their ideas on a simulated network with dimensions of 200m×200m comprising 100 nodes using an opnet network simulator. This research confirms our idea of the importance of the consideration of energy-awareness in the ICT infrastructure of the Smart Grid. However, they did not propose a proper ICT architecture for the Smart Grid according to the requirements for an ICT infrastructure in the Smart Grid. Although Nabati et al.’s research has confirmed the importance of energy-awareness within the communication in Smart Grids, they have only considered this energy efficiency for the WSN of such grids, while the energy-aware considerations in this thesis goes beyond only the WSN. In our proposed ICT architecture, energy-awareness has been considered in the design of such an architecture, as well as the WSN section of it.

One of the distinguishing architectural considerations in designing a system is the choice of either centralised, distributed or a hybrid approach. Research by Krkoleva et al. (2011) proposed a distributed approach. They proposed the Gossip algorithm to implement the communication infrastructure of the Smart Grid. The Gossip algorithm is a distributed approach that provides fault tolerance and guarantees the delivery of messages. Gossiping can offer robust communication for sub-Grids and it is a good choice when a global view of the network is not available. However, we know the topology of our test bed, thus not being aware of the topology of the network is not an issue in our project. Moreover, time to fulfil thorough message dissemination in the Gossip algorithm depends on the graph connectivity whereas in our architecture we need to support real-time data.

In 2012 and 2013, two papers by Negeri and Baken (2012) and Moghadam and Mozayani (2013) respectively studied a holarchy architecture for designing IT infrastructure for the Smart Grids. The word holon means a logical entity that in itself is a whole system while, recursively, it is an entity of wider system. Figure 2.5 depicts a holarchy system. The authors (Negeri and Baken, 2012), discussed whether a Smart Grid architecture should migrate from a centralised top-down approach to a decentralised bottom-up approach.
Prosumers (producers and consumers) are combined recursively from various aggregation layers to create the entire power grid. Negeri and Baken considered each individual prosumer as a holon; holons then form the overall power grid which is a holarchy.

Figure 2.5: A holarchy system comprising holons (Negeri and Baken, 2012).

In an investigation into the communication network architecture of the Smart Grid, Shao et al. (2013) introduced a three layer distribution and consumption network architecture for the Smart Grid. These three layers are: a power distribution communication network (PDCN), a user access network (UAN) and a home area network (HAN). These authors discussed applicable communication technologies in each individual layer and their business services and needs that could take place in each layer. However, they did not follow any specific architectural style or principles and also they did not attempt to simulate or implement their proposal.

Another study divided the Smart Grid communication network into three sub-layers (Al-Omar et al., 2012), based on the services they offer, the types of devices and the communication media. These three layers are the AMR networks layer, the AMI networks layer and the AMI + networks layer. Then Al-Omar et al. classified the communication network into consumer premises networks (CPNs), neighbourhood area networks (NANs), access area networks, backhaul networks, core and office networks, and external access networks. The main difference between the NAN architecture we have designed and the NAN proposed in Al-Omar’s paper is that the NAN in this paper is responsible for collecting data from the CPN via smart meters and conveying them to the utility data storage and to the processing unit, as shown in Figure 2.6. Thus data processing and analysis is not taking place in the NAN itself. Additionally, in this paper the substation monitoring is located in the core network, whereas we propose substation monitoring at the NAN
level as well as at the core level which offers information that has not previously been collected. The other difference is that, in our architecture, we are not only monitoring the electrical attributes which are collected through smart meters and substation monitoring devices, but, additionally, we are also collecting information about external systems such as environmental data that could affect the behaviour of the grid.

![Diagram of Smart Grid communication network](image)

Figure 2.6: A Smart Grid communication network (Al-Omar et al., 2012).

A study by López et al. (2012) discusses a model for the NAN in the Smart Grid. In order to evaluate which communication technology is the most appropriate for the NAN they proposed using simulation. However, the results of such simulations depend on the model proposed for the NAN and how well it matches real world scenarios. In their paper they proposed a model to evaluate the communication architecture of the NAN in the Smart Grid. Figure 2.7 depicts the overall communication architecture they used as a model. As can be seen, the NAN in this architecture comprises a CNTR (Concentrator) which is responsible for collecting data from the ADR EPs (Automatic Demand Response End Points) which are located in homes and buildings. These then pass this data to the M2M (Machine to Machine) gateway that is associated with substations and then convey this data out of the NAN to the higher levels of the Smart Grid for further analysis and control. The authors of this paper proposed that, in future, they intend to use simulation to evaluate several different issues such as the performance of selected communication technologies and the maximum number of users that can be served by a CNTR. The difference between this research and ours is that they did not discuss the monitoring and control
background and literature review

Aspects of the NAN, and it seems that data analysis is happening outside the NAN network. Moreover, although they discussed a communication architecture for the NAN, they did not consider a thorough ICT network design based on the styles and principles established for designing an architecture. The final difference between López (2012), Al-Omar et al. (2012) and ours is that they are going to implement their model in a simulation environment, whereas we are implementing our model in a real world environment.

Figure 2.7: The communication architecture used by López et al. (2012).

In 2013, Chen et al. (2013) proposed a four layer information architecture for the overall communication network of the Smart Grid. These four layers, as depicted in Figure 2.8, are: the equipment layer, the communication grid layer, the data storage layer and the data application layer. The equipment layer comprises numerous grid components and devices that enable transmission of data. The communication layer is responsible for providing communication between different devices. The data storage layer is responsible for storing data and providing integration of data from heterogeneous devices. Finally, the data application layer provides analyses and control functionalities. Chen et al. believed that a consideration of multiple layers in the information architecture provides a robust foundation for data transmission and supports the Smart Grid operation. The similarity between this research and ours is the use of the layering concept. However, the first difference between this research and ours is that we have proposed a specific architecture for the NAN level while their research has proposed a general information architecture for the whole Smart Grid. The second difference lies in the process of layering
and logic behind the architecture. For example, although our architecture provides the main functions of monitoring, data communication, data storage and control in different situations, these functionalities are mapped into five layers and a number of sub-layers, based on the similarity between their functionalities and responsibility, and we create a new layer when there is a need for a different level of abstraction. Additionally, we have not presented data communication as a separate layer, although it provides connectivity between various components of our architecture. The third difference is that the design of Chen et al.’s information architecture lacks a discussion on the architectural styles and principles. Finally, Chen et al.’s architecture, similar to other proposed information architectures, is only at the proposal stage and has not been simulated or implemented yet.

A study in 2013 (Hammoudeh et al., 2013) proposed a communication architecture for the NAN in the distribution network of a power grid. Hammoudeh et al. described five different communication architectures for the NAN, which are depicted in Figure 2.9.

The first architecture (as shown in the Figure 2.9a) is the simplest one, whereby each individual smart meter can communicate directly to the data hub inside the substation.
This architecture is effective for a low-density area. The second architecture (as shown in Figure 2.9b) uses data aggregators to aggregate data collected from the smart meters before transferring them to the data hub in the substation. This data aggregation is happening within each neighbourhood area network, which is responsible for establishing connections between smart meters in consumers’ homes and substations in the wide area network (WAN). The advantage of this architecture is that it reduces data rates. The third architecture (as shown in Figure 2.9c) is same as previous one but it provides communication between adjacent NANs. This is a viable option in the case of islanding. Islanding is a state in which a part of the electricity grid is detached and is no longer being powered by the electricity utility. This scenario enables the sharing of the distributed generation resources which reside within adjacent NANs. The fourth architecture (Figure 2.9d) contains the same features as the third architecture plus it, additionally, enables communication between the smart meters. Finally, the fifth architecture (Figure 2.9e) enables consumers to use their existing internet service to communicate with the utility data aggregation device. However, this is not a viable option for rural areas where an internet service is rarely available or is costly in the case of utilising satellite-based services. The advantage of this architecture is its low cost of deployment and usage, as it is assumed that consumers already have access to the internet. The other benefit it offers is that it eliminates the need for aggregators within the NAN or in the substation, as the consumers’ data can be stored on the cloud.

The first difference between Hammoudeh et al.’s research and ours is that the architectures proposed in Hammoudeh et al.’s paper are at the proposal stage and have not been implemented or simulated. The second difference is that Hammoudeh et al. did not consider the monitoring and control of the NAN itself. The NAN in their paper is a communication path for conveying data collected from the HAN to the WAN while we have considered different layers of monitoring and control for the NAN itself. The third difference is that their paper has only divided the area into a number of neighbourhood areas, which could be considered as incorporating clustering principles, while we have used various architectural styles and principles in order to describe how our architecture works, and how the different components within the architecture interact. Our architectural styles and principles will be discussed in chapter 6 of this thesis.
Figure 2.9: Communication architecture for the Smart Grid (Hammoudeh et al., 2013).

2.3.5 Summary

In summary, the research presented in this section outlines the critical role of the communication infrastructure within Smart Grids. It worth mentioning that these papers were mainly published either after we had completed the design of our network, or in parallel to our research. These investigations have mainly discussed the communication technology and the high-level infrastructure of such grids. Thus, these studies, in general, have shown the lack of research in designing an ICT architecture based on architectural styles.
and principles, and in investigating a physical and logical structure for the NAN area of Smart Grids. Additionally, the research presented above are mostly at the proposal stage and have rarely been simulated or even partially implemented in a real grid. The full implementation of such networks will take years to complete and, thus, is hardly possible for research groups to achieve, at the current state. Finally, having studied the available literature on this subject, we realise that there is a lack of detailed investigation on the energy awareness of the communication architecture. We have, therefore, designed an energy aware ICT architecture based on architectural styles and principles which has been partially implemented in a real environment.

2.4 Literature Review on the Energy Aware Topology of a Wireless Sensor Network

2.4.1 Introduction

Consideration of energy awareness is gaining more attention, due to environmental, economical and marketing motives. Sensors used in our designed ICT architecture require energy for various tasks such as sensing the environment, processing the collected data, and transmitting the gathered data to a more powerful computation unit. Since the greatest amount of energy is used for transmission rather than sensing or computation (Heinzelman et al., 2000), it is necessary to develop techniques to decrease the transmission energy required for communication purposes in the sensor network.

Energy aware considerations are important both for wired and wireless communications, but for different reasons. In wired networking, energy consideration is important because of the projected economic and environmental impacts. Recently, awareness of environmental problems which are caused by Green House Gases (GHGs) and their effect on climate change, has increased. GHGs will affect both environmental and economical issues (Bianzino et al., 2012). On the other hand, in wireless networking, energy consideration is important because wireless sensor networks suffer from a lack of resources such as a shortage in power supply. Difficulties arise when the deployed sensors in the Smart Grid are short of power, thus a specific area of the grid is no longer being monitored. Given that real-time data is being used in the control layer, the aforementioned problem may result in insufficiently accurate decision-making in the grid.
A number of studies have addressed the problem of energy efficiency in the communication network of the Smart Grid. These studies were mainly published after we had started our investigations on this project. However, they have supported our contention concerning the importance of energy efficiency within the ICT in the Smart Grid. For example, Smit (2012), Bu et al. (2012) and Kilic and Gungor (2013) have noted the importance of having efficient communications for an efficient Smart Grid.

Our approach to tackle the energy efficiency problem in the Smart Grid is different from the studies mentioned above. Since communication technologies are changing rapidly, it is not easy to predict which communication technology is suitable for the future power grid. As such, we have used techniques that offer energy awareness for the communication architecture regardless of what communication media is used. We have studied the energy limitation issue in WSNs and have followed similar approaches. Thus our techniques are practical even if communication technology, in the future, changes over time.

### 2.4.2 General Wireless Sensor Networks

WSNs have become an interesting area of research over the recent years. Recent advances in the field of sensor networks such as reductions in size, improvement in information processing units, data aggregation, and adaptability to harsh environments have led to a renewed interest in their application. Thus far WSNs have been implemented in various areas such as military and medical applications, gas and water networks’ monitoring, firefighting, health monitoring, transportation monitoring, tracking, agricultural applications, security applications and, finally, commercial and robotic functions. Based on such a wide range of applications we believe that they can also be considered a key technology for smart electrical networks. A WSN comprises a number of sensor devices which sense their surroundings, perform a limited amount of computation, and communicate wirelessly with each other and with a base station or a sink (Katiyar et al., 2010). These sensor devices are called nodes which themselves comprise several units namely: a power unit which is responsible for providing power to the sensor node, a sensing unit, a processing and storage unit and, finally, a communication or transmission unit (Raghunathan et al., 2004; Prakash et al., 2009; Saini et al., 2010). The diagram of a wireless sensor node as shown in (Saini et al., 2010)’s study is depicted in Figure 2.10.
Figure 2.10: Diagram of a wireless sensor node (Saini et al., 2010).

The sensing unit is in charge of measuring physical phenomena such as temperature, light and pressure. Generally, the sensing units in passive sensors (e.g. temperature and seismic sensors) use a smaller amount of energy as compared to other units of sensor nodes (Raghunathan et al., 2004).

The processing unit is in charge of processing the data collected from the field. The choice of the processing unit depends on the application scenario and the required performance level which will affect the power consumption characteristics of the node. This unit provides different operational states, namely, active, idle and sleep. Each of these modes consumes different amounts of energy. Therefore, the overall energy consumption of a sensor node depends on its operational mode, the transition cost between two modes, and the time spent in each mode (Raghunathan et al., 2004).

The communication or transmission unit is in charge of establishing communications by sending and receiving data, to and from other nodes, computers, base stations, and even to the external world. One of the issues that affect the energy usage of this unit is the transmit power (which can be determined by the transmission distance). It can operate in different operational modes namely transmit, receive, idle and sleep. Wireless communications are the main power consumer when a system is operating. It should be taken into consideration that transitioning between two different operational modes consumes a significant amount of power. Another significant observation concerning these operating modes is that an idle mode consumes nearly as much power as a receive mode. Thus, when nodes are not sending or receiving data, it has been suggested that they should be shut down instead of transitioning to idle mode (Raghunathan et al., 2004).

Since the sensors deployed in a WSN are currently powered by batteries and it is time consuming and expensive to replace a large number of batteries, energy aware considerations for designing such networks has become an important factor. As such, in the next
section, we will present a number of investigations attempting to support energy efficiency in a WSN, and will discuss the approach we follow to provide energy awareness in our design.

### 2.4.3 Energy Efficient Wireless Sensor Networks

Several studies have considered energy efficiency as a key design consideration of a WSN. In this section we will introduce different techniques that are believed to provide energy efficiency for a WSN and, finally, we will point out the technique which we have used in our design.

One of the techniques which is believed to alleviate the energy efficiency problem in a WSN is duty cycling. It is a technique in which, whenever communication is not required by the sensor, the node will be put into sleep mode. A recent research (Saraswat and Bhattacharya, 2013) has tackled the energy problem of a WSN by utilising duty cycling. In their paper, Saraswat and Bhattacharya have investigated the effect of duty cycling on estimated energy consumption. MATLAB simulation results reveal that if the duty cycle is less than 0.02% of the times, energy consumption of the WSN can be reduced. However, in denser networks the same is true for duty cycle values that are less than 0.01%. This analysis helps a network designer in assigning a suitable duty cycle value for their network while considering the node density.

In order to provide energy efficiency, one study (Alonso et al., 2006) has tried to give some recommendations on how to optimise energy consumption in a WSN. In order to do so they have experimentally measured the power used by the main operations in two different sensor nodes, namely Imote and Mica2. They have investigated the two most common operations of data transfer and CPU state change. The goal of evaluating the data transfer power consumption was to identify the power usage of packet transmission. They observed that the power consumption of the initial state in data transfer is (on average) 0.2280 W. Then, after posting the task there will be a major increase until the power consumption reaches 0.2340 W. After that, the maximum value happens when the transfer is finished, reaching around 0.2610 W. Although these values are interesting because they reveal the power consumption of every state of data transfer, more work needs to be done to derive a clear conclusion. On the other hand, the goal of analysing the CPU state change power consumption was to find out when transition to the low
power state is useful. Alonso et al. have observed that the power consumption of the initial state is 0.1450 W and the power consumption of the low power state is 0.1330 W while the transition cost is 0.0760 W. In conclusion, they have established that this state transition is only useful when the CPU stays in the low power consumption state long enough to pay the transition cost.

Another recent research (Tiwari and Kumar, 2013) presents the potentials of integrating the WSN with the electrical system. It investigates the performance of different WSN technologies in the Smart Grid against various criteria such as network coverage, latency, power consumption and security. In order to tackle the energy constraint problem of a WSN it also recommends using the sleep state of the sensors when their operation is not needed. The results show that duty cycling is an effective method of energy conservation but, since the sensors at the current stage of our project are communicating continuously and we assume that they are running at all times, it is not possible to put them to sleep.

Furthermore, in order to offer energy efficiency, Bhargava et al. (2003) have experimentally investigated the energy consumption of data mining algorithms on battery-powered devices. Comparing the energy consumption of data analysis in a mobile device with the energy required to transmit the same amount of data using a wireless network, they concluded that the energy spent for data transmission over a low bandwidth lossy wireless usually exceeds the energy consumed for data analysis.

An additional technique to offer energy efficiency is to use in-network query processing, such as in-network query aggregation, rather than processing the queries at the main base station (Madden et al., 2002). In in-network query aggregation, the aggregation process will be performed by each node inside the network prior to the transmission process. Research (Beaver et al., 2003; Sharaf et al., 2003) have introduced an in-network query aggregation scheme called TINA (Temporal coherency-aware in-Network Aggregation) which has extended this process by using temporal coherency tolerance. The temporal coherency tolerance will transmit sensors’ data only if the data vary more than the specified tolerance from the latest recorded data. This will reduce the number and size of the transmitted data. They have utilised simulation to examine their proposed technique. The results reveal that, having utilised TINA, a considerable amount of energy will be saved without a major loss of data when compared with other traditional in-network aggregation techniques. The reason we have not used this technique for our test bed is that, since
full data collection without loss of any sample of data is required at this stage of the project, it is not suitable for our case.

Finally, another technique, which is believed to offer energy efficiency, is called clustering. Clustering the WSN has been widely studied by researchers in the past (Abbasi and Younis, 2007). This is the technique which we have proposed to be used for the neighbourhood area in our Smart Grid test bed. In this technique the WSN is divided into a number of distinct clusters (Abbasi and Younis, 2007). Each individual cluster has a number of sensors called cluster members and a leader called Cluster Head (CH). The cluster members transmit their data directly or through multi-hop transmission to the CH. The CH is responsible for conveying the data collected from the members to the sink or base station (BS). The cluster members and CHs can be either stationary or mobile depending on the application of the WSN. The CH can be either a subset of deployed sensors in the WSN, or it can be resource-rich, meaning that the power unit, processing unit and communication unit of the sensors are more powerful than the cluster member sensors. A CH can be either pre-assigned or chosen randomly. The CH is responsible for either simply relaying the collected data from the cluster members, or for combining the collected data together and transmitting the compact data, or even for acting as a sink and taking decisions with regards to the detected phenomena.

Clustering the WSN has a number of advantages including the following (Katiyar et al., 2010; Abbasi and Younis, 2007): it can prolong the life of the sensors as well as the WSN, it can preserve the communication bandwidth within the WSN by limiting the communication between the CHs and avoiding transmission of redundant data, it can decrease the size of the routing table in each sensor by localising the route setup within clusters, it can prevent the sensors from being affected by changes in the network topology, it can reduce the size of transmitted data and, finally, it can reduce the topology maintenance costs.

An example of some research which has investigated an energy efficient clustering technique for a WSN is presented by Saeidmanesh et al. (2009). In this study, the authors have selected the CH by considering the residual energy of the sensor and the distance between the sensor node and the base station. As such, the sensors with less energy and with a farther distance to the BS have less chance to become a CH within the current round. By using simulation they have shown that this technique could extend the WSN’s
lifetime by decreasing the total energy consumption and evenly distributing energy depletion. However, the main difference between this research and ours lies in the fact that we are dealing with a heterogeneous sensor network in which CHs are considered to be pre-selected and are more powerful sensors than other nodes, thus we are not considering techniques for rotating and selecting CHs. However, we are concerned with having an optimised number of clusters in a WSN. Thus in the next section, firstly we will discuss heterogeneous WSNs and then present a number of discussions in the literature which have studied the optimised cluster count in both homogenous and heterogeneous WSNs.

2.4.4 Related Work

2.4.4.1 Heterogeneous Wireless Sensor Networks

WSNs are not always homogeneous and sometimes adding a number of heterogeneous nodes to the WSN can offer benefits. Generally, heterogeneity in a WSN can vary between computational heterogeneity, link heterogeneity and energy heterogeneity, or a combination of all three. These networks are suitable for real deployments as they are close to real network conditions. It is believed that heterogeneous WSNs can decrease the latency of data transportation, prolong the network lifetime and improve the reliability of data transmission (Sheikhpour et al., 2011).

To determine the effect of energy efficiency in a heterogeneous WSN, Saravanakumar et al. (2011) proposed a new routing system for heterogeneous WSNs and compared it with a homogeneous one. Based on the principles of one of the most well-known traditional routing algorithms, namely LEACH (Low-Energy Adaptive Clustering Hierarchy), which has been proposed for a homogeneous WSN, they proposed a new routing approach for heterogeneous LEACH. In this new approach they considered that 0.1% of sensors have twice the initial energy of the other sensors. The formation of the clusters and the selection of CHs, which are based on the residual energy of each sensor, is the same as for normal LEACH. Simulation results show that energy efficiency in heterogeneous LEACH has increased by nearly 40% compared to homogeneous LEACH.

A survey by Katiyar et al. (2010) has investigated clustering algorithms in heterogeneous WSNs. They have studied a number of energy efficient protocols for clustering such a network. To complement Katiyar et al.’s survey another study (Sheikhpour et al., 2011)
also surveyed some other energy efficient clustering protocols for heterogeneous WSNs. In these investigations, the resource-rich sensors are usually randomly deployed in the sensing field, thus the authors studied the process of cluster head selection. The CH could be either a normal sensor or resource-rich sensor based on various parameters such as the initial energy and the residual energy of nodes. Although these studies provide an overview of clustering techniques in heterogeneous WSNs, they have not discussed the optimal number of clusters in such networks, which is our concern.

### 2.4.4.2 Analysis of the Ideal Number of Clusters in a WSN

One of the objectives in using a cluster-based WSN, in which each individual sensor sends their data to the CH, is to provide energy efficiency. Accordingly, the number of clusters in a network is important for determining energy aware communication. As such, network designers should avoid having too many or too few clusters. In our research we investigate into finding the optimal number of clusters, and cluster shapes and locations, in a heterogeneous WSN. A number of studies have been published on the optimal number of clusters in a homogeneous WSN, while there are relatively fewer studying the ideal number of clusters in a heterogeneous WSN. Therefore, we first present a number of examples from the literature which investigate such studies in homogeneous WSNs and then we look at the literature investigating the ideal number of clusters in a heterogeneous WSNs.

Jin et al. (2003) have used a method based on a Genetic Algorithm (GA) to find the optimal number of CHs in a homogeneous WSN. In this process, a GA is used to randomly select the CHs. In order to find the appropriate number of CHs, Jin et al. (2003) have adjusted CHs based on a fitness function. The total transmission distance and the number of CHs are the main factors in their fitness function. Accordingly, decreasing the transmission distance, as well as decreasing the number of CHs, will result in higher fitness value. The GA is used to maximise this fitness value. The results show that the optimal number of CHs is about 10% of the total number of nodes.

Investigations by Heinzelman et al. (2000; 2002) are one of the classical, and most well-known energy-efficient cluster-based, studies called LEACH which have also analysed the optimal number of clusters in a WSN. They proposed an adaptive clustering system and rotating the CHs to enable an even distribution of energy among all the sensors. LEACH has also proposed the use of local computation within each cluster to reduce the
transmitted bits and to achieve less energy dissipation in a network. In LEACH each round of communication is divided into two phases, namely, the setup-phase and the steady-state phase. The setup-phase is when the clusters are structured. In this phase a sensor selects a random number between 0 and 1 and, if this number is below the defined threshold $T(n)$, the sensor would act as the CH in the current phase. However, if the sensor has been selected as the CH previously $T(n)$ would equal zero. When the CH has been selected, the rest of the sensors will join the nearest CH. This cluster set-up phase is followed by a steady-state phase in which data communication is performed. In this phase, each sensor transmits its sensed data to the CHs. The CH performs data reduction and sends reduced data to the base station. Therefore, LEACH reduces the energy consumption and extends the lifetime of a WSN. Additionally, Heinzelman et al. (2000; 2002) investigated an analytical formula to find the optimal number of clusters in an M×M network by considering the energy required for data transmission, reception and computation. Their result shows that, in a network with dimensions of 100m×100m and 100 nodes randomly deployed, the expected optimum number of clusters is between one and six. To verify their analytical formula they used simulation which revealed that the optimum number of clusters is between three and five which is within the range of their analytical analysis. These works by Heinzelman et al. (2000; 2002) are considered as a basis for other studies in this area. These further investigations, which we will discuss in the rest of this section, are largely based upon the analysis carried out by Heinzelman et al. (2000; 2002). However, one of the differences between LEACH and our method is that we do not need to adopt the cluster head selection process since we have assumed that our WSN is a heterogeneous one and that the CHs are resource-rich and are not assumed to run out of battery soon. Additionally, our nodes are not randomly deployed; they are assumed to be located on a grid since we are dealing with a street level environment with a grid shaped network. Moreover, these studies did not consider the energy incurred by sensing. They also did not consider a compression ratio for the reduced transmitted bits by the CHs. We will discuss the analytical formula presented by Heinzelmann et al.’s research in chapter 4.

A relatively recent study by Tandon (2012) has studied the problem of inefficient CH selection which could result in inefficient energy consumption within a WSN. He considered a circular shaped WSN where sensors are deployed around the centrally placed base station. Tandon (2012) divided the network into concentric rings around the base
station and the clusters were assumed to be wedge-shaped clusters. Accordingly, he proposed an analytical model to find the ideal number of CHs as a function of distance from the base station. Finally, this study suggested that fewer CHs should be selected for the rings that are located at the further distance from the base station. This study was undertaken in parallel to our study, with a number of different initial assumptions, and its results confirm our result that a lesser number of clusters should be located at the further distance from the base station. The difference between this work and ours is in the shape of the WSN which is a rectangular grid in our case. Moreover, in Tandon’s study the base station is assumed to be located at the centre of the network, while in our network the base station is assumed to be placed at the corner of the grid. Additionally, the WSN in Tandon’s study is homogeneous while the WSN in our study is assumed to be a heterogeneous network.

Kim et al. (2005) have estimated the optimal number of clusters by deriving an analytical formula in order to minimise the total energy consumption of a WSN. This approach is similar to the one proposed by Heinzelman et al. (2002). In the Kim et al. study the optimal number of CHs for a WSN with 100 nodes randomly deployed within 100×100m was derived to be between 1 to 11 clusters and for 200 nodes randomly deployed in same environment between 1 to 15 clusters. It should be noted that energy for sensing was ignored in this analysis.

Since, in this research, we propose to have a heterogeneous WSN with resource-rich CHs, we now present literature investigating an optimal number of clusters in a heterogeneous network.

One of the first studies concerning the optimal number of clusters in a heterogeneous WSN was reported by Duarte-Melo and Liu (2002). In this research, the authors formulated the energy consumption in a heterogeneous WSN with two types of sensors, called normal and overlay sensors, which are more powerful sensors than normal ones in terms of battery power. Then they quantified the optimal number of clusters in their proposed environment. The results, using simulation, indicated that, under the considered circumstances such as having 100 sensors (both normal and overlay sensors) and locating the base station D meters away from the sensing field (0,-D), the optimal number of clusters is between 4 and 10, regardless of the type of the network (homogeneous or heterogeneous). Additionally, scaling down the network dimensions and D with the same ratio will
not affect this number, whilst, reversing the ratio between the network dimension and D will not offer any clear range for optimal number of clusters. However, it should be considered that the sensors in Duarte-Melo and Liu’s research are randomly deployed whereas in our environment they are considered to be placed on the grid. The base station in Duarte-Melo and Liu’s research is assumed to be D meters away from the network whilst in our analysis the base station is located at the corner of the network. Moreover, since this study by Duarte-Melo and Liu was a preliminary investigation in this domain, energy for computation was ignored while formulating the energy consumption of the network.

Another study, which set out to determine the optimum number of clusters, was carried out by Gu et al. (2010). They studied the problem of selecting the optimal number of clusters in a pre-deployed heterogeneous WSN in order to minimise the total energy consumption of the data communication from the cluster member sensors to the base station, through CHs, in each round of communication. They derived an analytical formula which was affected by the number and location of the CHs, as well as by compression ratio. The simulation results showed that, by varying the number of deployed sensors, the number of optimal clusters may change. For example in a network within a square region of M×M, such as 200×200, with a uniform distribution of 200 sensors, the optimal value of clusters is derived as 6 while, with 900 sensors, the optimal number of clusters is 13. One of the interesting points about this research is that, unlike other studies, they have considered a ratio for data aggregation which will affect the optimal number of clusters in a WSN. The difference between Gu et al.’s research and ours is that they have considered that the CHs consume the same energy for data transmission and reception as normal sensors whereas we have considered that our CHs are more powerful sensors, thus that they consume more energy for such tasks. They have also ignored the energy spent on sensing. We will discuss this analysis further in chapter 4.

A study by Zhou et al. (2010) has proposed an analytical formula to find the optimal number of clusters in a heterogeneous WSN. They considered a square M×M network model comprising type_0, type_1 and management nodes. The type_0 and type_1 nodes perform data transmission and aggregation whereas the management nodes offer management information to the other nodes and have not been considered in energy consumption analysis. The type_1 nodes are assumed to be more powerful nodes than type_0
nodes. Zhou et al. (2010) introduced a mathematical formula similar to the one introduced by Heinzelman et al. (2002), but for a heterogeneous WSN. Although consideration of a heterogeneous WSN with two levels of heterogeneity is similar to our network model assumption, there still exist a number of different assumptions between Zhou et al.’s research and ours. In Zhou et al.’s research each cluster comprises a number of both types of nodes and the CH can be either a type_1 or type_0 node whereas, in our network, we have assumed that type_0 nodes can only be cluster members and type_1 nodes are CHs. The other difference is that, although Zhou et al.’s research has considered a network with 100 nodes, similar to our assumption, the percentage of each type of node is predetermined whilst in our research we vary the number of type_1 nodes while keeping the total number of nodes constant in order to find the ideal number of clusters where type_1 nodes only can act as a CH. Thus, in our study, the number of clusters and the number of type_1 nodes are the same. Moreover, Zhou et al.’s research has ignored the energy consumed by sensing. Finally, their base station is considered to be at the centre of the network while our base station is assumed to be located at the corner of the network, which will be discussed in chapter 4.

In 2012, Tuah et al. (2012) proposed an analytical formula for a three-level heterogeneous WSN to minimise energy consumption by considering energy consumption per iteration. With the help of simulation they validated the correctness of their analytical formula and established the importance of an optimal number of clusters in decreasing energy consumption. They observed that, in a network with three levels of heterogeneity, a dimension of 200×200m, and 200 nodes, the optimal number of clusters is three whereas, in a network with same dimensions but with fewer sensors (100 nodes), the optimal number of clusters is five. Some of the differences between Tuah et al.’s research and ours, is that we are dealing with a two-level heterogeneity. Moreover, the CHs in Tuah et al.’s research could be either a normal sensor, an advanced sensor, or a super advanced sensor while in our WSN we have assumed that only advanced sensors can act as CHs and normal sensors are all cluster members. Additionally, in this study the energy for sensing has been ignored. The other difference is that, although Tuah et al.’s research has considered a network with 100 nodes similar to our assumption, the percentage of the normal sensors, advanced sensors, and super advanced sensors are predetermined and, by knowing these numbers, they are trying to find the optimal number of clusters whereas, in our research, the percentage of our advanced sensors which are supposed to be CHs are not
Chapter 2

2.4.5 Summary

Summarising all the research that has been mentioned so far, it has highlighted the need for finding an ideal number of clusters in a WSN to reduce the total energy consumption of a network. Although the various studies have proposed a simplified analytical analysis to find this optimal number, they either ignore the energy spend for sensing within the environment, or the energy spend for data computation, or a compression ratio to specify how much data has been reduced and transmitted by a CH to the base station. Additionally, a number of these studies consider identical clustering approach to simplify their analysis which is not a realistic consideration in some scenarios. Moreover, these studies consider a WSN with randomly deployed nodes whilst our WSN is a grid shaped network and the nodes are located on the grid points. The final difference between the aforementioned studies and ours is that we are investigating with the aim of finding the optimal number of clusters in a heterogeneous WSN with resource-rich nodes acting as cluster heads only (thus the optimal number of clusters in our study would be the same as the number of resource-rich sensors), whereas, in the mentioned studies, resource-rich sensors can be either a CH or a cluster member.

2.5 Literature Review on Data Reduction

2.5.1 Introduction

Deploying a large number of monitoring devices in the Smart Grid environment that transmits huge volumes of data can potentially saturate the devices’ resources and consume their energy at an unacceptably rapid rate. As discussed earlier, some of the key constraints of wireless sensor devices deployed in the Smart Grid are their limited resources such as memory, battery and processing power. These limitations necessitate the development of techniques to utilise sensor resources more efficiently in order to achieve a better quality network, a longer lifetime and time between maintenance sessions. In addition to this, environmental and economical considerations necessitate the develop-
ment of techniques to utilise network resources more effectively. Since the data transmission process is one of the main power consuming process in a network, we realise that savings in energy can be produced by minimising the volume of data transmitted.

### 2.5.2 Energy Efficient Data Transmission Techniques

We have classified data transmission techniques, into three different categories. The first category is when sensors transmit their data after receiving a request from the sink. The second category is when sensors send data whenever a threshold condition is violated or whenever an emergency situation has occurred. The third category is when sensors collect data and broadcast data continuously. The first and second categories are more energy efficient methods of data transmission because the data are being shipped with lower frequency. However, the NAN monitoring network in our Smart Grid test bed necessitates the third category. This requirement is due to the fact that electrical engineers do not fully understand the behaviour of the sub-Grid level, so we had no choice but to sample data at a high rate at all times so that we could capture the fastest fluctuations.

A review of the current literature reveals that energy efficient radio communication can be accomplished through different means such as duty cycling, optimising the routing algorithm, optimising the network topology, and in-network processing. Duty cycling can be achieved through scheduling the sleep/wakeup programme of the sensors in the WSN. However, as discussed, we cannot use adaptive methods until the behaviour of networks is better understood. Optimising the routing algorithm could be accomplished by developing a multi-hop routing algorithm that can identify the next optimal hop to route the message to the sink. Optimising the network topology could be achieved through managing the communication distance which has been discussed earlier in this thesis.

Finally, in-network processing can be classified into two classes. The first group is the data aggregation techniques being implemented in conjunction with WSN routing protocols. A survey of data aggregation techniques in WSNs (Thangaraj and Ponmalar, 2011) has introduced and analysed several such data aggregation protocols. The second group of in-network processing methods is called data reduction which is performed by implementing data reduction algorithms to reduce the communication cost by minimising the
size of transmitted data. Applying data reduction will result in efficient bandwidth utilisation, and also in power saving, caused by minimised size data transmission which will increase the network lifetime (Kimura and Latifi, 2005). The technique used in this research to enhance the efficiency of the communication network belongs entirely to the second class of in-network processing i.e. the data reduction method.

2.5.3 Data Reduction Techniques

Data reduction techniques can be divided into lossy and lossless methods. In the lossy reduction method the receiver regenerates the original data with some degree of information loss. This technique is useful for applications that can tolerate data loss such as video and audio compression. Conversely, in the lossless technique, the receiver can regenerate the original data without information loss. This method is useful in applications where data loss is not acceptable, such as medical images and computer executable files (Kodituwakku and Amarasinghe, 2011). Since the control protocols of the Smart Grid are still being developed, we do not yet know how much data loss is acceptable in transmission. Therefore, our design requires that the whole procedure of data transmission, including data reduction and regeneration, be lossless.

Data reduction techniques can be classified into data aggregation, data fusion and in-network data compression.

Data Aggregation: The goal of data aggregation is to reduce the communication overheads and cost. This method will reduce the message size by utilising one of the aggregation functions such as Min, Max, Sum and Average (Tan et al., 2007). Two methods for implementing the in-network data aggregation techniques in the sensor networks are pipelined aggregation and interval-based aggregation. In the former, each node aggregates its present data with the data received from its children in the previous interval, then transmits the aggregated data to its parent. The latter approach, called interval-based aggregation, is very similar to the former one. However, the difference lies in the fact that the latter approach combines data from the same time interval and then transmits them to its parent.

Data fusion: Data fusion is a more elegant method in comparison with data aggregation. In this method various unreliable data will be combined to eliminate the related noise and produce a more accurate signal (Abdelgawad and Bayoumi, 2012).
Data compression: Data compression can be described as the procedure of processing raw data into a condensed structure compared to its original format. The two participants of this procedure are the compressor and decompressor. Each of these entities is located at either side of a communication channel. One of the challenges in the data compression technique is the accuracy of the decompression algorithm when reconstructing the data. Data compression is usually used in applications where full data collection is required.

Since electrical engineers working on our Smart Grid applications are still evaluating the data we do not use fusion or aggregation. Thus, our data reduction algorithm is purely a compression method that keeps the quality and integrity of the data.

Figure 2.11 demonstrates the categories and subcategories of efficient data transmission, as has been discussed above, and highlights (in green) the contribution of our research to this area.

![Diagram of efficient data transmission](image)

Figure 2.11: Efficient data transmission.

### 2.5.4 Lossless Data Reduction Techniques

As discussed earlier we are interested in lossless data reduction techniques. A number of key lossless data reduction techniques which have been developed are Huffman, Arithmetic, Run Length and Dictionary Based Coding.
Huffman Coding: Huffman coding (Huffman, 1952) which uses variable length coding is one of the famous lossless data compression techniques and is the basis of much research in this area. The variable length coding converts the symbols into binary symbols based on the probability of occurrence of that symbol. Thus, most messages composed of repeated symbols can be compressed to the shorter bit stream. Huffman uses self-terminating variable length code-words, which represent each symbol as an identical string of bits while no code-word can be prefix (or initial segment) of another code-word in the system. Thus, the Huffman is a uniquely decodable code, in which the receiver can reconstruct the original symbol without having special markers between them. Huffman applies a specific method to represent each symbol as an identical string of bits. First it sort symbols according to their probability of occurrence. Then the two symbols with lowest probability will be merged, this process will continue until the full tree is created. Next, each of the branches of the constructed tree will be labelled as 1s and 0s. Finally, to binary encode each symbol, it will start reading 1s and 0s from top of the tree down to the symbol. Consequently, after the codification process the symbols will occupy less space.

Arithmetic Coding: Arithmetic coding (Campos, 1999) is another method of data reduction, which takes a stream of symbols and replaces them with a single number. Two main factors in the coding process in this method are the occurrence probability and the cumulative probabilities of a symbol sequence. Firstly, we associate to the stream of symbols the subinterval of [0, 1) according to their occurrence probability. Then, the cumulative probabilities will be calculated and the range of subinterval of initial interval [0, 1) will be identified. While iterating through the source message for each character, the existing subinterval will be divided into subintervals according to the probabilities of the character. This process will continue until the end of the source message. Once the subinterval becomes very narrow, a number, which is a fraction of the final subinterval, will be extracted. This number will be the output of the coding process. Finally, in order to reconstruct the original message, the number of characters in the source and the probability should be known. One of the main disadvantages of this method is its slow processing which makes it inappropriate for the real-time applications.

Run Length Coding: This method (Blelloch, 2013) simply considers the redundancy of characters. The repetitive consecutive sequence of characters will be recognised as a run
and will be represented together with the length of the run to compress the original message. The other sequence of characters will be considered as non-run and will be represented with no compression process.

Dictionary Based Coding: This method uses a dictionary that stores a table of possible words instead of using a statistical model. It uses indexes of entries, thus while compressing these indexes are used as an alternative to the larger and repeating strings. An example of this technique is the Lempel Zev Welch algorithm (LZW) (Welch, 1984).

In order to measure the efficiency of a data reduction technique, a range of criteria exist that depend on the reason why data reduction is used in an application (Mengyi Pu, 2005). For example, in some applications that require data transmission, speed is the main concern. The transmission speed depends on the number of transmitted bits, the time spent for compression and the time spent for the decompression process. In other applications that are concerned with data storage or energy efficiency, the compression ratio might be the main concern. In general, it is difficult to assess the efficiency of data reduction algorithms as they depend on several factors such as types of input files and the category of the method used, namely, lossy or lossless. Although the compression efficiency, time efficiency and space efficiency in lossy algorithms are higher than in lossless ones (Kodituwakku and Amarasinghe, 2011) still, for the reason mentioned earlier, we have used lossless data compression. In Chapter 5, we will discuss the efficiency of our developed data reduction algorithm and compare it with existing algorithms.

2.5.5 Related work

2.5.5.1 Related Work on Data Reduction for Smart Grids

A survey of the current literature has indicated that there is little work published on data reduction in Smart Grids. Allalouf et al. (2011) have argued that the huge amount of data communication in the Smart Grid will put the ICT architecture under substantial strain. Therefore, they have examined the benefit that can be gained by applying data reduction techniques to intermediate nodes to ease the flow of data. They do not give an explicit description of how their data reduction process performs, but since they have stated that applying volume reduction will decrease the accuracy of the data, it appears that the key difference between this research and ours lies in the fact that they have used a lossy...
technique. Thus we and Allalouf et al. have followed two different in-network processing classifications.

In another paper, Khalifa et al. (2010) have used a simulation to demonstrate that a centralised architecture, where hundreds of thousands of metering devices transmit their readings to the central data collection server, would fail to serve the Smart Grid infrastructure. They consider that the source of such a problem is due to the large amount of traffic produced by these devices resulting in excessive retransmission of data and, thus, degrading the throughput. To overcome this problem, they have used a Split and Aggregate TCP (SA-TCP) approach. In contrast to a traditional approach, the meters in the SA-TCP will create TCP connections with an aggregator node that is placed before the bottleneck. Thus the data gets aggregated at this point. Then the aggregator node will generate a new TCP connection with the data collection server. The aggregator node is responsible for revising the transmission rate as the network congestion conditions alter. If the data loss happens after this point, the retransmission rate will decrease because the dropped data will be retransmitted from the aggregator node rather than the actual meter. This approach introduces improvements in network stability and bandwidth utilisation. However, the data transmission delay and the need to maintain a large buffer in the aggregator node that should adjust to the changes in the internet traffic are two of its drawbacks.

The idea of having an intermediate node in between the sender and receiver is similar to our approach in the cluster-based WSN. Instead of having aggregator nodes we assigned Cluster Heads in the WSN. However, the main distinction between these two approaches is that we realise that data aggregation is not an appropriate data reduction technique to be employed in the Smart Grids’ application for our specific test bed; thus we follow the data compression technique. Khalifa et al. (2010) claimed that decreasing data traffic in the WSN is not possible, whereas our research has demonstrated (in Chapter 5) that data traffic can be reduced by applying lossless data compression techniques while preserving all the associated data.

Since there is a limited amount of literature based on data reduction in Smart Grids, we decided to study the literature based on data reduction in other fields. Over the past decades a large body of literature has investigated a range of data reduction techniques for different areas of science. However, the fact that some of these techniques (e.g. Welch
(1984)) consume a great amount of processing power makes them inapplicable for resource-limited networks.

2.5.5.2 Related Work on Data Reduction for WSNs

Having studied the literature on various methods for data reduction, we have followed a new approach. We have applied the ideas that have been developed for the WSN to the new domain called the Smart Grid. This selected approach can satisfy our Smart Grid application requirements. One of these requirements is to develop a simple algorithm that can be performed on resource constrained devices. The rest of this section only considers the literature specifically relevant to a resource constrained wireless sensor network. Moreover, having access to real data collected with high acquisition rates from the electrical grid enables us to assess the behaviour of these data, and to select the appropriate approach accordingly, and then evaluate the efficiency of our selected technique in the real environment.

A considerable amount of literature has tried to tackle the problem of the efficient transmission of data within WSNs proposing different methods. For example, a survey conducted by (Kimura and Latifi, 2005) has reported that data transmission is more power consuming than data processing. Thus reducing the size of the data before transmission is an effective method of saving the energy of a node. Naotoa and Shahram go on further and introduce a number of data reduction techniques such as coding by ordering (Petrovic et al., 2003) and distributed compression (Kusuma et al., 2001; Pradhan et al., 2002) that are believed to be applicable to WSNs.

Another research (Lin et al., 2005) has introduced a dictionary based data compression method to compress historical data in a cluster-based WSN. This method first builds a codebook from the sensor data and then applies Learning Vector Quantization (LVQ) to the codebook to offer a more optimal codebook. Next, it applies a compression technique to compresses codebook update. Finally, it uses Dynamic Bandwidth Allocation (DBA) by assigning different amounts of bandwidth to each sensor in the cluster. Therefore, Lin et al. have claimed that they can offer efficient utilisation of bandwidth while improving compression accuracy.

Another research (Li and Li, 2005) has investigated the inaccuracy of gathered data and the power constraint problem of sensor nodes. They have proposed a two-step approach,
namely, a sampling frequency control technique and a data compression algorithm. It is argued that the first step can decrease the sampling time as well as the power consumption. The second step will use limited storage capacity and computing ability and will decrease the broadcast data. In this algorithm only a part of the data are transmitted instead of the whole data. The first step in their approach can save energy but it is not applicable in all research areas. For example, in our case, it is preferable to keep the frequency of data acquisition high in order to observe time variations with more accuracy and only apply a data reduction technique to utilise the network resources efficiently.

2.5.5.3 Related Work on WSNs Based on Differences between Readings

One of the techniques developed for WSNs, on which our data reduction algorithm is based, considers the differences between each sensor reading. This technique is most appropriate where devices collect similar values, as in our test bed. Considering that our proposed data reduction is based on this technique, the rest of this section will discuss the literature that discusses this specific area.

Vidhyapriya and Vanathi (2009) have proposed a lossless compression technique utilising the codebook compression method. In this technique, prior to transmitting data to the sink, a sensor starts discovering the address of its neighbours who are able to send and receive data from source. Upon receiving the broadcasting message from the neighbouring node, each sensor will decide to discard or transmit the message based on its available energy. Then the shortest path algorithm is used to route the data from the source to the sink. Data packets with similar, most significant, bits are merged to create a single packet. Afterwards Vidhyapriya and Vanathi use a codebook method to leave out the shared bits and compress the merged packet. In their codebook method both the sender and receiver nodes have the dictionary, thus the strings of characters can be replaced with single codes. The advantage of this technique is that it has compressed and decompressed small blocks of data, thus if a packet is lost it will only affect the following data in the same block. Considering that there is a trade-off between having a higher compression ratio and the reliability of data transmission, these techniques are suitable for the situations where the data loss is reasonably high.

The EasiPC mechanism (Ju and Cui, 2005) is the other compression method based on differences between each readings. It was developed to manage the energy consumption in WSNs by shortening the length of the data packets. It has introduced a compression
layer between the data link layer and the network layer in the protocol stack of a WSN. It has classified the data packet into a different packet field. Then it applied the technique of difference between readings to some specific fields where compression is applicable. This results in reducing the number of transmitted bits and achieving a compression ratio of about 50%. The problem with this method lies in the fact that the loss of some packets can compromise the accurate reconstruction of the subsequent packets.

Aquino et al. (2008) proposed a data compression method based on differences between readings. In this method they generated new data based on the previously collected data and a common base defined by the central node. In each round of reported data, the common base will be generated by considering the data from many sensors and will be based on the most frequent bit in each position. Figure 2.12 depicts how the common base can be defined. In this example (Figure 2.12) for the most significant bits in each sensor node, “0” has the highest frequency. For the second most significant bit again “0” is more frequent. This process will continue until we reach the least significant bit. Here, as we can see, “1” is the most frequent in the position of the least significant bit. This is how a common base can be formed.

![Figure 2.12: Generating the common base (Aquino et al., 2008).](image)

In points of aggregation, the technique based on differences between readings will be applied to the collected data. The node stores the differences between each sensor reading and the common base in a buffer. This process will continue for a defined period of time. Then these differential readings will be concatenated and will be sent together with another byte called “position of readings” to spot the final position of each sensor reading. This will help in reconstructing the data. Figure 2.13 illustrates the described procedure. It should be noted that not all the applications can afford the time interval to generate a common base which is based on the sensors reading in a specific period of time.
PINCO (Arici et al., 2003) is a pipelined in-network compression method based on the difference between each reading. The collected data are stored in a buffer for a period of time. During this period, data packets are joined together in a pipelined compression method to create a new data packet, called the compressed data packet, whilst satisfying the user end-to-end latency requirements. This new data packet removes the redundancy between each sensor reading which will result in decreasing the data transmission bits and energy. In this algorithm the original data packets’ format is: <measured value, node ID, timestamp>. The compressed data packets’ format is <shared prefix, suffix list, node ID list, timestamp list>. The “shared prefix” are the most common significant bits in the collected data, and “suffix list” is the list of collected values excluding shared prefix. The “node ID list” is a list of node IDs and the “timestamp list” is a list of timestamps.

![Diagram of compression and decompression process](Aquino et al., 2008)

The effectiveness of the PINCO is based on the length of the prefix which shows the similarity of the data. Figure 2.14 depicted by Kimura and Latifi (2005) shows the PINCO process and how three different sensors transmit their data packets to the com-
pression node. As a result, the three data packets, which have 33 bits in total, are compressed into one data packet containing 27 bits. This indicates that the number of transmitted bits decreased by 6 bits.

![Diagram](image)

Figure 2.14: In-network compression (Kimura and Latifi, 2005).

Since PINCO is not sending a “common base” and the “position of readings” together with the data packets, like the other method mentioned earlier, it can offer better energy efficiency and can decrease the number of transmitted bits compared with the previous method. However, transmitting the shared prefix in the compressed data packet can also increase the number of transmitted bits. Moreover, in the case of security attack, having the shared prefix in each data packet makes the attacker’s job easier in identifying the original data packets out of the compressed data packets. It is frequently claimed in the literature that the energy for transmitting one single bit of data is the same as the energy spent for executing a thousand instructions (Li and Li, 2005). Accordingly, in our proposed data reduction algorithm we try to prevent sending the shared prefix to reduce the number of transmitted bits as much as possible. Thus we only send the changing bits (herein called the suffix) after applying our defined logical operations on them.

Hoang and Motani (2007) have proposed a methodology to explore the broadcast characteristics of the wireless medium in correlated WSNs. They used a data compression approach to extend the lifetime of a cluster-based WSN. Since data collected by the sensors inside the clusters contain similarities, the technique, based on differences between consequent values, has been applied to reduce the transmitted bits. Since, in this approach, a sensor can compress data based on the data of another sensor inside the cluster, a number of problems might affect the data compression scheme. The first issue is the vulnerability of this approach to the loss of intermediate sensors which may result in transmitting uncompressed data by the compressor node. The other problem may occur in the case of data modification attack. In this case if the attacker alters the intermediate
packet before reaching the compression point, the compression process will end in an incorrect format. The incorrect compressed data will affect the correct reconstruction of data, which belong to the attacked node, as well as the compressor node data.

Another research (Sacaleanu et al., 2012a; Sacaleanu et al., 2012b) bases itself on the Huffman coding to present a data compression scheme for WSNs. In order to offer a better compression performance, Sacaleanu et al. have introduced a compression scheme that combines the two techniques of Extrapolation Predictor and the Static Huffman method (EPSH). Since the collected data are highly correlated in time, the subsequent data can be predicted from the three previous values obtained. In this approach firstly the difference between the obtained data and the predicted data is calculated. Then the calculated value will be compressed using the Static Huffman technique. Moreover, to further optimise the compression scheme, it utilises the Bit Aggregation Technique (BAT) (Sacaleanu et al., 2012b). By combining the compression technique and the data aggregation technique, Sacaleanu et al. can offer 75% efficiency in the amount of transmitted bytes. However, this efficiency ratio depends on the characteristics of the data and may vary.

Another research (Marcelloni and Vecchio, 2008) has proposed lossless data compression by exploiting the correlation between consecutive samples of data in a WSN and also considering the principles of entropy compression. Considering these concepts, Marcelloni and Vecchio have compressed the collected data with the help of a small dictionary. The algorithm functions are as follows: it first finds the differences between each two successive values. Then, by utilising two’s complement, it converts these differences into a set of least significant bits. Finally, it concatenates the compressed data with the Huffman variable length code. Marcelloni and Vecchio have claimed that they have provided 66.99% and 67.33% compression efficiency for temperature data and humidity data respectively, but we believe that the compression ratio depends on the characteristics of data and cannot be generalised. In a future chapter (chapter 5), we will compare the performance of our proposed data reduction algorithm with this algorithm.

Another research (Sornsiriaphilux et al., 2010a; Sornsiriaphilux et al., 2010b) has modified the approach discussed above (Marcelloni and Vecchio, 2008) to enable data compression on wider range of sensors with higher standard deviations. Sornsiriaphilux et al. have proposed a new version of the previously discussed algorithm called Fixed Index.
They stated that the two approaches for applying data compression algorithms are: either to implement a number of compression algorithms together on the data collected from a WSN, or to develop a single compression algorithm that offers a satisfactory compression ratio. The new algorithm discussed in Sornsiriaphilux et al.’s research applies two modifications to the above-mentioned algorithm (Marcelloni and Vecchio, 2008). In the original data compression algorithm (Marcelloni and Vecchio, 2008), each set of compressed data is a combination of a group of high order bits and low order bits. High order bits represent the number of bits needed to show the difference between each two consecutive values. Low order bits represent the differences in the data. The first alteration is to use one’s complement instead of using two’s complement for showing the low-order bits. The second revision is to use “Fixed Index” instead of the Huffman variable length code in the high order bits. The former modification will reduce the number of operations needed and the later modification will keep the length of bits constant, which is useful when the standard deviation of data increase. By this technique they fixed the length of the high order bits to four bits. As an example when the difference between two values are 8, this 8 should be represented in the low order bits after 1’s complement has been applied to it. Therefore 8 will be represented as 0111. Next, the high order bits has to represent the number of bits that low order bits will occupy. This high order bits will be identified through the four bit fixed-index table provided in the above-mentioned paper. As such, since 8 requires four bits (0100), therefore the high order bits will be 0100. Finally, the compressed data will be equal to 01000111. Sornsiriaphilux et al. have claimed that the Fixed Index algorithm performs better than the previous algorithm using the Huffman length code when the standard deviation increases. However, further on in this thesis (in Chapter 5), we will establish that our developed compression algorithm offers a better compression ratio as the standard deviation of data increases when compared to these final two algorithms.

2.5.6 Summary

In summary, all the research that has been mentioned so far, has highlighted the need for data reduction in different area of research. However, there is relatively little study on data reduction techniques that can be applied to the Smart Grid environment. In this research we have adopted the technique that has been established for reducing the volume of data in a WSN, and apply it to a new domain, namely the Smart Grid. We have applied
the selected data reduction technique on the data collected from a NAN area such as substation monitoring and smart meter data. The selected technique is based on the difference between each two consecutive value which will result in decreasing the number of transmitted bits. Accordingly, we have developed our data reduction algorithm based on the mentioned technique and discussed how it can be incorporated into an ICT network for the NAN level of the Smart Grid. Furthermore, most of the works that have been mentioned in this section have been tested against simulated data, while we have tested our data reduction algorithm on synthesized data as well as real data and evaluated its applicability to the Smart Grid environment.
Chapter 3. ICT Architecture for the NAN in the Smart Grid

3.1 Introduction

As mentioned earlier, a Smart Grid is the integration of a power network and an Information and Communication Technology (ICT) network to meet the future needs for energy supply. In this work we have focused on, and particularly investigated, the design and deployment of an ICT architecture in the urban environment, specifically in a university campus that is embedded in a city, thus it represents the neighbourhood area network (NAN) level of the Smart Grid. A series of discussions with a team of professionals working in the power grid system, alongside having access to the characteristics of a real NAN, has enabled us to identify the requirements of such a system. Accordingly, we have examined important parts of our architecture within this research to check if they fit within a real world environment. To design these architectures at this level we need to gather and process data from environmental sensors (monitoring e.g. temperature, movement of people and vehicles) that can provide useful information about changes in the loading of the NAN, together with data from the instrumentation of the power grid itself. Energy constraints are one of the limitations of the communication network in the Smart Grid, especially where wireless networking is proposed. Therefore, we have considered energy-aware methods of transmitting data. The main contribution of this chapter to the thesis is that it proposes and discusses the implementation of an ICT network and also discusses our experimental results. To our knowledge, there is little or no work on the development of such architectures at the NAN level of the grid that can collect data
to provide the basis for a Decision Support Tools (DSTs) which provides GIS functionalities and computerised analysis of the grid.

This chapter is structured as follows: Section 3.2 studies the related background information. Section 3.3 introduces our proposed ICT architecture for the NAN in a Smart Grid. Section 3.4 focuses on the implementation issues arising from the ICT architecture deployment on the experiment test bed. Section 3.5 presents the WSN applications in the Smart Grid. Finally section 3.6 presents a summary of the chapter.

### 3.2 Background Knowledge

Here, we present the available intelligent monitoring systems in place for other relevant environments as well as for the traditional electrical grid and then we present the general issue of what needs to be added to a power grid to convert it to a Smart Grid.

Initially, we review works on the monitoring and control of other types of distributed networks, such as water distribution grids (Khan et al., 2010; Machell et al., 2010; Stoianov et al., 2007). The water distribution grid in the UK has a modular structure, being divided into District Metered Areas (DMAs) that can be controlled in isolation from the rest of the network. An example of a water grid that uses sensor data for monitoring purposes is the Neptune project\(^5\). Our work extends this approach from a water distribution grid to an electrical grid where the monitoring systems need to take account of much more rapid changes in the state of the network (in seconds rather than hours) and control is more pervasive.

Another study (Hughes et al., 2008) describes a flood monitoring system which allows the integration of a wireless sensor network (WSN) with a remote fixed-network for computationally-intensive tasks, as well as performing on-site grid computations to support timely predictions and flood warnings. This system is able to switch between different communication technologies, and also to adapt to different network topologies and switch from a network with low power consumption to a network with high power consumption. These adaptations are currently based on an awareness of data about internal systems and also could be based on external information as well. For example, as the

\(^5\) [http://www.shef.ac.uk/neptune/projectdetails](http://www.shef.ac.uk/neptune/projectdetails)
external condition of the network changes to a critical condition, sensors start sending data with higher frequency.

In an electrical distribution grid, the SCADA (Supervisory Control and Data Acquisition) system that provides the communication infrastructure across the electrical grid from 11 kV to 132 kV is used as the intelligent monitoring system in place. Yang et al. (2011) explained the implementation of SCADA via the distribution network operators (DNOs). This system contains a master terminal and many remote telemetry units (RTUs). The RTUs are responsible for gathering network measurements from the grid and transmitting commands to the control devices and the master node. The master node is located at the control centre of the DNO and is in charge of processing and storing the received data. There can be heterogeneous communication channels and various physical media between the RTUs and the master terminal. In this system the data is updated every 10 - 20 seconds, a rate that is too slow to provide sufficiently continuous data delivery and real-time applications (Roberts, 2004). Our system requires faster monitoring since, in the implementation of our architecture, the substation data are sensed 1 to 4 times a second. The other limitation of this system is that it fails to monitor the whole sub-Grid and only monitors the critical areas of the network. These facts make SCADA inappropriate in supporting applications in a timely manner and in supporting fast acting control functions.

In our architecture, we have used other systems such as sensor network data instead of SCADA data, similar to the approaches in Kayastha et al. (2012). However, our sensor networks collect from three sources of information: from the energy consumption data of buildings via metering, from the environment via WSNs, and from the electrical network via reconfigurable real-time control and acquisition systems. If all this information across the whole grid is collected at a single database, we face problems such as information overflow and an increase in communication energy consumption. To avoid these issues, we adapt techniques such as clustering methods developed in the studies of sensor networks (Youssef et al., 2002; Abbasi and Younis, 2007) and apply it to the power grid.
3.3 The Proposed ICT Architecture for the NAN in the Smart Grid

Electricity grids are centrally monitored at the level of a national grid. The current system lacks monitoring and control at the NAN level. In this research we mainly focus on the NAN area in the distribution power network, although we believe that the general principles of our architecture are applicable to other networked systems as well. Having considered Smart Grid requirements at this level, both from the literature and through a series of discussions with power engineer professionals in the School of Electrical and Electronic Engineering in the University of Manchester, we have introduced and developed our prototype ICT architecture.

In this chapter we will present the design and implementation of our ICT architecture for a Cyber-Physical System for the monitoring and control of the NAN. Cyber-Physical Systems (Lee, 2006) integrate the functioning physical processes with digital sensing and computation. A thermostat is a very simple example of such a system. Such an embedded system requires developments in both hardware and software. The former, which is embedded in the physical system, is responsible for monitoring and capturing events and conditions. The latter, which may be distributed or centralised, is required to control the behaviour of the system by carrying out computations that express the state of the system and guide the actions needed to control it. Other examples of Cyber-Physical Systems are deployed in fire and flood control, traffic control, water distribution grids and electrical grids. An example of a Cyber-Physical System in an electrical grid is the SCADA system which is deployed in critical sections of the current grid in order to perform monitoring and control for those particular areas. However, monitoring and control should be scaled throughout the Smart Grid. Therefore, we propose an ICT architecture for a Cyber-Physical System extending into areas of an electrical grid beyond the current SCADA.

Our proposed ICT architecture also considers the energy awareness of the communication system. In recent years, energy awareness considerations of ICT networks have emerged as one of the most challenging concerns of computer scientists (Bianzino et al., 2012). Having studied and conducted experiments in the real environment, we realise that a lack of consideration of the energy awareness in the ICT architecture for the Smart
Grid might lead to the malfunctioning of such system in the future. Adding energy awareness to an already designed system is a difficult task. Therefore, communication energy awareness should be included in the design process right from the beginning. Energy awareness is important both for wired and wireless technologies, but for different reasons in each case which we will address later. Considerations of energy efficiency apply across a range of networks: in offices, data centres and employed in distributed physical networks, such as electricity networks. However, in the latter case, there are special constraints on the energy considerations of the ICT infrastructure that are relevant to the Smart Grid. Therefore, our ICT network design is targeted towards providing a solution to the key issue of energy aware consideration required for communication. This consideration of energy has impacted on the design of our architecture.

Now, we will present an abstract view of our ICT architecture proposed for the NAN in the Smart Grid. It is believed that a vital function of ICT is that it enables the process of data generation to data utilisation. ICT can be defined as the technology by which data are created, gathered, stored, transceived, processed, and finally utilised by individuals or companies (Robin, 1994).

This design is a layered architecture that provides the main functions of monitoring, data movement, data storage and control of different situations (Figure 3.1). As such, some parts of this architecture are more concerned with monitoring, collecting, and transmitting data. However, some other parts of this architecture are more concerned with processing, visualising and controlling the grid; this is where our designed software architecture fits (represented in Appendix B). Together these different parts will fulfil the goal of ICT in this level. Accordingly, we have proposed our ICT architecture by adapting and extending established architectural styles and principles.

The proposed ICT architecture is based on hybrid communication technologies that integrate sensing and computation to enable monitoring, data gathering, control and prediction of the future state of the sub-Grid. Figure 3.1 depicts an abstract view of our proposed ICT architecture at the NAN level. The proposed ICT architecture has also addressed the issues in moving from a centralised architecture (where data collected from the entire system are stored in a single database and where controls are only applied from this central location) to a more decentralised system. It shows a collective of single NANs
(NAN 1, NAN 2 ...) that should communicate together to construct a wider NAN. Figure 3.1 shows a number of NANs communicating through a networking cloud. The networking cloud can use different communication media, such as wired or wireless, and also uses different architectural styles such as peer-to-peer or hierarchical. This does not affect the design of each individual smaller NAN (e.g. NAN1, NAN2). We will discuss the design and development of our ICT architecture for a single NAN in detail later on in this chapter.\(^6\)

![Diagram of ICT Architecture for the NAN in the Smart Grid](image)

Figure 3.1: An abstract view of the proposed ICT architecture.

The design of the ICT architecture also contains a software architecture aspect which should be structured to meet the requirements of our system. Accordingly, in addition to

\(^6\) Please note that in this thesis a NAN refers to a single NAN (e.g. NAN1, NAN2,...) which is a subdivision of a wider NAN.
the ICT architecture which is the main contribution discussed in this chapter, we have also designed and developed the software architecture aspect of our ICT system as a proof of concept which will is presented in Appendix B. The developed software tool, whose design is based on our software architecture, will operate at the highest layer of the ICT architecture (layer 5) for the NAN area. This software architecture describes how we will process and analyse the data gathered by the communication aspect of the ICT architecture and convert them to useful information. Collected data streams can be converted to information via different techniques. One of these techniques is data visualisation which we have used in this project. This information will be useful for grid operators and field engineers in order to monitor, analyse, control and take appropriate decisions. The implementation of our software tool has utilised the standard technology that exists today and the same design can be integrated with future developments in hardware, communication protocols and software engineering. This software architecture will be responsible for the control of the NAN and for integrating different NANs to provide information to the higher layers of the grid.

Figure 3.2 represents an abstract view of our designed software architecture. In Appendix B, we will introduce the detailed architecture of our implemented software tools and will discuss its design and present its implementation based on the actual environment of the University of Manchester sub-Grid.
The points of this study’s approach is: we address how monitoring, data collection, data transmission, data storage and data processing needs in a NAN could be met at this level of the electrical grid.

### 3.4 Implementation of the ICT Architecture on the University Campus

In this section we will discuss the implementation of our proposed ICT architecture in a real environment. As stated earlier, our environment is an experimental test bed, built on the campus sub-Grid of the University of Manchester at the sub-6.6 kV level. Figure 3.3 shows the deployment of our ICT architecture based on the principles which will be discussed later.

The first layer of the architecture consists of smart meter monitoring systems which are the gateway from the HAN to the NAN and are used to monitor the building level data. These monitoring devices are located in all the buildings in our campus test bed, sensing data every 30 minutes. They are already connected to the network and transmit data through wired connections to the database layer. A wireless communication link can also be considered as a backup link to substitute for the wired communication in case of failure. These monitoring devices provide information about power usage and permit the management of power generation and consumption. This data can be combined with information about real-time energy prices to offer an effective demand response control, beneficial both for energy consumers and providers.

The second layer of the architecture is composed of hundreds of sensors situated in the street areas. These monitoring systems implemented are wireless sensor networks which are used to monitor the environmental data such as temperature, light and humidity, or perform car park monitoring for future electrical cars. This information can be logged every second.
In future, there might be possible communication and query processing between layer 1 and layer 2, and also between layer 2 and layer 3. However, because of the clarity of the architecture, the arrows are not added to the figure. Additionally, data transmission from each of the first three layers to the layer 5 should be provided.

---

7 In future, there might be possible communication and query processing between layer 1 and layer 2, and also between layer 2 and layer 3. However, because of the clarity of the architecture, the arrows are not added to the figure. Additionally, data transmission from each of the first three layers to the layer 5 should be provided.
These environmental data are important for understanding the response of the system to variables such as number of people and cars, weather, temperature, humidity and so on. Since the sensors monitoring these parameters are not available yet to be implemented in the real environment, we have extended the WSN query-processing engine called TinyDB (Madden et al., 2005) by adding a Smart Grid component to it. Thus now we are able to simulate environmental data, receive live data in response to queries and feed the received data to another source of computation to apply timely-manner system controls in the future. We will briefly discuss the extension to TinyDB in Appendix A. This layer can provide both monitoring and control of the environmental conditions which ultimately will help in controlling the power grid since they can provide information that can be used to anticipate demand and to improve control actions. Some of the controls over the environment which can be offered by this layer are: control of smart parking, control on the battery charging of electric cars, street lighting.

As mentioned above, this layer of the architecture is comprised of a number of WSNs. For reasons of efficient utilisation of energy in collecting and transmitting data from each WSN, we propose to use cluster-based communication for these WSNs in this layer. Each cluster has a cluster head (CH) which can be a more powerful sensor than the other sensors (cluster members). The cluster members will send their data to the cluster head wirelessly and then the cluster head is responsible for transmitting the data to the base station, and from the base station data will be transmitted to the database layer. A survey (Abbasi and Younis, 2007) on clustering algorithms for a wireless sensor network argues that such cluster-based communication provides more communication efficiency and a longer network lifetime. The survey goes on to state that, in addition to the advantages of clustering such as network scalability and energy efficiency, clustering can localise the route set up within the clusters and consequently decrease the size of the routing table stored at a single node. Moreover, the range of inter-cluster interactions to the CH is restricted and redundant message exchange is prevented which helps in preserving communication bandwidth. In addition, the network topology is stabilised with the help of clustering at sensor level resulting in cuts in the overheads of network topology maintenance. Also the sensors are only concerned with their connection to their CH and thus will not be affected by the modifications at inter-CH levels. On the other hand, based on the application requirements, the events monitored can be either continual or intermittent. Continual monitoring ends up in generating a considerable amount of traffic to be routed to
the sink. In within-network data processing, similar packets from different nodes can be aggregated in order to reduce the number of transmissions. Since the energy consumed for transmitting one bit is equal to the energy required for processing thousands of instructions (Sacaleanu et al., 2012b), this technique can save a substantial amount of energy.

Accordingly, layer 2 itself, is divided into three sub-layers, namely sub-layer 2.1, sub-layer 2.2, and sub-layer 2.3. The sensors in sub-layer 2.1 are cluster members that run on batteries. They usually have a short range of communication and directly send their data via wireless links to the more powerful sensor designed to be the CH. The CHs (sub-layer 2.2) provide a longer range of communication and are able to receive data from sub-layer 2.1 and transmit the received data to the base station (sub-layer 2.3) via wired or wireless technologies. Since the sensors designated as CHs are powerful sensors, they are able to apply limited data computation such as data reduction. Then the base station in each WSN is responsible to transmit data to the layer 4 (database layer). These base stations are able to process data and apply decision-making if required. Thus, in future, if the Smart Grid needs to distribute control at the environmental level, this architecture can incorporate it.

The third layer of the architecture incorporates substation monitoring and control. This layer itself is divided into three sub-layers. The third layer is already implemented by a reconfigurable real-time control and acquisition system called Compact RIO (cRIO) (sub-layer 3.1), data storage (sub-layer 3.2), a control unit (sub-layer 3.3) and a router to relay the data to the higher level (shown in Figure 3.4). The control unit (sub-layer 3.3) is the LabVIEW (LabVIEW, 2007;NI, 2011) programme which is responsible for applying control over the substations only. The reason we need a different layer of abstraction for this layer is that layer 2 was responsible for applying control over the environmental factors, whereas this layer is responsible for controlling the power grid itself; these are two distinct functionalities. Regarding our test bed, this layer consists of eleven 6.6 kV substations that are equipped with sixteen monitoring systems. The substations with one transformer are equipped with one cRIO, whereas the substations with two transformers are supplied with two cRIOS. The cRIO (NI, 2010) (sub-layer 3.1) in each box is composed of an FPGA module, a real-time controller, a reconfigurable I/O module and an external expansion chassis. These cRIOS are running at 1 Hz to 4 Hz, thus we are sensing
one to four samples per second, measuring three phases of voltage, current, active power, power factor, voltage spectrum (eight channels for each phase) and current spectra (eight channels) and frequency which can be used for the identification of faults at this level, for power quality analysis and for other applications. The data monitored by each cRIO will be saved in the data storage (sub-layer 3.2), thus if we lose communication with any of them we can collect data manually from the substation. These monitoring boxes are connected to the power network and are able to communicate via FTP in order to transmit data to the higher layers using both wired and wireless technologies. Both wired and wireless technologies are used to prevent data loss, so that if one of the links goes down there exists another communication medium for data transmission. Moreover, to avoid data loss, the collected data can be stored locally in the memory and transferred once a day to the database layer. Subsequently, the live data will be sent from each cRIO to the fourth layer (database), for example, via wireless communication. In the future, these substations should also be able to communicate with each other in order to apply better control by coordinating their decisions and preventing conflicting scenarios.

Figure 3.4: Monitoring system at the substations.

The fourth layer is the database (DB) layer that will store data received from the layers below and will feed the NAN Control Unit (NCU), which is located on layer five, with collected data. This layer has been implemented by a PostgreSQL database.

The NCU that is the top layer will apply control over the entire neighbourhood area (a single unit of NAN). In this test bed the NCU is located at the Sackville Street Building in the University of Manchester. It should access sensing units directly in emergency
situations or indirectly through the DB layer in normal conditions. Given that better monitoring will result in a more efficient control over the system, we have developed a GIS enhanced display of the network. This visualisation tool can be considered as a component located in the fifth layer. It is helpful for engineers to utilise the visualisation tool in order to track and discover the faulty part of the grid and take remedial action.

Figure 3.3 illustrates these ideas applied to one NAN. Numerous such NANs would be joined in order to monitor and control an entire sub-Grid. We will consider here only one such NAN, namely a university campus area as part of a wider urban sub-Grid. Since each NAN can take optimal decisions for its own region, which are not necessarily the optimal decisions for the whole network, another layer of communication should be added over the top layer to make each individual NAN aware of the state of the other NANs and thus enable them to coordinate their decisions.

The proposed architecture which is a combination of centralised and distributed control has a number of advantages compared with a centralised control of an entire electricity grid which will be discussed in the Chapter 6, together with Architectural styles and principles that inform the design of this architecture. However, here we will also present a few other benefits and techniques to avoid failures in this architecture.

One of the advantages of this architecture is that, if one NAN goes down, it will not affect the rest of the wider network. Additionally, by using clustering in the layer two, we can reduce the communication energy of the resource-constrained sensors. Also, in the second layer of the architecture, the cluster member sensors (which provide the actual data) produce data streams that show a high level of correlation if they are distributed sufficiently densely, thus, the failure of one sensor will not severely affect the whole NAN. The CHs are responsible for collecting and sending the gathered data to the base station, thus the loss of a CH will result in losing all the data collected from its cluster members. Thus, if the CH is down, the cluster member sensors in sub-layer 2.1 should transmit their data to a neighbouring CH via either multi-hop or direct communication if the neighbour CH is within the transmission range of the sensor. If the CH’s communication paths to the base station are down, the CH should transmit its received data to the neighbouring CH which will be responsible for sending its own cluster data and its neighbour cluster data to the base station. In case, if the base station is down, the visualisation tool should be able to send notification when it is not receiving data from each individual
base station for a predefined time. Thus the operators will gauge that either the base station is down or the communication path is faulty.

### 3.5 Sensor Network Applications in the Smart Grid

As discussed earlier, power grids have historically been centrally controlled, with the NAN and HAN levels being essentially passive. Detailed monitoring at this level has, therefore, not been a priority. As a grid evolves to a higher degree of localised control, monitoring devices should be more pervasive and widely deployed and the type of these devices and computational units should become more lightweight. As such, we have chosen to monitor the NAN by sensor networks. In this section we have identified a range of applications of sensor networks in the Smart Grid and especially in the distribution networks (of which NANs are an example) of the Smart Grid.

Recent advances in the field of sensor networks such as reduction in size, improvement in information processing units, data aggregation and adaptability to harsh environments have led to a renewed interest in their applications. For example, thus far WSNs have been implemented for military and medical applications, gas and water networks’ monitoring, firefighting, health monitoring, transportation monitoring, agricultural applications, security applications and, finally, for commercial and robotic functions. Based on such a wide range of applications we can hypothesise that WSNs can also be considered as a key technology for smart electrical networks. They can be applied at all levels of an electrical grid, from generation to transmission and finally to the distribution network. As an example, a Smart Grid aims to exploit various renewable energy sources which are usually placed in the remote area. This fact necessitates having continuous monitoring of the power generation by utilising low cost sensor networks. Additionally, sensors can be used for asset management and equipment diagnostics in the power generation network.

Sensor networks can also be used in transmission networks. A list of potential applications of WSNs in transmission networks is presented below (Veleva and Davcev, 2012):

1. Equipment status reporter such as failure
2. Disconnection of a communication or degradation function
3. Heat and vibration applications
4. Intrusion detection and security analysis
5. GIS applications
6. Ground potential and high voltage potential applications
7. Digital fault recording applications

A number of applications of sensor networks in distribution networks which have been identified through our research, and also have been introduced by Veleva and Davcev (2012), are as follows:

1. Real-time data collecting applications
2. Home Area Network (HAN) applications
3. Substation monitoring applications
4. Energy management applications
5. Power quality analysis
6. Equipment monitoring
7. Equipment theft prevention
8. Traffic monitoring applications
9. Weather (temperature and humidity) monitoring applications
10. Outage warning
11. Fast fault identification and rectification
12. Planned outage scheduling
13. System maintenance scheduling
14. GIS applications
15. Motion applications
16. Car park monitoring for electrical vehicles

Having sensor networks deployed in a Smart Grid for the above-mentioned applications will bring several advantages. Some of these benefits include reduction in manpower, reduction in downtime, reduction in electricity usage costs, maintenance optimisation and reduction in operational costs.

3.6 Summary

In this chapter we have focused on the NAN area of the electrical network and proposed an ICT architecture for such an area. In this design we first do not assume that sensors
can necessarily be powered from the power network itself, and second due to economic and environmental considerations, energy awareness became a driver in the design of our ICT architecture. This assumption was confirmed in the practical implementation decisions we made in developing the university campus NAN monitoring. We have described the design and implementation of our ICT network architecture on a sub-Grid covering the medium voltage power network of the University of Manchester campus which owns its own distribution grid. This allows us to check our design on real equipment with real data and input from experts in power engineering.

The key contribution of our work is that the designed architecture can deliver information from building levels, environmental conditions and, finally, from the power grid below 6.6 kV, where such a system has not been previously proposed and deployed and such information from this area has remained unknown until now. It will deliver the collected data to experts and will demonstrate what is happening in a lower voltage network and thus will consequently offer better control over a grid in the future.
Chapter 4. Energy-Aware Topology of Wireless Sensor Networks for Environmental Monitoring

4.1 Introduction

As discussed earlier, monitoring the NAN level of an electrical grid is very underdeveloped. A Wireless Sensor Network (WSN) can be considered as an essential component of the monitoring function in the Smart Grid. A WSN is responsible for monitoring and collecting real-time data from the field. It will send live data to a NAN Control Unit to provide more accurate prediction.

The second layer of our proposed ICT architecture is composed of hundreds of sensors situated in the street areas that communicate wirelessly. These sensors can sense attributes such as temperature, humidity, traffic, motion, occupancy and so on. We require that the data acquisition rate should be sufficient for real-time control of the network. Despite the advantages of a WSN, such a network suffers from a lack of resources such as shortage of power and processing capabilities. Difficulties arise when the deployed sensors in the Smart Grid are short of power meaning that a specific area of the grid is no longer being monitored at a sufficient rate. Given that real-time data is being used in the control layer, this may result in inaccurate decision-making in the grid. Due to the energy constraint drawback of wireless sensors, we intend to reduce their energy usage. Therefore, as it is believed that locality can enhance energy awareness within the system, we have utilised the concept of locality in this level of the architecture as well. Accordingly, we
have selected the concept of a cluster-based method as a method of communication in a WSN to offer energy efficiency. Consequently, the sensors in the second layer of the architecture are grouped into clusters, sending their data wirelessly to the more powerful sensor designed to be the cluster head (CH) and the CH is responsible for transmitting the received data to the base station.

To further alleviate the energy limitation drawback of wireless sensors, in this chapter we examine the energy consumption cost of a network and identify a suitable topology for a WSN that could reduce the total energy consumption of such networks. In this research, we have supposed that the CHs deployed in our test bed are resource-rich; this will impose a limitation on the number of CHs. In fact, one of the fundamental issues in cluster-based communication in a WSN is the identification of an optimal number of clusters (Gu et al., 2010). Having the optimised number of clusters is particularly important when the CH is a resource-rich node, as they are more expensive than cluster member nodes.

In this chapter we also compare the total energy consumption of our cluster-based WSN with the total energy consumption of the same WSN with direct communication. Additionally, we also present that, although we have used a different energy consumption analysis, the pattern of energy usage in our WSN follows the pattern of energy consumption of a WSN proposed by other researchers, which confirms the correctness of our analysis. We also discuss our results and the results achieved by other researchers, and highlight some of the limitations.

### 4.2 Application of the WSN for the Second Layer of the Architecture

In order to design the second layer of our proposed ICT architecture for the NAN level we have considered this layer of the architecture as comprising several WSNs. In this approach we may not cover the whole campus area with a WSN, but we will cover selected areas with different WSNs. In this approach each WSN contains a base station, which is located at the corner of the WSN; thus four adjacent WSNs can share a base station. This base station is responsible for collecting data from the environment and then transmitting the collected data to the NCU (NAN control unit). The second layer of the architecture requires a number of WSNs with different densities and sizes. These WSNs
could be used for equipment health monitoring, equipment theft prevention, weather monitoring, and car park monitoring for electrical cars. In future, we might require a detailed analysis of how the electric cars can interact with the electrical grid and how they can be used to charge each other. Thus, for example, a dense WSN could be used for car parks. In this case our WSN would be a medium scale WSN covering a public car park located in our campus test bed, with width of approximately less than 100m. Accordingly, in this chapter we will suggest an optimised number of clusters and a suitable topology for a medium-scale 90m×90m and a small scale 9m×9m WSN, which will result in less energy dissipation in an entire WSN. Application of the small scale WSN could be a small parking.

4.3 Energy-Aware Topology for the Wireless Sensor Network

More than a decade ago researchers started to realise the importance of energy conservation within WSNs and proposed different techniques as a solution. Utilising the cluster-based topology, which we have adopted for the second layer of our architecture, is one of these solutions. Therefore, we divided our WSN into a number of clusters and studied the optimised number of such clusters that could affect the total energy consumption of the WSN. In this section we will present our assumptions, our network model and our energy model which are used to analyse the total energy dissipation of this layer of the architecture.

4.3.1 Network Model and Assumptions

In this section we present the network model and the assumptions used to perform our analysis. We are analysing the energy consumption cost of the WSN in an urban area where the sensors cannot be deployed anywhere on the network (randomly). This architecture is going to be deployed on a university sub-Grid. The university campus is embedded in a city containing streets and roads. The whole campus is connected by an approximately rectangular grid, even the parking layout is a grid shaped structure. Since we are dealing with an urban area the sensors are located in fixed locations. The relevant WSN will follow these structures, which means we are dealing with a rectangular grid.
This is one of the differences between our network model and most of the other researchers’ network models as they have considered randomly deployed nodes and did not need to engineer or predetermine the location of their nodes.

In order to model our WSN in a NAN, we could locate the base station either in the centre or the corner of each WSN. Since having the base station at the corner of one WSN makes it at the centre of four WSNs, we have assumed that the base station is deployed at the corner of each network. Thus by having one base station we can serve four WSNs which is efficient in terms of installation costs and maintenance. As an example, Figure 4.1 depicts 16 WSNs comprising 4 base stations located at the corner of each WSN (highlighted in green), instead of having 16 base stations for the whole area.

![Figure 4.1: 16 WSNs comprising 4 base stations.](image)

Additionally, it should be noted that our proposed environment is a heterogeneous WSN. This network comprises two types of sensors: the first type of sensors are normal sensors which are assumed to be cluster members, and the second type of sensors are resource-rich sensors which are assumed to be CHs. These CH sensors are more expensive and their hardware and software are more complicated than cluster member sensors. They also have a wider range of communication and are able to perform data computation, such as data reduction, and a relatively small amount of decision-making if required in future.

The rest of the assumptions and simplifications used to calculate the total energy consumption of our WSN are presented as follows:
All nodes are stationary, because they are located in fixed places such as substations and etc.

The total number of nodes is known, because the nodes are pre-deployed, and adding new sensors is within the responsibility of the grid operator. Therefore, the total number of deployed sensors are known.

The location of nodes is known, because nodes are located in fixed places.

All CH sensors are within communication range of their cluster members and the base station is within communication range of the CHs. This is because if we consider cluster members using communication technology, as an example Bluetooth, with coverage of 100m with extended antenna, then with the network size of 100m x 100m or 200m x 200m, the CH within each cluster in the network will always be within the communication range of its cluster member. Moreover, since the CHs are considered to be sensors utilising communication technology with longer range of communication such as IEEE 802.11 or GSM, therefore, in such networks, the base station will be within the communication coverage of the CHs.

It is assumed that the nodes have a power control feature which enables them to adjust their transmitting power to an appropriate level that is necessary for successful data transmission.

All the cluster members transmit directly to a CH and CHs transmit directly to the base station. Since direct transmission is easier to manage and practical, therefore, in this network we have chosen direct transmission as the method of communication.

All the sensors in each category consume their energy resources at the similar rate. This is because we have considered identical sensors in each categories, namely cluster member category and CHs category. However, it should be mentioned that although the rate of energy consumption is similar in the identical sensors in our network, but the amount of energy consumption is different. This is because the transmission range and the amount of received data is different from sensor to sensor, which affects their energy consumption.
**Chapter 4: Energy-Aware Topology of Wireless Sensor Networks for Environmental Monitoring**

- The time, during which the cluster members sense and transmit data to their designated CH and then, following this, the CHs sense, receive, compute, and transmit the data collected from their cluster members to the base station, is called a round of communication.

- In each round of communication the data sensed by cluster members and CHs have same number of bits. This is assumption is considered in order to simplify the analysis, however, the user of the program can change the number of transmitted bits according to the application requirement.

- The CHs are responsible for applying data reduction on the data received from its cluster members. This is because the CHs have more powerful processing unit capable of applying data reduction in order to transmit less amount of data.

### 4.3.2 Energy Model

As discussed earlier each sensor in a WSN consists of a sensing unit, a processor unit and a transceiver unit. Each of these units consumes energy while a sensor is running. In our analysis, in order to compute the energy of data transmission, we have used the first order radio model which is a simple model for radio energy dissipation for transmission as described in work of Heinzelman et al. (2000; 2002). In this model, the transmitters spend energy on running both the radio electronics ($E_{elec}$), and the power amplifier ($E_{fs}$ or $E_{mp}$). The energy dissipated by the power amplifier depends on the Euclidean distances between the sender and the receiver; this distance is called $d$. Accordingly, for short distances free space fading ($fs$), $d^2$, and for longer distances multipath fading ($mp$), $d^4$, has been considered (Heinzelman et al., 2000; 2002). In a medium size WSN, since the transmission distance from a CH to the base station is generally longer than the transmission distances from cluster members to a CH within a cluster, we have adopted ($mp$) a multipath fading channel for communication between a CH and the base station and a ($fs$) free space fading channel for communication within clusters. Multipath fading is typically initiated by the reflection of radio waves of things like mountains, buildings and other structures\(^8\). Therefore, the energy spend for transmitting $k$ bits of data over distance $d$ is analysed as:

\[^{8}\text{An analysis of these values is out of the scope of this research. In this thesis we have used the generally accepted values for these parameters in this domain of research.}\]
\[ E_T = E_{elec}k + E_{fs}kd^2 \text{ (for short distances)} \] (4.1)

\[ E_T = E_{elec}k + E_{mp}kd^4 \text{ (for long distances)} \] (4.2)

Additionally, the receiver spends energy just on running the radio electronics to receive \( k \) bits of data. Accordingly the energy spend for receiving data is:

\[ E_R = E_{elec}k \] (4.3)

The energy spend for sensing is also analysed as (Duarte-Melo and Liu, 2002).

\[ E_{se} = E_{elec}k \] (4.4)

We have also analysed the energy spend for data computation, such as aggregation or compression, as below. Given that the energy spent for a data transmission is \( n \) times bigger than the energy spent data computation (Hingne et al., 2003; Heinzelman et al., 2000; Sacaleanu et al., 2012b; Barran and Asanovic´c, 2003), we assume the energy spent in computation is:

\[ E_C = \frac{E_{elec}}{n} \] (4.5)

In the literature review other researchers have considered the energy of computing constant as equal to 5 \( \left( \frac{nJ}{b} \right) \) (Heinzelman et al., 2002; Gu et al., 2010), for simple data computation. This means they have considered \( n \), which is the communication to computation ratio equal to 10. However, we believe the energy dissipated for this process is application specific and may vary from case to case depending on the data reduction method used in that particular case. Therefore, we have considered \( n \) as a communication to computation ratio that could change in different scenarios. The value of \( n \) can be specified by the user of the program. For example, when the CHs are dealing with a complicated data reduction algorithm, or even in cases when CHs are undertaking decision-making, \( n \) will decrease as the processor will consume more energy. However, while the processor is performing simple data aggregation, \( n \) will increase as the processor is dissipating less energy. In our analysis we have considered a lower \( n \) as communication to computation ratio, since we assume our data compression technique is more complicated than the ones specified in the literature. It should be noted that the value of \( n \) will not
change the behaviour of the energy consumption of our network, however, by changing $n$ the absolute value where the minimum number of CHs happens may differ, as it is subject to various assumptions. However, in this analysis we are not looking for the absolute value for minimum number of clusters, but we are looking for an insight into a range of optimised number of clusters that could be deployed in our test bed.

### 4.3.3 Energy Consumption Analysis

With the aim of achieving an energy aware topology within a WSN we needed to find an appropriate number of clusters in our network. In order to do so we have examined the minimum energy consumption of a network by varying the number of clusters and the number of their cluster members, their shapes and locations while keeping the total number of nodes in our network constant.

In this analysis we have considered a heterogeneous WSN with $N$ sensors deployed in a grid bounded by $L \times L (m^2)$ region, with the base station located at the corner of the grid. Given these network assumptions, the total energy consumption of the WSN is presented below.

At beginning of each round of transmission cluster member sensors will spend energy on sensing the $K$ bits of the data called ($E_{se}$) analysed as $E_{se} = E_{elec} \times K$. In order to send the sensed data, the sensor will spend energy in running the transmitter circuitry called ($E_{stt}$), analysed as $E_{stt} = P_t \times T$ (where $P_t$ is the power used in the transmitter circuitry and $T$ is the start-up time), and the energy for transmitting $K$ bits message to the destination located at the distance $d$ to the CH, called ($E_T$) which is analysed as $E_T = E_{elec}k + E_{fs}K d_{toCH}^2$. The transmission energy for communication between cluster members and the CH is calculated using the $f_s$ model.

Additionally, the CHs which are responsible for sensing, receiving data from cluster members, compressing and sending these data to the next destination, spend energy on sensing the $K$ bits of the data called ($E_{se}$) analysed as $E_{se} = E_{elec} \times K$, running the reception circuitry ($E_{str}$) analysed as $E_{str} = P_r \times T$ (where $P_r$ is the power used in the receiver circuitry and $T$ is the start-up time) and the energy for receiving the data ($E_R$), analysed as $E_R = E_{elec}K$, plus the energy for computation ($E_C$), analysed as $E_C = \frac{E_{elec}}{n}$, and the energy for running the transmitter circuitry called ($E_{stt}$), analysed as
Energy-Aware Topology of Wireless Sensor Networks for Environmental Monitoring

\[ E_{stt} = P_t \times T, \] and the energy for data transmitting (\( E_T \)) analysed as \( E_T = E_{elec} k + E_{mp} k d_{toBS}^4 \). The transmission energy for communication between CH and the base station is calculated using the \( mp \) model (for a medium scale WSN).

Table 4.1 demonstrates the energy models used in our analysis and Table 4.2 defines the parameters used in our calculations.

**Table 4.1: Energy models used in our analysis.**

<table>
<thead>
<tr>
<th>Energy calculation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{se} = E_{elec} \times K )</td>
<td>Energy for sensing data</td>
</tr>
<tr>
<td>( E_{stt} = P_t \times T )</td>
<td>Energy for starting up the transmitter circuitry</td>
</tr>
<tr>
<td>( E_T = E_{elec} k + E_{fs} k d_{toCH}^2 )</td>
<td>Energy for transmitting data within clusters</td>
</tr>
<tr>
<td>( E_T = E_{elec} k + E_{fs} k d_{toBS}^2 )</td>
<td>Energy for transmitting data from CH to a base station for small scale WSN</td>
</tr>
<tr>
<td>( E_T = E_{elec} k + E_{mp} k d_{toBS}^4 )</td>
<td>Energy for transmitting data from CH to a base station for medium scale WSN</td>
</tr>
<tr>
<td>( E_C = \frac{E_{elec}}{n} )</td>
<td>Energy for computation</td>
</tr>
<tr>
<td>( E_{str} = P_r \times T )</td>
<td>Energy for starting up the reception circuitry</td>
</tr>
<tr>
<td>( E_r = E_{elec} K )</td>
<td>Energy for receiving data</td>
</tr>
</tbody>
</table>

The energy spent in a single cluster is the sum of the energy spent by the non-CH sensors plus the energy spent by the CH sensor. Accordingly, the energy consumed by each cluster member or non-CH is analysed as follow:

\[
E_{nonCH} = E_{se} + E_{stt} + E_T
\] (4.6)

\[
E_{nonCH} = E_{elec} K + P_f T + E_{elec} K + E_{fs} K d_{toCH}^2
\] (4.7)
## Table 4.2: Parameters used in our analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{elec}$</td>
<td>50 (nJ/b)</td>
<td>Energy disseminated by the radio per bit to run the transceiver and sensor circuitry</td>
</tr>
<tr>
<td>$E_{fs}$</td>
<td>100 (pJ/b/m²)</td>
<td>Energy spent per bit per m² for the transmit amplifier</td>
</tr>
<tr>
<td>$E_{mp}$</td>
<td>0.0013 (pJ/b/m⁴)</td>
<td>Energy spent per bit per m⁴ for the transmit amplifier</td>
</tr>
<tr>
<td>$P_t$</td>
<td>0.66 watt</td>
<td>Power used in the transmitter circuitry</td>
</tr>
<tr>
<td>$P_r$</td>
<td>0.395 watt</td>
<td>Power used in the receiver circuitry</td>
</tr>
<tr>
<td>$T$</td>
<td>0.001 second</td>
<td>Start-up time</td>
</tr>
<tr>
<td>$K$</td>
<td>2000 bits</td>
<td>Number of bits of data</td>
</tr>
<tr>
<td>$d$</td>
<td>variable</td>
<td>Distance between sending device and receiving device</td>
</tr>
<tr>
<td>$N$</td>
<td>100</td>
<td>Number of nodes in the network</td>
</tr>
<tr>
<td>$N'$</td>
<td>variable</td>
<td>Number of nodes in each cluster</td>
</tr>
<tr>
<td>$C$</td>
<td>variable</td>
<td>Number of clusters</td>
</tr>
<tr>
<td>$n$</td>
<td>3</td>
<td>communication to computation ratio</td>
</tr>
<tr>
<td>$r$</td>
<td>2</td>
<td>Compression ratio (e.g. $K$ bits of data are compressed to $k/2$)</td>
</tr>
<tr>
<td>$z$</td>
<td>2</td>
<td>The powerful CH consumes $z$ times more energy than normal cluster members</td>
</tr>
</tbody>
</table>

The energy spent by the CH is analysed as follow:

$$E_{CH} = z \left[ E_{se} + E_{str} + N'E_R + (N' + 1)(K)E_C + E_{stt} + \left( \frac{N' + 1}{r} \right)E_T \right]$$

(4.8)

$$E_{CH} = z \left[ E_{elec}K + P_tT + N'E_{elec}K + (N' + 1)(K)\frac{E_{elec}}{n} + P_T T + \left( \frac{N' + 1}{r} \right)\frac{E_{elec}K}{r} + \left( \frac{N' + 1}{r} \right)\frac{E_{mp}K}{r}a^4_{toBS} \right]$$

(4.9)

In these calculations $z$ presents the fact that powerful CHs with complicated hardware and software consume more energy than normal cluster members’ sensors. Moreover, traditionally, it is assumed that a CH performs complete data reduction, which means that the $K$ number of bits transmitted from each of the cluster members will be reduced to only one set of $K$ number of bits via the CH. However, in this analysis, we have assumed ($r$) to be a compression ratio. This ($r$) may differ from case to case for diverse data reduction algorithms. Note that, although we have assumed that all the CHs apply the same data reduction algorithm with the same compression ratio, still the reduced data...
size is not the same for all the CHs. This is because each individual cluster may have a
different number of cluster members. Therefore, the size of transmitted data varies from
CH to CH.

The energy dissipated by a single cluster is analysed as follow:

\[ E_{\text{cluster}} = E_{CH} + \sum_{i=1}^{N'} E_{\text{nonCH}_i} \]  \hspace{1cm} (4.10)

Finally, the total energy consumed in a WSN is analysed as follow:

\[ E_{\text{Total}} = \sum_{j=1}^{c} E_{\text{cluster}_j} \]  \hspace{1cm} (4.11)

With the help of above analysis and, in order to find an energy aware topology for our
WSN, we studied the optimised number of clusters \((C)\) that results in a minimum energy
consumption by the WSN \((E_{\text{Total}})\). We analysed the total energy consumption in different
scenarios by dividing the network into a different number of clusters. For this study
we simulated two networks with different network sizes in MATLAB. The first one was
a small network with dimensions of approximately 9\(\times\)9\(m^2\) and the second network was
a medium size network with dimensions of 90\(\times\)90\(m^2\). Since, in a small WSN, all the
communication distances are short, we considered the free space model both for within
the cluster communication, as well as for the communication from a CH to the base sta-
tion. While for the medium size network, we considered the free space model for within
cluster communication and the multipath fading model for the communication from a
CH to the base station. In this study we have kept the total number of sensors fixed and
created networks with 4 clusters, 6 clusters, and so on, ending with 16 clusters. Then we
examined the total energy consumption for each network by varying the number of nodes
in the clusters, cluster shapes and locations for 10 different configurations, all of which
preserved the number of clusters. Since, in reality, we were not always able to deploy the
sensors in the most optimal topology, we considered the average of these 10 configura-
tions.
Figure 4.2 plots the total energy consumption against the number of clusters for 9\times9 \((m^2)\). The curve shows that a considerable energy reduction can be achieved beyond a minimum of 6 clusters; however we can achieve only a smaller amount of improvement afterwards. It shows that the variation between 6 and 14 clusters is very small, i.e. the shape of the minimum is approximately asymmetric. However, this curve shows a minimum at 8 clusters.

![Figure 4.2: Energy for L=9 m.](image)

Figure 4.3 plots the total energy consumption against the number of clusters for 90\times90 \((m^2)\). The curve shows that a considerable energy reduction can be achieved beyond a minimum of 8 clusters. It shows that we can achieve a smaller improvement beyond 8 clusters whereas, the minimum point of the curve happens at 12. These analysis reveal that, in such networks, if we are bound to cost restrictions or a suitable location for deploying CHs, then by having 8 clusters we can achieve energy efficiency. However, if we are not restricted to such considerations, then by having 12 clusters we can reduce the total energy dissipation further. The result that the minimum point occurs at a specific number is a function of several parameters such as the total size of the grid, compression ratio, cluster shapes, sizes and locations. However, this method could be used on grids of arbitrary size with different assumptions for different variables.
In the analysis mentioned above we considered that CHs consume their energy resources 2 times more than cluster member sensors. In another set of experiments we tested the effect of increasing the energy consumption of CHs for the cases when they consumed 5 times and 10 times more energy than the cluster members. The results show that this parameter does not change the behaviour of the curve. As expected, it reveals that as the number of clusters increase in a network the gap between these three cases will increase. Figures 4.4 and 4.5 depict these three cases in which $E_{Total_2}$ addresses the total energy consumption of a network when the CHs consume 2 times more energy than other nodes; $E_{Total_5}$ refers to the total energy consumption of a network when the CHs dissipate 5 times more energy, and $E_{Total_{10}}$ addresses the total energy consumption of a network when the CHs consume 10 times more energy than normal nodes. Figure 4.4 reveals that, in network scale of $9\times9\,(m^2)$ when the CHs consume more than 2 times more energy than the normal sensors, we cannot achieve energy efficiency. On the other hand, such a scenario will consume more energy than the direct communication scenario. Direct communication dissipates approximately around 0.2 joule of energy for a network of $9m\times9m$ thus, after this experimentation, we realised that the scenarios in a $9m\times9m$ network are irrelevant. However, Figure 4.5 shows that, in a network scale of $90m\times90m$, the $z$ parameter does not seriously affect where the range of optimal number of CHs appears. In all these scenarios for $90m\times90m$ we can still achieve energy efficiency compared to the direct communication.
4.4 Discussion

The results of our analysis show that having fewer number of clusters in a WSN will result in more energy dissipation in the system because the cluster members have to transmit their data over long distances to reach their designated CH. Through our experimentation, we have confirmed that transmission distance is one of the most influential factors on the total energy consumption of a network. On the other hand, having more
clusters than the optimised cluster count will also result in more energy usage of the system because having more CHs results in more energy dissipation for data reception and data computation, more long distance communication between the CHs and the base station, and less data compression by the CHs which results in the transmission of more data.

The examples in this section illustrate that the total energy consumption in the network depends on the shape, size, and location of its clusters. In these examples we will illustrate some cases for each network topology scenarios with 4, 6, 8, 10, 12, 14 and 16 clusters and check how the size, shape and location of these clusters can affect the total energy consumption of such networks. In each figure the blue dots represent cluster members, black dots represent the CHs and the green box at the corner of the network represents the base station.

It has been concluded that the shape, size and location of the clusters are determining factors for energy consumption. The results show that if the clusters are rectangular, then the best result is when the rectangle is square. Additionally, we have realised that, having relatively big clusters in the network, will result in more energy dissipation. Less energy dissipation can be achieved when clusters are similar in shape and size. However, evenly distributing the clusters is difficult to achieve in a grid shaped network. Also, we observed that if we allow clusters to be different in size, then if smaller clusters are near the base station and bigger clusters are located farther from the base station, this improves the energy efficiency.

Figure 4.6 compares the total energy consumption of a grid (90m×90m) with 4 clusters. It shows that minimum energy consumption happens when the network comprises four similar clusters regarding their shape, size and number of nodes (Figure 4.6a). Subsequently, Figure 4.6b and Figure 4.6c show that the energy dissipation increases as we change the size of the clusters. It shows that the bigger cluster we have in a network, the more energy dissipation it will cause. Finally, as is depicted in Figure 4.6d, the shape of the clusters is an important and determining factor in total energy consumption.
Figure 4.6: The effect of clustering size, location and shape on total energy consumption in a 90m×90m network.

In a network with four clusters (see Figure 4.7) we have observed that, if a WSN is comprised of big clusters, even by locating the smaller clusters near the base station this network topology still consumes more energy than the network topology with a more even distribution of clusters. Thus, this suggests that shapes of the clusters are a more effective factor than their locations.
In these examples for a network topology with 6 clusters (see Figure 4.8) we can observe the effect of having a rectangular cluster shape in a network which will result in an increase in total energy dissipation.

In these examples for a network topology with 8 clusters (see Figure 4.9) we can observe the effect of a rectangular cluster shape. Even when the smaller clusters are located near the base station and the bigger clusters are farther away having a rectangular cluster will result in more energy dissipation in the network.
In these examples for a network topology with 10 clusters (see Figure 4.10) we can observe the effect of having similar clusters with similar shapes and sizes that results in less total energy dissipation in a network.

Figure 4.10: 10 CHs.

In these examples for a network topology with 12 clusters (see Figure 4.11) we can observe the effect of having bigger clusters in a network (a). Even if they are located farther away from the base station, the network still consumes more energy than other cases.
In these examples for a network topology with 14 (see Figure 4.12) clusters we intend to check the effect of the location of the clusters. Thus two networks with the same cluster size and shape are compared. We observe that topology (a) with bigger clusters near the base station consumes more energy than the other topology, in which smaller clusters are located near the base station.

In these examples for a network topology with 16 clusters (see Figure 4.13) we can observe the effect of the location of the clusters on the total energy consumption of the system.
4.5 Evaluation

In this section we will first validate our assumption that a cluster-based WSN is generally more energy efficient than a WSN with direct communication between its nodes and the base station. Then we will validate the behaviour of the total energy consumption in our WSN as the number of clusters increases with the results produced by previous works. Finally, we will present the analytical results produced by other research and discuss their limitations.

4.5.1 Comparing Direct Communication with Cluster-Based Communication in a Wireless Sensor Network

It is believed that cluster-based communications are generally more energy efficient and scalable than direct communications (Duarte-Melo and Liu, 2002). The communication pattern of many-to-one in a direct communication with large number of nodes will result in the lesser scalability of a system. An additional limitation of direct communication is the communication distance between the sensors and the base station, because direct communication limits the location of the base station as it should be in the communication range of all the sensors in the network.

In order to confirm the energy efficiency of our cluster-based WSN, we created two scenarios and compared their results. The first scenario was direct communication where
each sensor transmits its data directly to the base station. These sensors only spend energy on sensing, starting up the transmitter circuitry, and transmitting data to the base station. The second scenario was cluster-based communication, where a number of sensors are grouped in clusters and the CHs are responsible for compressing and transmitting the collected data to the base station. The energy dissipation analysis of this scenario is discussed earlier in this chapter. The result shows (Figure 4.14) that, for a small network such as $9 \times 9 (m^2)$, cluster-based communication is energy efficient only if the number of the clusters in a WSN is more than 4 clusters. The energy efficiency ratio between the energy consumption of direct communication and the average energy consumption of cluster-based communication when the number of clusters is between 5 and 16 is approximately 20.7%. However, the results (Figure 4.15) for a medium size network such as $90 \times 90 (m^2)$ show that cluster-based communication is generally energy efficient. In this case, the energy efficiency ratio between the energy consumption of direct communication and the average energy consumption of cluster-based communication when the number of clusters is between 8 and 16 is approximately around 94%. These results confirm the assumption that utilising a cluster-based WSN in the second layer of our designed ICT architecture for the Smart Grid will offer energy awareness in the communication system of such a network.

![Figure 4.14: Normalised energy for L=9 m (z=2).](image-url)
4.5.2 Validation of the Behaviour of the Total Energy Consumption in a Wireless Sensor Network

As discussed earlier, a number of papers have been published which have investigated the optimal number of clusters in a cluster-based WSN. Although finding an optimal value for cluster counts in a WSN is subject to assumptions and parameters considered while analysing the total energy consumption, still the behaviour of the total energy consumption of such a network as the number of cluster increases can confirm the correctness of our method and assumption.

Accordingly, in order to show that the behaviour of the total energy consumption in our WSN as the number of clusters increased is consistent with the behaviour of the total energy consumption in the WSN models proposed by other researchers as they escalate the number of clusters, we depict the graphs below. This is not intended to be an exhaustive list of works representing the similar behaviour for such networks but to validate our methodology and assumptions.

The results of an investigation into an optimal cluster count for a WSN is presented in Figure 4.16. This graph plots the average energy consumption per round versus the number of clusters as the cluster count varies from 1 to 11 in a homogeneous network with area size of 100m×100m and 100 nodes (Heinzelman et al., 2002). It reveals that the
most energy efficient state of Heinzelman et al’s WSN happens when the cluster count is between 3 and 5, and after 5 the energy consumption increases.

![Figure 4.16: Optimal number of clusters (Heinzelman et al., 2002).](image)

Furthermore, Figure 4.17 also depicts the total energy consumption versus the number of clusters in a heterogeneous WSN with dimensions of 200m×200m comprising 200 nodes. This study by Gu et al. (2010) shows that the optimal cluster count happen at 8 clusters, and after 8 the total energy consumption increases.

![Figure 4.17: Optimal number of clusters (Gu et al., 2010).](image)

The results of another investigation into the optimal number of clusters is presented in Figure 4.18. It shows the energy consumption per round versus the number of clusters for a network with area size of 200m×200m and 100 nodes in a heterogeneous WSN.
Chapter 4

Energy-Aware Topology of Wireless Sensor Networks for Environmental Monitoring

(Tuah et al., 2012). It shows that the optimised cluster count is 5, and after 5 the total energy consumption slowly starts to increase.

Figure 4.18: Optimal number of clusters (Tuah et al., 2012).

The graphs presented above reveal that there exist an optimal value or a range of optimal values for cluster count which result in minimum energy consumption by the system. Since the behaviour of our graph conforms to the behaviour of the graphs produced by these works, we can confirm that our results are viable. The results presented above allow the sensors to be placed anywhere in a 2D region. In this thesis we show that the result also applies when the sensors are constrained to be on a rectangular grid. Accordingly, we are able to undertake our analysis on any particular size of a WSN, with different assumptions, and could find the range of the optimised number of clusters in that network, depending on the size, shape and location of the clusters embedded within it.

4.5.3 Analysis of Other Works

In this section we will discuss the reason why we have not used the analytical formulas already published by previous works to propose an optimal number of clusters in a WSN and have utilised our own methodology to identify an optimised cluster count in such networks.

A work published by Heinzelman et al. (2002) proposed an analytical formula in order to find the optimal cluster count. Formula (4.12) is derived by setting the first derivative of $E_{Total}$ of the system with respect to number of cluster to zero. In the following formula
$K_{opt}$ denotes the optimal number of clusters, $N$ total number of nodes, $M$ the network dimension, and $d_{toBS}^2$ the distance between the CHs to the base station. A constraint of this work is that they limit the $d_{toBS}$ to be between 75 and 185 meters for a network with a dimension of 100m×100m. However, while simulating their network, their simulation assumptions contradict this limit on $d_{toBS}$ in their analytical method by placing the nodes throughout their network with no considerations on the $d_{toBS}$.

$$K_{opt} = \frac{\sqrt{N}}{\sqrt{2\pi}} \frac{\varepsilon_f}{\varepsilon_{mp}} \frac{M}{d_{toBS}^2}$$

(4.12)

They have concluded that the optimal range of clusters in a network with their assumptions is between 1 and 6 ($1 < K_{opt} < 6$). The results of this analytical formula on our WSN reveals the optimal number of clusters should be between 3 and 18 ($3 < K_{opt} < 18$) for a network of 90m×90m. Although our simulation results for the optimised number of clusters is within this range, still there exist a number of limitations that should be considered when one is using this formula. The first limitation is that this work has not considered the energy of sensing while analysing $E_{Total}$. Additionally, the energy of computation has been considered as a constant value which does not change when the computation algorithm changes. Furthermore, since this work only considered full data aggregation, the compression ratio in such an analysis is neglected.

Another work published by Gu et al. (2010) has also proposed an analytical formula to identify the optimal number of clusters. This formula (4.13) is also derived by setting the first derivative of $E_{Total}$ of the system with respect to number of cluster to zero. In the following analysis $K$ represents the optimal number of clusters, $n$ the total number of nodes, $L$ the network dimension and $\alpha$ the compression ratio. In this analysis the authors have considered that all the distances from the CHs to the base station are identical to simplify their analysis. However, we have realised that the main constraint of this work is that this formula is only applicable to large WSNs. We have considered a number of different parameters as an input to this formula and have realised that this analytical method is not applicable for small or medium size networks. For example, in a network
with dimensions of 100m×100m when the compression ratio is anything less than α<0.9 the denominator would become negative which would end in an incorrect result.

\[K = \sqrt{\frac{3nL^2\varepsilon_{fs}}{9(\alpha - 2)E_{elec} + 4\alpha L^4 \varepsilon_{mp}}}\] (4.13)

In this section we have looked at other works that have proposed an analytical formula for this purpose but they have some limitations that have been identified through our study. These formulas should not be used without considering the physical restrictions within their assumptions, such as having identical clusters with the same number of nodes and similar distances from the cluster members to the CHs, which limits their formula. However, in our study we have assumed that clusters can be partitioned unevenly, with different numbers of nodes in each. This is because, in real practice, it is not always possible to partition clusters evenly. Therefore, as the formulas presented above are not applicable to some situations, we have utilised our own methodology which is believed to be practical for a wider range of networks.

### 4.6 Summary

In this chapter we have studied the problem of identifying an optimised range of cluster counts in a cluster-based WSN which results in less energy dissipation of the system. We have analysed the topology of a WSN that is a part of our designed ICT architecture in terms of offering energy awareness. We have considered two network scenarios: the first one was a small size network in which we utilised the free space model both for communications within clusters, and between the CHs and the base station. The second scenario was a medium size network in which we utilised the free space model for communication within clusters and the multi path fading model for communications from the CHs to the base station. To better understand the effect of the shape and the location of clusters on the total energy consumption in such networks we have undertaken experiments with over 450 different cases. We have observed and analysed the changes in each case individually.
We have evaluated, experimentally, WSNs placed on a rectangular grid representing a city environment. By varying the number of clusters we have established that an optimal number of clusters in terms of energy efficiency exists for a given size of rectangular grid. For a given number of clusters there are particular arrangements of the clusters that give a minimum of total energy consumption of the network. Thus the number of clusters, their sizes, shapes and the way the clusters are geographically grouped are important in the energy efficiency of the system.

Additionally, we have validated our assumption that cluster-based communications are generally more energy efficient than direct communications. Our simulation results also reveal the problem of over simplification in an analytical analysis for such problems that have been presented by previous works. Comparing our analysis with other existing works with different assumptions, we have confirmed the correctness of the behaviour of our curve for the total energy consumption of the network, however the absolute value may be different which is due to the fact that total energy consumption is subjected to various assumptions. Our analysis confirms that a range of optimised numbers of clusters exists within a WSN which can be used to decide on the real size, shape and place of these clusters. These analyses can be performed for networks of various sizes, and assumptions, to identify the range of the optimised number of clusters. Although, in real situations, we may not have the complete freedom to deploy these sensors in the most energy efficient way, still these analyses give us an insight into a range of optimised cluster-based WSN topologies that could be employed in a real network implementation.
Chapter 5. A Data Reduction Algorithm for the Smart Grid

5.1 Introduction

As discussed earlier in this thesis, energy awareness is one of the major considerations in the ICT networks of the Smart Grid. In order to prevent poor communication, inaccurate decision-making, high costs, and to fit within the potential energy saving of the Smart Grid, our system’s design aims to provide a solution for certain energy issues within the ICT network in the Smart Grid.

Since it is known (Heinzelman et al., 2000) that the energy used by sensors for data transmission is higher than for sensing, or for computation, reducing the data transmission energy will help the energy reduction of whole systems wherein data transmission is one of the important activities. According to the first order radio model (see formula 4.2), where $E_T$ presents the energy for data transmission, there exists two important factors affecting the energy consumption of data transmission. The first critical factor is the distance over which the data will be transmitted. This has been discussed earlier in this thesis. The second important factor is $k$, the number of transmitted bits. Given that the energy consumed for transmitting one bit is equal to the energy for processing approximately 1000 instructions (Sacaleanu et al., 2012b), we can save energy by processing a data reduction algorithm before sending the data.

Therefore, the main focus of this chapter is to develop a data reduction method within an ICT architecture at the NAN level of the Smart Grid. This data reduction technique, which will be introduced later on in this chapter, is called DRACO, “Data Reduction
A Data Reduction Algorithm for the Smart Grid

Algorithm for COrrelated data”. We describe the algorithm itself and we also show how it can be incorporated into an ICT network for the NAN level of the Smart Grid. We also present an evaluation of DRACO within this environment. We have tested DRACO on synthesized data, as well as on real data collected from the third layer of our designed ICT architecture which comprises cRIO devices for substation monitoring. We have also validated DRACO against real data collected from the first layer of the architecture comprising smart meters located in buildings. We consider a key strength of our approach to be that, not only we have designed this architecture and integrated DRACO within it, but we have actually deployed a working realisation of the architecture within a working NAN sub-Grid. Thus our evaluation is carried out not only in the computing laboratory but also in the field in a realistic working environment.

Since the University of Manchester owns the distribution grid embedded in its campus, it intends to provide a better understanding of the behaviour of the electrical grid, at the sub-Grid level, by finding out when fluctuations start, under what conditions, and what factors might influence them. In order to comprehend the characteristics of this level of the Smart Grid we have to monitor the behaviour of the grid with high frequency and accuracy. Consequently, our system requires DRACO to be a lossless method after the truncation of data. Therefore, rather than anticipating when the network is going to change and adapting the rate of sampling, we monitor the grid at all the times with high frequency. The core of this research is to use DRACO to extract data at a high data sampling rate and transmit the essential information, rather than sending all the data.

In this chapter we use techniques that have been established by other researchers, which have been discussed in Chapter 2, for reducing the volume of data in the WSN, and apply it to a new domain, namely the smart electrical network. Then we have developed our own data reduction algorithm called DRACO based on these concepts and have evaluated its applicability to this area.
5.2 Proposed Data Reduction Algorithm

In this section we will introduce our proposed Data Reduction Algorithm for COrelated data, “DRACO”. This algorithm is suitable for Smart Grid applications, in that it can improve the energy efficiency of the communication network by minimising the communication energy cost, while maintaining the integrity and quality of data.

5.2.1 Design Considerations for DRACO

DRACO has been designed for data that is sampled at a higher rate than the rate at which successive values change significantly. We confirmed experimentally that the data from the neighbourhood area of the Smart Grid conformed to this pattern. In order to design DRACO we have addressed the following issues.

1. Since the communication energy is the primary source of energy consumption within networks, DRACO should minimise the volume of data that is sent between devices.

2. The designed algorithm should be simple enough to be implemented on resource-constrained devices as well as on powerful devices.

3. It requires the whole procedure of data transmission, including compression and decompression, to be lossless after truncation of data.

4. The data collected from our network contains high correlations; therefore, we could take advantage of this feature.

5. The logic of the algorithm should be independent of data type.

6. DRACO should be independent of routing algorithms. Thus, if in future the routing algorithm changes, our compression algorithm will not be affected.

5.2.2 Design of DRACO

In Smart Grid applications where the metering devices collect data with a high acquisition rate and transmit them to the NCU (NAN control unit), a great degree of data correlation occurs. Taking this fact into consideration, we have developed a data reduction algorithm which discards the redundant parts between each two consecutive measured
values, and transmits the changing parts only: these parts are a small portion of the binary representation. This algorithm can improve the energy efficiency of the communication network by transmitting a smaller volume of data while keeping data integrity. Figure 5.1 illustrates an abstract overview of the proposed process, where the difference between data has been analysed on the sender side and transmitted to the receiver, and the receiver will reconstruct the original data out of the received reduced data.

The DRACO algorithm works as follows in order to reduce the size of the text files being transmitted by the monitoring devices located in our test bed. At the sender side of our proposed algorithm the digit-based representation of signed decimal values are ready for transmission. The algorithm first reads and keeps the signs and converts the value to a positive digit-based decimal value. Then it will convert the positive digit-based decimal values to positive digit-based integer values by multiplying the value by $10^x$, where $x$ is the number of decimal points we need. In this work, in some cases, we truncate the measured value to one decimal point, since we have been advised by professionals in the electrical engineering field (who are going to use DRACO) that they are not interested in low level variations of data and consider that one decimal point reveals enough information about the system. After these modifications, at the beginning of each round of transmission, the sender will transmit the modified original full value of the first measured data. This full value indicates the start of each round of transmission. Frequent transmission of the updated full value of the measured data will reduce the risk of data loss in the communication network. If a number of measured data are missed in the transmission channel, then the receiver side will decode the received values incorrectly. In order to prevent such data loss, our strategy is to send the modified full measured value on a
regular basis. Therefore, a decision on how often the full value need be transmitted depends on the requirements of the user of the system. However, since in this scenario we are dealing with file transmission, each file contains data collected for the past one hour which are being logged every one second. In this case, the first value of each file will be transmitted as the original full value, and the data reduction will be applied on the second value onwards until the end of the file. The decision on how large or small the original file will be depends on the application for which these data are collected.

To discard the redundancy between the two consecutive values DRACO works as follows. After taking the digit-based representations of a decimal value, reading and keeping their signs and changing them to digit representations of absolute integer values, then we convert these absolute integer values to digit-based binary-representations. Subsequently, we initiate the data comparison on the binary representations by applying XOR on each two consecutive values. Next, the XORed values will be converted back to absolute digit-based representations of integers. Finally, they will be multiplied by their signs and will be transmitted to the receiver point. Thus, in this process, the signed digit-based representations of integer value that is the result of the XOR process will be transmitted.

On the receiver side, the reception device will receive a file comprising the changed parts only. It will first read and keep the signs of each value and change them to positive values. It then converts the base 10 representations to the binary representations. Subsequently, it can reconstruct the original value by applying the XOR to the value “n” and to the reconstructed value “n-1”, then converting them back to digit-based representations of integer values and multiplying them by their signs. Finally, these values will be converted to the original values with a decimal fraction part, based on how many decimal points are needed. This algorithm is called DRACO-1. Tables 5.1 and 5.2 demonstrate a simple example of the compression and decompression of DRACO-1 on the sender and receiver side.
Table 5.1: The transmitter side (DRACO-1).

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Matrix of signs</th>
<th>Absolute value</th>
<th>Binary representation</th>
<th>XORed value</th>
<th>Absolute value of reduced part</th>
<th>Final sent value (signed reduced value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5.7</td>
<td>+1</td>
<td>57</td>
<td>111001</td>
<td>57</td>
<td>+1</td>
<td>+57</td>
</tr>
<tr>
<td>-6.2</td>
<td>-1</td>
<td>62</td>
<td>111110</td>
<td>111</td>
<td>7</td>
<td>-7</td>
</tr>
<tr>
<td>+6.1</td>
<td>+1</td>
<td>61</td>
<td>111101</td>
<td>11</td>
<td>3</td>
<td>+3</td>
</tr>
<tr>
<td>-5.7</td>
<td>-1</td>
<td>57</td>
<td>111001</td>
<td>100</td>
<td>4</td>
<td>-4</td>
</tr>
<tr>
<td>+6.3</td>
<td>+1</td>
<td>63</td>
<td>111111</td>
<td>6</td>
<td>+1</td>
<td>+6</td>
</tr>
</tbody>
</table>

Table 5.2: The receiver side (DRACO-1).

<table>
<thead>
<tr>
<th>Received value</th>
<th>Matrix of signs</th>
<th>Absolute value</th>
<th>Binary representation</th>
<th>XORed value</th>
<th>Absolute reconstructed value</th>
<th>Absolute reconstructed value with decimal points</th>
<th>Matrix of signs</th>
<th>Signed reconstructed value (original value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+57</td>
<td>+1</td>
<td>57</td>
<td>111001</td>
<td>57</td>
<td>5.7</td>
<td>+1</td>
<td>+57</td>
<td>+57</td>
</tr>
<tr>
<td>-7</td>
<td>-1</td>
<td>7</td>
<td>111</td>
<td>111</td>
<td>6.2</td>
<td>-1</td>
<td>-6.2</td>
<td></td>
</tr>
<tr>
<td>+3</td>
<td>+1</td>
<td>3</td>
<td>111</td>
<td>61</td>
<td>6.1</td>
<td>+1</td>
<td>+6.1</td>
<td></td>
</tr>
<tr>
<td>-4</td>
<td>-1</td>
<td>4</td>
<td>100</td>
<td>111</td>
<td>5.7</td>
<td>-1</td>
<td>-5.7</td>
<td></td>
</tr>
<tr>
<td>+6</td>
<td>+1</td>
<td>6</td>
<td>111</td>
<td>63</td>
<td>6.3</td>
<td>+1</td>
<td>+6.3</td>
<td></td>
</tr>
</tbody>
</table>

After several rounds of testing the real data and analysing the results we recognised that DRACO-1 could be improved to offer more compression efficiency for data with a higher correlation degree. The improved DRACO-1 is called DRACO-2, which, however, can only be applied in cases where correlation between the collected data is very high (e.g. this is the case for frequency and voltage readings). The difference between DRACO-1 and DRACO-2 is that, on the transmitter side, after applying XOR and converting the binary values back to integer values, if any consecutive value appears as “0”, DRACO-2 will only send one instance of previous value together with the number of repetition times. Although DRACO-2 is not as stable and general as DRACO-1, still DRACO-2 is very helpful for data in high volumes with strong correlations and in these cases it can perform better than DRACO-1. Tables 5.3 and 5.4 demonstrate a simple example of the compression and decompression of DRACO-2 on the sender and receiver side.
Table 5.3: The transmitter side (DRACO-2).

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Matrix of signs</th>
<th>Absolute value</th>
<th>Binary representations</th>
<th>XORed values</th>
<th>Absolute value of reduced part</th>
<th>Matrix of signs</th>
<th>Signed value of reduce part</th>
<th>Final sent value (signed value with number of repetition times)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+49.5</td>
<td>+1</td>
<td>495</td>
<td>111101111</td>
<td>111101111</td>
<td>495</td>
<td>+1</td>
<td>+495</td>
<td>+495,0</td>
</tr>
<tr>
<td>+50.3</td>
<td>+1</td>
<td>503</td>
<td>111101111</td>
<td>1000</td>
<td>24</td>
<td>+1</td>
<td>+24</td>
<td>+24,4</td>
</tr>
<tr>
<td>+50.3</td>
<td>+1</td>
<td>503</td>
<td>111101111</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>-53,0</td>
</tr>
<tr>
<td>+50.3</td>
<td>+1</td>
<td>503</td>
<td>111101111</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>+49,0</td>
</tr>
<tr>
<td>+50.3</td>
<td>+1</td>
<td>503</td>
<td>111101111</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>+194,2</td>
</tr>
<tr>
<td>-45</td>
<td>-1</td>
<td>450</td>
<td>1110000010</td>
<td>110101</td>
<td>53</td>
<td>-1</td>
<td>-53</td>
<td></td>
</tr>
<tr>
<td>+49.9</td>
<td>+1</td>
<td>499</td>
<td>1111010011</td>
<td>110001</td>
<td>49</td>
<td>+1</td>
<td>+49</td>
<td></td>
</tr>
<tr>
<td>+30.5</td>
<td>+1</td>
<td>305</td>
<td>1001100001</td>
<td>110000010</td>
<td>194</td>
<td>+1</td>
<td>+194</td>
<td></td>
</tr>
<tr>
<td>+30.5</td>
<td>+1</td>
<td>305</td>
<td>1001100001</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>+30.5</td>
<td>+1</td>
<td>305</td>
<td>1001100001</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The reason we use XOR in DRACOs over subtraction is that by testing both subtraction and XOR over our collected data, and comparing the size of the compressed data we realise that both these techniques will result in similar compression ratio (see Table 5.7). This is the result of the technique we use to represent data. However, the logic diagram of XOR is simpler than subtraction, thus it is easier to be executed on various type of devices.

Moreover, the reason we chose XOR over bit by bit comparison is that we realise that a problem exists when using a normal comparison between bits.

Table 5.4: The receiver side (DRACO-2).

<table>
<thead>
<tr>
<th>Received values</th>
<th>Ordered values</th>
<th>Matrix of signs</th>
<th>Absolute values</th>
<th>Binary representations</th>
<th>Reconstructed XORed values</th>
<th>Absolute reconstructed values</th>
<th>Absolute reconstructed value with decimal points</th>
<th>Matrix of signs</th>
<th>Signed reconstructed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>+495.0</td>
<td>+495</td>
<td>+1</td>
<td>495</td>
<td>111101111</td>
<td>111101111</td>
<td>495</td>
<td>+1</td>
<td>+495.0</td>
<td></td>
</tr>
<tr>
<td>+24.4</td>
<td>+24</td>
<td>+1</td>
<td>24</td>
<td>11000</td>
<td>111101111</td>
<td>503</td>
<td>+1</td>
<td>+50.3</td>
<td></td>
</tr>
<tr>
<td>-53.0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>111101111</td>
<td>503</td>
<td>+1</td>
<td>+50.3</td>
<td></td>
</tr>
<tr>
<td>+49.0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>111101111</td>
<td>503</td>
<td>+1</td>
<td>+50.3</td>
<td></td>
</tr>
<tr>
<td>+194.2</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>111101111</td>
<td>503</td>
<td>+1</td>
<td>+50.3</td>
<td></td>
</tr>
<tr>
<td>-53</td>
<td>-1</td>
<td>53</td>
<td>110101</td>
<td>111101111</td>
<td>499</td>
<td>49.9</td>
<td>+1</td>
<td>+49.9</td>
<td></td>
</tr>
<tr>
<td>+49</td>
<td>+1</td>
<td>49</td>
<td>11000</td>
<td>111101111</td>
<td>499</td>
<td>49.9</td>
<td>+1</td>
<td>+49.9</td>
<td></td>
</tr>
<tr>
<td>+194</td>
<td>+1</td>
<td>194</td>
<td>11000010</td>
<td>1001100001</td>
<td>305</td>
<td>30.5</td>
<td>+1</td>
<td>+30.5</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1001100001</td>
<td>305</td>
<td>+1</td>
<td>+30.5</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1001100001</td>
<td>305</td>
<td>+1</td>
<td>+30.5</td>
<td></td>
</tr>
</tbody>
</table>
In a normal comparison, to discard the redundancy between values, we start by comparing each of two consecutive digit-based binary representation values. The comparison of these values starts with comparing the most significant digit in binary representation of that value. This process will continue until the first difference between two digits is found. Then the comparison will be halted and the redundant digit will be discarded. The bits starting from the first dissimilar digit (which are called the changed digits) are then converted to base 10 representations before transmission, and then they will be multiplied by their signs.

The receiver side will first read the signs and convert the unsigned numbers to positive digit-based integers. Then it will convert the base 10 representations to binary representations. This process is needed to implement the binary comparison. Subsequently, it can reconstruct the original value by knowing only a sample of the modified full data that was transmitted at the beginning of each round of transmission. Having one sample of modified full data discloses enough information to generate the original values out of the received compressed values. This information could be such as the number of bits each value occupies, and the pattern of bits. Then, the signs will be added to the digit-based integer values and, finally, these values will be converted to the original values with a decimal fraction part.

Our experiments reveal that a problem with this system occurs when the first changed digit appears as “0” rather than “1”. In this case, when converting the binary representation changed digits back to the digit-based integer, the “0”s before the first “1” will be ignored. Thus, on the receiver side, when the reception unit receives the digit-based integer value, it is not able to reconstruct the correct original value because the number of “0” before the first “1” is unknown. Tables 5.5 and 5.6 demonstrate examples of the case when this algorithm malfunctions. For example, the binary representations of 61 and 57 in the third and fourth row are “111101”, and “111001”. After comparing these values with their previous values and discarding the redundant digits, the remaining digits are “01” and “001” respectively. When converting them back to the integer representation the “0”s before the “1” will be ignored. Thus, both “01” and “001” will be converted to integer number 1. So when the receiver side receives the changed parts of these two rows (integer 1), it cannot identify how many “0”s appears before the first “1”. Thus the receiver side will reconstruct an incorrect value as the original value. As Tables 5.5 and
5.6 show, when rebuilding the values 61 and 57, both reconstructed values will be 63, which are not the correct values.

Table 5.5: The transmitter side.

<table>
<thead>
<tr>
<th>Counter</th>
<th>Measured value</th>
<th>Measured binary representations</th>
<th>Binary representations after comparison</th>
<th>Reduced value ready for transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57</td>
<td>111001</td>
<td>111001</td>
<td>57</td>
</tr>
<tr>
<td>2</td>
<td>62</td>
<td>111110</td>
<td>110</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>61</td>
<td>111101</td>
<td>01</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>57</td>
<td>111001</td>
<td>001</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>63</td>
<td>111111</td>
<td>111</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 5.6: The receiver side.

<table>
<thead>
<tr>
<th>Counter</th>
<th>Received value</th>
<th>Received binary representations</th>
<th>Binary reconstructed representations</th>
<th>Original (reconstructed decimal value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57</td>
<td>1111001</td>
<td>111001</td>
<td>57</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>110</td>
<td>111110</td>
<td>62</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>111111</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>111111</td>
<td>63</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>111</td>
<td>111111</td>
<td>63</td>
</tr>
</tbody>
</table>

Therefore, to avoid the above-mentioned problem, we proposed a viable solution which is to use exclusive OR (XOR). The difference between utilising the XOR and the normal comparison is that when the XOR is used the first changed digits always appear as “1”. This is a result of the fact that the XOR between two similar digits will result in 0 (1 ⊕ 1 = 0 and 0 ⊕ 0 = 0) and the XOR between two dissimilar digits will result in 1 (1 ⊕ 0 = 1 and 0 ⊕ 1 = 1). Thus, while converting the changed digits which always start with 1 to the integer format we can trust that we are not losing any digits.

Since, in this research, we are dealing with data transmission through text files we are considering both the string of digits for transmission and binary representation of the compressed data. When transmitting text file, each digit or character will occupy 8 bits, thus this is not an efficient method of transmission. A more efficient technique of data transmission is to transmit binary data. In this method we have considered the fixed length of four bits for transmitting our compressed data. Having four bits, we could transmit up to 16 different characters. However, in this technique we have only thirteen different characters. These thirteen characters are as following: ‘0’, ’1’, ’2’, ’3’, ’4’, ’5’, ’6’, ’7’, ’8’, ’9’, ’+’, ’-’, ‘.’. It should be mentioned that the character
‘:’ will only be used in DRACO-2. In this technique instead of sending 8 bit per character, we send 4 bits only. The starting point of each value will be identified by the character ‘+’ or ‘-’ which will be represented by ‘1010’ and ‘1011’ respectively. However, it should be mentioned that the DRACO can be improved by sending variable length and self-terminating codes in future.

5.2.3 Implementation

As discussed earlier, we are implementing DRACO in a university sub-Grid at the University of Manchester. Our technique is purely a compression method that keeps the quality and integrity of data. DRACO is lossless after the truncation of data, however, the decision to apply truncation or not depends on the user requirements, and influence the compression ratio. The codes of the compression and decompression are available online (http://j.mp/ManchesterSmartGrid) for experiments and public use.

Although the proposed algorithm is applicable to diverse data size and behaviour, it is most suitable for data where consecutive values vary only in the least significant digits when represented as binary, i.e. the rate of change of the data is slow with respect to the sensing rate. The efficiency of this process, which depends on the degree of data correlation, can be described by the following formula (if the data size is inflated we indicate this in the results by a minus sign, as given by the formula below).

\[
\text{Compression efficiency} = \frac{\text{original data size} - \text{compressed data size}}{\text{original data size}} \times 100
\]  

(5.1)

DRACO is economic in terms of the execution time. The tests on different sources of data indicate that the executing time of DRACO is acceptable; this will be discussed later in this chapter. It is also efficient in terms of communication energy consumption which depend on the number of transmitted bits.

5.3 Evaluation of DRACO on Real Data Captured from Substation Level

In this section, firstly we evaluate DRACO with the simulated data, then with the real data collected from substations.
In Figure 5.2 we present the results from the performance of algorithm for seven diverse cases, each comprising 17,982 data values. These are the simulated data for one hour, being logged approximately 5 times a second. Using formula (5.1) our experiments reveal that in the normal conditions of the electrical grid we are able to achieve over 70% efficiency on average in terms of data volume.

![Figure 5.2: Effect of DRACO on simulated data.](image)

We now examine the results of the tests using real data collected from the substation level of the Grid. Comparing the efficiency of the algorithm on both simulated data and real data, we obtained similar results. Below are the results from some of our experiments on real data collected by the cRIO devices located in the 6.6 kV substations in the University of Manchester campus.

5.3.1 Evaluating the Effect of Compression Ratio in Different Hours of a Day

We examined the DRACOs over 24 hours of real data (collected from 8:00 am on 24th April 2013 to 8:00 am on 25th April 2013) to assess the efficiency of the data reduction algorithm on different hours of a day and to check the behaviour of the electrical grid during peak hours and non-peak hours. We have considered voltage, current and frequency data because their characteristics are different. The voltages’ variations are less, whereas currents’ variations are much more substantial with a higher rate of changes. Additionally, the rate of changes in the frequency data is very low unless some problem occurs in the power grid. Therefore, our data reduction algorithm will perform differently on these three attributes.
Figure 5.3 compares DRACO-1 (blue line) and DRACO-2 (red line) using voltages’ data. It shows that DRACO-2 gains more compression ratio and is a more efficient algorithm for voltage compression. Moreover, it reveals that after 16:00 hours we can gradually achieve a better compression (over 89%) ratio until 1:00 hours, which means the electrical grid is steadier and, as a result, the data correlation is higher during this period of time.

![Figure 5.3: 24 hours of compressed voltage data.](image)

Figure 5.4 compares DRACO-1 (blue line) with DRACO-2 (red line) using the data for current amplitude. Firstly, it shows that, overall, we can achieve a lower compression ratio in current data compared to voltage data, as expected, due to its high variation. Secondly, it reveals that the best compression ratio is achieved roughly between 17:00 hours to 1:00 hours showing that the data are becoming ever steadier. Comparing DRACO-1 and DRACO-2 we could suggest a switching algorithm for the monitoring system of current data in the substations. Between 17:00 to 1:00 the compression ratio of DRACO-2 exceeds the compression ratio of DRACO-1; therefore, during this time period we could use DRACO-2 as the compression algorithm for the current data, and for the rest of the day DRACO-1 could be applied.
Figure 5.4: 24 hours of compressed current data.

Figure 5.5 compares DRACO-1 (blue line) and DRACO-2 (red line) using the frequency data. Considering that the frequency data has a lower rate of change compared with the voltage and current data, DRACO-1 gained over 76% compression efficiency, while DRACO-2 achieved over 99% compression efficiency. Thus, it is suggested that DRACO-2 be used for compressing the frequency data all the time. This is an interesting result because, without using DRACO-2, it would be very wasteful, in terms of data transmission, to send these data at such a high sampling rate. It is very important to monitor frequency data at such a high sampling rate because frequency could go out of range very quickly, which is potentially catastrophic for the system. As a result, this is a very good example of where DRACO is very efficient with an over 99% compression ratio for frequency data.

Figure 5.5: 24 Hours of compressed frequency data.
5.3.2 Evaluating the Effect of Different Data Acquisition Rates

An experiment was designed to assess the effect of various sampling rates on the efficiency of our data reduction algorithm. We examined the data being logged with different frequencies such as: once every second (1 Hz), once every two seconds (0.5 Hz), once every four seconds (0.25 Hz), once every eight seconds (0.125 Hz), once every 10 seconds (0.1 Hz), and, finally, once every 20 seconds (0.05 Hz). Figure 5.6 shows that, as the frequency of the data acquisition rate increases, the original size of the data will increase, which is logical. However, as we start to sample more frequently the gap between the original data size and the reduced data will grow as well. Thus, although with a higher sampling rate we are transmitting more information about the grid, with the use of the DRACOs we could send data more efficiently in terms of data volume. This means by using DRACOs we can achieve a better compression ratio in a higher acquisition rate. This result confirms the fact that, when data are being sampled at a faster rate, the correlation between each two consecutive values is higher and DRACO performs best on data with stronger correlations. In a simplified scenario, this result can also be beneficial in terms of bandwidth utilisation. In the case where we want to transmit data with a higher frequency, which results in a higher volume of data, we can transmit more information using the same amount of bandwidth.

![Data size vs Frequency of data](image)

Figure 5.6: Data acquisition rate evaluation.
5.3.3 Evaluating the Effect of Different Bit-rates

In this section we now examine the effect of DRACO on the bit-rate. This experiment was set out to determine the link between significant events in the actual data profile and the maximum/minimum bit-rate. Since our analysis shows that the total active power attribute has one of the highest variations of all the attributes, here we have selected this attribute as the test data. Consequently, the changes in the bit-rate can be visibly seen. We have estimated the bit-rate by dividing the size of the reduced data by time, which is 30 seconds in this experiment (byte/second). Figure 5.7 shows the actual profile of the total active power and the bit-rate\(^9\) after applying DRACO. Analysing both the behaviour of the original data and the data transfer rate we realise that, when there are less spikes and minimum changes between consecutive data, the data transfer rate is low. Conversely, when there is big jump in the data and when the data variation is high, we observe a higher transfer rate. This result can be seen in the two ringed areas in the top figure corresponding to the areas where minimum and maximum changes happen, and their corresponding sending rate in the bottom figure. The red ring in the bit-rate graph shows the maximum data transfer rate where data varies a lot (compared to the other slots) and has the biggest jump amongst the rest of the slots in this profile. The green ring demonstrates the lowest bit-rate where data are very similar. Although there is a small jump in this time period, the rest of the data in this slot have the most similarities (very steady) which cause the bit-rate to be minimum. In conclusion, the correlation between the two graphs indicates the dependency of the data transfer rate on the rate of change of the quantity being measured (in this case total active power).

---

\(^9\) The bit-rate is sometimes called the data transfer rate (Forouzan and Fegan, 2007).
Figure 5.7: Total Active Power (top figure) and the corresponding bit-rate (bottom figure).

5.3.4 Evaluating the Applicability of the DRACO in Other Areas

DRACOs have been designed based on the structure of data and, as long as the variations between two consecutive values occur at the least significant part of the data, they can offer compression efficiency. Therefore, our experimental results indicate that DRACOs are not only applicable to substation monitoring in a NAN but they can also be applied to other areas such as home area monitoring via smart meters in the Smart Grid.
We have conducted two different sets of tests on smart meters located in a University of Manchester campus building. The first set of tests examined the efficiency of DRACOs on a smart electrical meter located in the Kilburn building of the University of Manchester campus. These data were collected between 6 June 2013 and 13 June 2013, with a sampling rate of every 30 minutes. The results show that, on average, DRACO-1 achieved 53% compression efficiency and DRACO-2 achieved 33% compression efficiency. Earlier in this section we proved that the higher the sampling rate, the higher compression efficiency we could achieve. Since sampling every 30 minutes is a very low sampling rate, we believe that we could achieve a higher compression ratio if the data were being logged at a higher rate.

The second set of tests was conducted on a smart water meter located in the Kilburn building. These data were collected from 16 March 2012 to 5 April 2012, being sampled every half an hour. The results of these experiments indicate that, on average, we achieved 40% compression efficiency using DRACO-1 and 24% compression efficiency using DRACO-2. Achieving lower efficiency in a smart water meter compared to a smart electrical meter is as a result of the fact that data collected from water meters varies more than the data collected from electrical meters.

We should consider that the DRACOs were originally developed for situations where data are being sampled at a very high rate, such as substation monitoring applications, so that the data collected from these environments are very much correlated. However, having conducted the above-mentioned experiments on smart meter data with a low sampling rate, we found out that the DRACOs offer a reasonably good compression ratio for other areas with a lower frequency rate as well. Therefore, the DRACOs are expected to have a wide range of applications.

Finally, the DRACOs can be generalised more and can be applied to other distribution networks where their collected data contains strong similarities to data collected in electricity grids, such as water distribution grids. This is a result of the fact that the collected data from these areas contain similar characteristics to the NAN and they hold high correlations.
5.4 Comparison with Other Work

To assess the efficiency of the DRACOs we have compared their performance with other data reduction algorithms. In order to do so, we have followed two different approaches. In the first approach we have produced data as described in other published work and apply these generated data to the DRACOs, and compare the results of having applied these generated data to the DRACOs and to other data reduction algorithms. In the second approach we have applied our data on other developed algorithms and compared the cases when our data was being applied to the DRACO as well as to other algorithms.

5.4.1 The First Approach

In the first approach, experiments were carried out to compare the compression efficiency of our data reduction algorithms (DRACOs) with two other existing data reduction algorithms specifically developed for sensor data based on the Huffman and Fixed-index methods (both methods have been discussed earlier). These two algorithms were chosen because they have been designed particularly for sensor networks with resource limitations’ problems and use low complexity data reduction techniques suitable for such environments. Moreover, their designs are also based on the correlations between each of two consecutive data values, which will reduce the number of transmitted bits.

In this scenario we tested the DRACOs on data which were generated using the method described in our literature study. Thus, we are not only evaluating the DRACOs on sub-Grid data but are also evaluating them with more general data that are not tailored just for sub-Grids. Since we can collect data across different sensing environments with a wide range of standard deviations, we can start comparing these algorithms when the standard deviation is varied. In this set of tests we assigned the mean of data to 0 and spread data equally on both the positive and negative sides. This is actually affecting the way in which the DRACOs perform. In fact, the high standard deviation and the less correlated data can affect DRACO. The DRACOs could execute efficiently when the data were scattering around a particular value, rather than spreading in a wide range. However, the standard deviation does not indicate how data are linked in time (e.g. with a same standard deviation, values could be differently linked in time). These two issues (high standard deviation and lower data correlation) will decrease the effectiveness of DRACO. But, in order to evaluate our algorithm on various ranges of data rather than on
data that were gathered from the university sub-Grid, we set out the following experiment.

In this experiment the data reduction algorithm, which is based on Huffman, is called Paper_Huffman, and the one that uses Fixed-index is simply called Fix_index.

In order to initiate comparison, we first started generating test data to assess the performance of DRACOs on these new data sets. The similar data was generated according to the procedure described in the research by (Sornsiriaphilux et al., 2010b). We produced 14,400 samples of random data using normal or Gaussian distribution. It was assumed that these data were generated by a sensor at a rate of once a minute during 10 days’ period of time (60×24×10=14400). It is believed that this assumption is realistic for measuring data values derived from environmental phenomena. The mean of the simulator was assigned to 0, while the standard deviations ranged from 0 to 250. Then we applied DRACOs on these generated data and checked the compression ratio for each value of the standard deviation. Therefore, we have compared these four algorithms in similar situations.

In the Sornsiriaphilux et al. (2010a) investigations the decimal precision for test data is not given when executing their algorithms\(^\text{10}\). However, the decimal precision is important for DRACOs, thus we have considered different precisions in two scenarios called best case scenario and worst case scenario. The best case scenario is when we considered only one decimal point and the worst-case scenario is when we considered full decimal points. Note that DRACO is designed for electrical network monitoring where small variations in the decimal points are not important from the control point of view. We have been advised that any variation after the first decimal place is not needed by electrical engineers. Thus, we truncated the values up to the point where variations of each number are still important. So we put the key variations immediately to the right of the decimal point where the data reduction algorithm can be applied.

After executing DRACOs on the generated data and drawing their curves, the second step was to draw the Paper_Huffman and Fix_index curves.

\(^{10}\) We have made a request to have access to their data or codes, but have not received a response. Therefore, we consider the two scenarios of best case and worst case.
The results of these comparisons are shown in the Figure 5.8. It shows that, in the best case scenario, both our algorithms performed better than the other two algorithms. Moreover, the compression ratio of our methods is more stable over the ranges of standard deviations, whereas the compression ratio of the other two algorithms varies substantially. Thus the performance of DRACO is resistant to changes in data and, as the standard deviations of the data grow, we do not lose much compression efficiency. In the worst case scenarios, when the standard deviation value is small, the other two algorithms perform better. However, as the standard deviations increase DRACO-1 performs better than the other two algorithms. Also, with the bigger standard deviations DRACO-2 performs better than the Paper_Huffman and eventually reaches the Fix_index algorithm and performs better in higher standard deviation. DRACO-2 is a more steady compression algorithm compared to the Paper_Huffman and Fix_Index in which the compression ratio decreases rapidly as the standard deviation increases.

![Figure 5.8: Comparison with other data reduction algorithms.](image)

### 5.4.2 The Second Approach

In the second round of tests we compared the DRACO with three different compression algorithms. These algorithms are the Huffman and Arithmetic which are amongst the best-known data reduction techniques and another algorithm which compress data by transmitting the result of subtraction between each two consecutive value. We have considered the binary transmission technique in this analysis as discussed in the section 5.2.2. Comparisons between these algorithms were made by applying our data as an input to the Huffman, Arithmetic, subtraction and the DRACO in similar situations. These data
were collected from monitoring devices during the period of one hour being sampled once every second, located in the substation level. The input data were rounded to the same precision for all 4 algorithms to keep the comparison fair.

The results, as shown in Table 5.7, indicate that, Huffman compression ratio is only 1% to 2% better than DRACO-1 for attributes with smaller variation amongst their data such as voltage, frequency, and total power factor. However, for the attributes with higher variation such as current DRACO-1 performs 4% better than Huffman. This is a result of the fact that Huffman obtains its compression efficiency based on frequency of occurrence of each value. Since the rate of reappearance of each value in current was low in our data, this makes Huffman perform not as good as DRACO-1 for such attributes. Also our experiments revealed that the average execution time of the Huffman is higher than the DRACO (Table 5.8).

Comparing the results of the Arithmetic algorithm with DRACO-1 reveals that, for attributes with low variations and high frequency of occurrence such as total power factor and frequency, arithmetic compression ratio is 2% higher than DRACO-1. However, for attributes with higher variations such as voltage the compression ratio of DRACO-1 is 2% higher than Arithmetic. While for the attributes with even bigger variations such as current, the compression ratio of DRACAO-1 is 7% higher than Arithmetic. This is again the result of the fact that compression efficiency of Arithmetic coding depends on the frequency of occurrence of data. Also our experiments revealed that the average execution time of the Arithmetic is higher than the DRACO (Table 5.8).

It should be noted that we consider the starting point of this process in Matlab program. Accordingly, the original data size is the size of the data in the Matlab, and the compressed data size is size of data after applying the DRACO.

Table 5.7: Compression efficiency of different data reduction algorithms.

<table>
<thead>
<tr>
<th></th>
<th>Original size (b)</th>
<th>Huffman size (b)</th>
<th>ratio (%)</th>
<th>Arithmetic size (b)</th>
<th>ratio (%)</th>
<th>DRACO-1 size (b)</th>
<th>ratio (%)</th>
<th>Subtraction ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>230464</td>
<td>13664</td>
<td>94%</td>
<td>19600</td>
<td>91%</td>
<td>14822</td>
<td>93%</td>
<td>14410</td>
</tr>
<tr>
<td>Current</td>
<td>230464</td>
<td>26841</td>
<td>88%</td>
<td>33392</td>
<td>85%</td>
<td>17700</td>
<td>92%</td>
<td>15734</td>
</tr>
<tr>
<td>Frequency</td>
<td>371456</td>
<td>4979</td>
<td>98%</td>
<td>4176</td>
<td>98%</td>
<td>14408</td>
<td>96%</td>
<td>14408</td>
</tr>
<tr>
<td>Total Power Factor (^1)</td>
<td>371288</td>
<td>7209</td>
<td>98%</td>
<td>6648</td>
<td>98%</td>
<td>14520</td>
<td>96%</td>
<td>14406</td>
</tr>
</tbody>
</table>

\(^1\) In these analysis total power factor has been quantized up to 2 decimal points in order to enable the user to identify the changes in the behaviour of this attribute.
Chapter 5

A Data Reduction Algorithm for the Smart Grid

Table 5.8: Execution time of different data reduction algorithms.

<table>
<thead>
<tr>
<th></th>
<th>Huffman (s)</th>
<th>Arithmetic (s)</th>
<th>DRACO-I (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>0.36</td>
<td>3.61</td>
<td>0.25</td>
</tr>
<tr>
<td>Current</td>
<td>1.06</td>
<td>3.52</td>
<td>0.25</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.31</td>
<td>0.53</td>
<td>0.24</td>
</tr>
</tbody>
</table>

5.5 Summary

Given that energy awareness is one of the drivers in modern computing, we have developed an energy aware architecture to solve this problem. In order to incorporate energy awareness in our developed architecture, we have ascertained that data reduction could be used as an appropriate technique in this regard. Our survey (chapter 2) of data compression algorithms shows that there is no one method that is superior for all forms of data stream. Therefore, we have devised a practical data reduction algorithm based on readings from monitoring devices that are typical of sub-Grid data patterns. The efficiency of the proposed technique depends on the degree of correlation between data.

An important part of this work is that we have been able to validate and test DRACO on data from real electrical sub-Grids which were produced at a very high sampling rate. This is useful in terms of identifying the key changes in the behaviour of electrical systems. One significant contribution of this research is that the developed algorithm can reduce power consumption and can improve the overall energy efficiency of the communication network in the proposed architecture.

In addition to the energy awareness issue, DRACO might be able to provide an efficient flow of information by reducing data traffic, which needs further investigations. Since, in such networks, bottlenecks are caused by the fact that thousands of sensors are sending their data to the central point, in some cases by applying DRACO we may reduce the risk of bottlenecks. Moreover, the growth in the number of monitoring devices in the Smart Grid in the near future will lead to an explosion in data volume. This will cause storage and network congestion problems in addition to a greater demand for energy which is required for transmitting this data. At this stage we are not prepared to manage such a
volume of data. We have to start developing new methods and techniques to ease these forthcoming issues. Thus, DRACO could be a preliminary point for solving some of these problems. In this thesis we have focused on proving the energy awareness but storage limitation and network congestion problems can be considered as a possible future work for further investigations.
Chapter 6. Architectural Considerations and Evaluation of the Proposed ICT Architecture

6.1 Introduction

In this chapter, we discuss the architectural styles and principles that inform the design of our ICT and then qualitatively evaluate our designed ICT architecture. In order to design our ICT architecture we have used some of the established architectural styles and principles of software architectures and distributed systems and have applied them to the design of our ICT architecture. Our ICT architecture is a hybrid architecture, i.e. it encompasses different architectural styles and principles. Section 6.2 discusses the architectural styles used in the design of our ICT architecture and section 6.3 presents the principles derived from the utilised architectural styles. Some parts of the proposed architecture have been implemented; therefore, some of these principles have actually been tested in a real environment. The unimplemented parts are those that are dependent on the fuller deployment of the infrastructure for monitoring the campus test bed which is not in our control. Accordingly, in this research, we deal with the data that are currently available and can integrate new data streams in future deployments as our architecture is scalable. Section 6.4 discusses the evaluation of the design of the proposed architecture according to the parameters identified for this purpose. Finally, section 6.5 summarise this chapter.
6.2 Architectural Styles

In this section we will discuss the architectural styles used in the design of our ICT architecture. The architectural styles each represent a framework for the system. Each of these styles portrays a different feature of our architecture. It may signify the structure, the design or the deployment consideration.

Our ICT architecture structure and design for the wider NAN is achieved by sub-dividing it into smaller zones. A wider NAN is a collective of single NANs called NAN-1, NAN-2, NAN-3 and so on. NANs are the gateways from HANs to WANs. In this research we have designed an ICT architecture for a single NAN, such as NAN-1, but for ease of reading we will refer to NAN-1 as NAN only. The idea of sub-dividing the NAN is taken from water distribution grids and WSNs. In water distribution grids there is the concept of DMA (District Metering Area). DMAs (Farley, 2001) are the sub-divided zones in the water distribution grid that enable the monitoring and control of that region. Each DMA covers 500 to 3,000 properties. This assists the management of the large-scale water distribution network by a number of methods, such as identifying leaks and maintaining the pressure in the distribution network. Additionally, in other areas, such as WSN, there is the concept of clustering where a big WSN is sub-divided into clusters (Abbasi and Younis, 2007). Each cluster can be managed and controlled independently. Accordingly, we have adopted these concepts from the above-mentioned infrastructures and brought them to the ICT of the Smart Grid. Consequently, we have divided the wider NAN into a number of smaller manageable and controllable NANs. We have chosen the size of our sub-divided NAN to be similar to the size of our campus test bed which covers approximately 100 buildings.

The architectural styles that we have used in the design of our ICT architecture are: hierarchical, layered, and component-based. The rest of this section will discuss each of these styles.

A hierarchical network is a type of network wherein processing and control functionalities are performed at different levels (FederalStandard_1037C, 1996). These functionalities can be on top of, or below, each other or else they can be at the same level. In our design we represent hierarchical relations through the use of layers. As defined by the
National Communications System Technology and Standards Division in the US (FederalStandard_1037C, 1996), layering in a communication system is referred to as “a group of related functions that are performed in a given level in a hierarchy of related functions”. Figure 6.1 depicts an abstract view of a layered system.

![Layered System Diagram](image)

**Figure 6.1**: Abstract view of layered system.

According to this definition, we have grouped similar functionalities that are related to a common role or responsibility in the same layer and have created a new layer where there was a need for a different level of abstraction.

Our ICT architecture is a layered architecture in the sense that it structures networks’ functions. It contains five layers that cooperate to provide the main functions of monitoring, data movement, data storage and control of different situations. The control function can be sub-divided into the three categories of control of environment, control of power grid, and overall control of each single NAN.

The reason that these five layers are mapped onto these functions is that, although the lowest three layers are three different sensor networks that all represent the same monitoring function, they offer different types of control functionalities for different situations. Therefore, each of these three sensor networks needs a different layer of abstraction. As discussed earlier, the first layer is mainly responsible for sensing, measuring and collecting data from buildings. The next two layers are responsible for sensing, measuring and collecting data, plus applying control on the environment and on the power grid. The final two layers present the database and control layer responsible for storing, computing, visualising and controlling the NAN. Finally, the data movement function refers to the connectivity between the layers, thus it is not represented as a layer itself.
The next architectural style that we have used in our design is a component-based style. A component has been defined by the National Communications System Technology and Standards Division (FederalStandard_1037C, 1996) as a part of a system that is essential for the operation of a bigger system and it is a direct sub-division of the system to which it belongs. The idea of using components in software architecture was first published at a NATO conference on software engineering in 1968, in a paper by Mcilroy (1968). A component-based architecture is created by analysing the system into distinct functional or logical components (Microsoft, 2009). Some of the components that result from a sub-division of our ICT architecture are: smart meters, WSNs, monitoring devices in the substations, databases and visualisation tool. Accordingly, some of these components can also be sub-divided into other components. For example, monitoring devices in the substations can be componentised into other components, namely cRIOs, a data storage, a control unit and a router.

In this thesis, we have designed a component-based style included with in a layered style architecture. Our overall designed architecture is a layered architecture while, in these layers, we have various components interacting with each other. Figure 6.2 depicts an abstract view of a component-based style within layered architecture.

![Diagram](image)

Figure 6.2: Abstract view of a component-based system within a layered architecture.

The other architectural style that we have proposed to enable communication between each individual NAN is peer-to-peer style. As discussed earlier, our architecture is a hybrid architecture that combines hierarchical architecture and peer-to-peer architecture. Peer-to-peer architecture became well known via Napster which was initially released in
Napster uses a peer-to-peer architecture to share music files. However, as discussed by Schollmeier (2002), a peer-to-peer architecture is not only about file sharing; it is also about resource and concept sharing. He goes on further and used the concept of Servent, which is a combination of the two terms of server and client, to define peer-to-peer architecture. In discussing the concept of Servent as a basis for a peer-to-peer architecture, he argues that each node in such systems can act both as service and resource provider, as well as service and resource user. In these systems, if any node fails, it will not disrupt the whole network and only the resources or services of that particular node will not be available to others during that time. In this thesis the architecture of each single NAN is a hierarchical architecture while a number of such NANs should communicate to monitor and control an overall NAN. Since each single NAN can take optimal decisions for its own region, which is not necessarily the optimal decision for the whole network, another layer of communication is added over the top layer to make each individual NAN aware of the state of the other NANs. Currently, we have proposed that NANs can communicate in a peer-to-peer manner in order to coordinate their actions. Each NAN provides data to other NANs and also uses the data from other NANs in order to make a control decision. However, in future, we will be able to change this peer-to-peer style to other styles, such as the hierarchical style. This design decision is dependent on the further deployment of a real Smart Grid. When engineers have fully gathered and analysed data collected from each individual NAN, and from the wider area, we might realise that communication between NANs can be performed in a hierarchical manner instead of peer-to-peer. However, we have designed our ICT architecture in such a way that this alteration between the NANs does not affect the design of each individual NAN.

6.3 Architectural Principles

Each architectural style described in the previous section contains a number of principles. These architectural principles describe the characteristics of each chosen style while they shape the overall architecture. In this section we discuss the architectural principles used in our design of an ICT architecture for a NAN. Some of the common principles for designing a layered hierarchical architectural style are (Microsoft, 2009): abstraction, encapsulation, clarity, high cohesion, loose coupling and reusability. These principles are
generally established for designing a software architecture. However, in this chapter, we have adopted these terms in order to propose an ICT architecture. Below we define each of these terms (Microsoft, 2009).

- Abstraction allows for the viewing of an architecture as a structured whole, with the distraction of the details of the implementation removed. It should present adequate information about the roles and responsibilities of each layer.
- Encapsulation is concerned with hiding details on data types, methods and the implementation of the design, in order to concentrate on the interactions of the components or layers rather than on the details of the internal composition of these.
- Clarity of structure is provided by clearly defining the functional layers. It concentrates on the functionality of each individual layer, the separation of the functionalities of each layer and the data flow between layers.
- Cohesion of each layer is achieved by grouping well-defined functionalities within each layer and by certifying that each layer encompasses functionalities which are related to the responsibility of that layer.
- Loose coupling of layers allows for flexibility of design, since each layer has a little or no knowledge about the internal details of the other layers and communication between layers is based on abstractions.
- Reusability is achieved by the independence of lower layers from higher layers which allow them to be used in other scenarios as well.

In a strictly layered hierarchical architecture, if one layer fails, the whole architecture will fail. This is because the entity in each layer can only interact with the entity of its own layer, or with the layer directly below, because the upper layer asks for services or data from layer below. However, we have prevented this single point of failure by proposing multiple routes of communication between layers. We have proposed that layers at different levels of the architecture can communicate with each other to circumvent failures in the strict hierarchy of levels. For example, in the scenario whereby layer 3 is transmitting data to layer 4 (the database layer) and data transmitted to layer 4 are about to be extracted by layer 5, then if layer 4 fails, data from layer 3 can be transmitted directly to layer 5, circumventing the failure of layer 4.
Now we will present some of the principles of the component-based style which are as follows: reusability, replaceability, extensibility and independence. Each of these terms is defined briefly below (Microsoft, 2009).

- **Reusability** is a shared principle between hierarchical style and component-based style. It is the ability of each component to be reused in other scenarios. Although some components could be designed in order to meet the needs of a particular task.
- **Replaceability** is the ability of components to be substituted with other components.
- **Extensibility** is the ability to increase the number of functionalities of a system or the ability of components to be extended in order to offer new behaviour.
- **Independence** of each component reveals its minimal dependence on other components. Consequently, each component can be deployed in other suitable scenarios without disturbing the other components, or the whole system.

In addition to the architectural styles and principles discussed earlier, we have also applied some principles from the theory of distributed systems to design our ICT architecture. These principles are such as scalability, fault tolerance, locality, transparency and minimisation of energy.

- **Scalability** is the ability of a system to support a large number of components (Fielding, 2000). In software systems it is the ability to increase the number of users while approximately maintaining the normal operations and performance of the system. In our context scalability has three aspects. Firstly, it is the ability to cope with an increase in the number of smaller NANs within the overall NAN. Secondly, it is the ability to increase the number of architectural layers within each NAN without affecting the whole system. Thirdly, it is the ability to increase the number of components within each layer.
- **Fault tolerance** is another principle in distributed systems (Emmerich, 1997). Fault tolerance is the ability to deal with the reliability of the system in the event of fault occurrence, it enables the system to progress despite the presence of fault in the system. It is usually implemented by circumventing a single point of failure in the system. In our ICT architecture we prevent the single point of failure caused
by the centralised architecture by moving to a more decentralised architecture. In this case if a single NAN fails to operate, it will not cause failure in the overall system. In our proposed ICT architecture for each individual NAN, faults can happen while providing communication between different layers or at the layer level itself. We have proposed avoidance of communication failure between the layers by providing redundant communication links with different communication technology between the layers. Thus, in case one communication medium malfunctions, another communication link can provide a substitute for the failed communication link. Additionally, if a layer within the architecture fails, our ICT architecture can partly deal with such failures.

- Locality is the ability to process information locally as much as possible. It has been discussed by Fielding (2000) that efficient architectural styles for a network-based application can be achieved by exploiting locality, for example, by bringing the processing of data near the source of data. Locality is known as a technique for reducing the communication load in order to prevent a bandwidth bottleneck (Schmid and Suomela, 2013). In order to design our ICT architecture, we applied the concept of locality to move the decision-making close to the sensing environment. We have divided the wider NAN into a number of smaller NANs, each with a local control unit called NCU (NAN control unit). Additionally, we have proposed the use of cluster-based communication in WSNs of the neighbourhood area, in which the whole WSN is divided into a number of clusters where data processing for each cluster can be executed inside the cluster near the sensing field.

- Transparency is the ability to hide the complexity of a system and thus appear to the user as a single system (Emmerich, 1997; Steen, 2009). There exist a number of different dimensions of transparency, which represent various properties of a system. Those which are related to our proposed architecture are the following five dimensions: access transparency, location transparency, concurrency transparency, fault transparency and scale transparency. The first is access transparency which allows different sources of information to be accessed in a uniform manner. We provide access transparency by allowing different types of data such as power grid data and smart meter data to be accessed or used by the NCU using identical operation. The second is location transparency which permits data to be
accessed regardless of its location. In our ICT architecture, the database layer stores data from different physical environments such as the substation environment, the street area, and residential and commercial buildings and then an NCU unit accesses these data sources regardless of their physical locations. The third is concurrency transparency which permits a number of processes to be executed concurrently, by using shared data, without interfering with each other. Our proposed ICT architecture can offer concurrency transparency by permitting the local control unit to execute various control decisions concurrently by using shared data in the database. The fourth is fault transparency which conceals the occurrence of a fault in the system and enables tasks to be completed without being affected by the failure in the system. Complete hiding of the failure of components is not easy to achieve. In this architecture, we have proposed a number of ways to tackle some of these failure situations in order to affect the overall system as little as possible. For example, in the case of a communication link failure, the redundant communication link can be activated to substitute for the link that has failed. In case of a Cluster Head (CH) failure in the WSN, sensors that belong to the failed cluster head can transmit their data to the nearest cluster head in order to pass their data to the higher layers of the architecture. Additionally, in the case of database layer failure, the control actions that require historical data can access the backup database which is located in another layer of the architecture, can extract the historical data and continue operations. The fifth dimension of transparency considered in this architecture is scaling transparency. Scaling transparency permits an increase in the scale of the system without alteration to the system structure. With regard to this issue, our proposed ICT architecture allows for an increase in the number of NANs communicating together to build a larger NAN without affecting the structure of our proposed system. Additionally, it allows for an increase in the number of sensing devices located in each layer, or even for an increase in the number sensing and controlling layers that might be required for the future needs of the Smart Grid. All these expansions in the number of the components or layers will not affect the overall structure of our proposed ICT architecture.

- Minimisation of energy is another principle that has been considered in the design of this architecture. Minimisation of energy is the ability to reduce the cost of
energy in the system either through the minimisation of computation cost or of communication cost. In this architecture we focus on the latter approach, i.e. minimisation of communication energy. Given that the energy for data transmission is much higher than the energy for data computation (Heinzelman et al., 2000), by reducing the transmission range and adding more computation units such as CHs or other sub-layers to the system we may achieve an energy aware architecture. Additionally, applying a data reduction technique prior to data transmission is another method used to reduce the energy consumption of the communication in the architecture.

6.4 Evaluation of the Design of the ICT Architecture

It has been suggested that it is preferable to evaluate an architecture before the implementation phase. A number of metrics have been identified by researchers that are normally necessary for the Smart Grid communication network. These metrics have been discussed in the literature review (section 2.3) of this thesis. Our proposed design for the ICT network of the NAN complies with the communication network requirements which are identified in the literature review chapter. Some of the requirements identified are similar to the evaluation parameters which will be discussed later in this section, such as scalability. Others are different, such as communication network management, migration from centralised to distributed architecture, and last mile communication, which have been discussed in the literature review chapter. In this section we have evaluated our architecture against more general metrics. Some of these metrics have been identified for evaluating a software architecture, while we have adopted these metrics for ICT network architecture and have evaluated our architecture against these metrics. This evaluation demonstrated that our ICT architecture is designed in such a way to meet these parameters. The future work for this project will be to test the designed architecture against these parameters after the full implementation.

An investigation (Hammoudeh et al., 2013) which proposed a number of different types of communication architecture for the NAN in a Smart Grid has selected ten metrics to evaluate a communication architecture for the Smart Grid. These metrics are: bandwidth, latency, security, scalability, reliability, interoperability, resilience, signal reach distance,
existing geographic coverage, and cost of ownership. Four out of ten of these metrics relate to the choice of communication technology and implementation issues, while the other six metrics relates to both implementation and design issues. The four implementation-related metrics are interoperability, signal reach distance, existing geographic coverage and cost of ownership. Since our architectural design is not tied to a specific communication technology or implementation, it can be implemented with various choices. The other six metrics which can be categorised both as implementation parameters and design parameters are scalability, resilience to failure, bandwidth, latency, reliability, and security. We will discuss some of these metrics later on in this section. Security and resilience in the communication network of a Smart Grid is a vast discipline that requires thorough separate research on this topic alone; thus it is out of the scope of this research.

It has been advised that, in order to evaluate an architecture, we need to evaluate its architectural design. To assess architectural design we have to evaluate the design rationale behind the architecture and then evaluate the properties that are derived from the restricted set of styles (Fielding, 2000). Accordingly, Fielding (2000) has introduced a series of parameters. Thus, architectural design can be evaluated against these parameters. These parameters were initially proposed for the evaluation of software architectures but, since we have adopted styles and principles from software architecture to design an ICT architecture, we can also evaluate our architecture against these parameters. In the rest of this section we will assess whether our ICT architecture design satisfies the needs of the NAN in a Smart Grid with regard to the parameters discussed by Fielding (2000).

Network Efficiency: Fielding (2000) believed that the best network efficiency can be achieved when the designed architecture uses no, or a minimum, network in order to perform its tasks. Since we are dealing with a Cyber-Physical System our architecture is physically distributed, thus it is not possible to avoid network usage. For example, the first, second and third layers of the architecture are distributed throughout various physical locations such as buildings, streets and substations. In our designed architecture we require network connectivity to support a consistent view of the grid and to enable control decisions over the NAN. However, in order to assess the network efficiency in our ICT architecture, we have divided the network efficiency into the two sub-categories of communication energy efficiency and bandwidth utilisation efficiency.
Communication energy efficiency: our designed ICT architecture supports communication energy efficiency by applying two techniques. Considering the fact that the energy for data transmission is much higher than the energy for data computation (Heinzelman et al., 2000), we have reduced the energy consumption of the architecture by applying cluster-based communication instead of direct communication for environmental monitoring. Cluster-based communication can reduce the overall energy consumption by reducing the data transmission range and adding more computation units such as CHs. In chapter 4 we have proved that the aforementioned technique can offer energy efficiency for the communication system. Furthermore, by applying a data reduction technique prior to the data transmission, we can also offer an energy consumption reduction for the communication in the architecture. In chapter 5 we have presented the result of applying such technique.

Bandwidth utilisation efficiency: applying data reduction before data transmission and transmitting the reduced data instead of the raw data can support bandwidth utilisation efficiency. Bandwidth is defined as the number of bits per a given time period (usually a second) that can be transmitted in a network (Forouzan and Fegan, 2007). In chapter 5 we have shown that, by applying data reduction, we can transmit more volume of information using same amount of bandwidth.

Scalability: as discussed earlier, scalability (Fielding, 2000) is defined as the ability to support a number of components and their interactions. It can be improved by distributing and decentralising the components and services across components respectively. This parameter will be influenced by the styles used to design the architecture and by the degree of distribution and coupling across components. According to this description, our ICT architecture is scalable in the sense that it contains a number of components that can easily be replaced or replicated. Also, a number of different services are distributed among these components. For instance, we are able to add more monitoring devices or data storage, or computational units, if required. In addition, our architecture is geographically scalable in the sense that we can expand our NANs to bigger NANs, or extend our proposed architecture from a neighbourhood area to a metropolitan area or even wider areas. This scalability is as a result of the fact that we have broken the wider NAN into several sub-divided NANs and have used a hierarchical architecture for each single NAN.
to have a consistent view of that specific zone, while each of these hierarchical architectures are able to communicate (for example in a peer-to-peer manner). Therefore, having divided our region into several sub-regions enables us to expand our region geographically by adding additional sub-regions which are also tied to the actual physical infrastructure of the power grid. This will not influence the performance of the existing sub-regions.

Modifiability: modifiability of an architecture can be assessed based on how easy it is to make changes in the architecture, as may be required over time (Fielding, 2000). Our designed ICT architecture supports the following sub-categories of modifiability.

Extensibility: as discussed earlier, extensibility is the ability to increase the functionality of the architecture. It can be influenced based on the degree of loose coupling between the components within an architecture. Our designed ICT architecture supports extensibility since it enables us to add more functionality to our architecture such as adding more control strategies to the NCU, and to the substation and environmental monitoring layers. We can also add more functionality to the monitoring devices by enabling them to perform different tasks, for example, duty-cycling or in-network processing such as data aggregation or fusion.

Customisability: customisability is defined as the capability to specially develop the behaviour of components of an architecture in order to perform a specific task for the system. An architectural component is called customisable when it can be extended by one user without affecting other users (Fielding, 2000). Our proposed ICT architecture can support customisability in the sense that each NAN area can be considered as a component of the whole system, thus each individual NAN can be customised according to the need of that specific region without affecting other NANs.

Reusability: as discussed in previous section, reusability is the ability of a component of a system to be able to be reused in other systems without alteration. Reusability can be influenced by the degree of coupling between the components within an architecture (Fielding, 2000). Our proposed architecture has been designed based on an appropriate level of loose coupling and abstraction; thus it will support reusability. This architecture is a reusable architecture in the sense that some of its components can be reused in other scenarios. For example, the monitoring devices in each level, or the data storage, can be
used for other applications. Even the visualisation tool component is able to run in applications other than NAN monitoring.

Finally, in addition to the qualitative evaluation of the ICT architecture described in this section, we have also undertaken quantitative evaluations for different parts of the proposed ICT architecture. These are presented in the chapters 4 and 5. In order to provide an energy-aware ICT architecture, we have used the principles of clustering for the wireless sensor network in the designed ICT architecture and the quantitative evaluation of the clustering principles is described in the chapter 4. Furthermore, we have used the principles of energy efficient data transmissions and have applied quantitative evaluation on our proposed data reduction algorithm. These are discussed in chapter 5.

6.5 Summary

To summarise, our proposed ICT architecture is based on a combination of styles. It is component-based within a layered architecture that combines hierarchical architecture and peer-to-peer architecture, tailored to hybrid communication technologies for transmitting data. It is designed to address modularity, scalability, reusability, replaceability, extensibility, transparency, fault tolerance and energy awareness. This architecture offers future proofing against changes in networking as its design is conceived at an abstract level independent from particular communication technologies. Our proposed ICT architecture has the following advantages owing to its layered and componentised design. It allows for changes of functionalities within a layer without affecting other layers. It allows for technology upgrades within each layer individually without affecting other layers. Layered architectures are known to improve scalability and reusability. Finally, this architecture has the following benefits with respect to the component-based architectural style. It allows for the exchange or upgrade of components without affecting other components or the system as a whole. A third party component can be used in the architecture to reduce the development, implementation and maintenance costs. Some components can be reused in other scenarios, or can be borrowed from other scenarios. This will also reduce the development, implementation and maintenance costs. This system is designed
for a future intelligent power grid, in that it is able to incorporate different control strategies at various levels of the NAN. One of the factors that influenced the design decisions is the relationship to the environmental conditions.

Finally, in order to evaluate our ICT architecture, we have used a set of architectural metrics and properties that have been defined previously by other research. These properties helped us to assess our design and to check if our design meets the parameters pointed out by Fielding (2000). Our ICT architecture is designed in order to meet these metrics. However, the next stage of this project will be to test this architecture against the identified parameters.

As far as we know, this architecture is one of the very first architectures proposed for a NAN that is designed based on established architectural styles and principles. The architectural principles used in our design specify the fundamental characteristics of the architecture. This architecture can integrate all the information from the various levels of NAN as a whole system and can, therefore, increase the awareness of these levels of an electrical grid.
Chapter 7. Conclusion and Future Work

7.1 Conclusion

Difficulties such as the energy crisis (the ever increasing demand for energy, increasing prices of energy, and the shortages in the available supply of energy) and environmental considerations (plans to decrease CO₂ emissions) have led to the birth of Smart Grids. The Smart Grids have to cope with a greater numbers of future electricity generators, consumers and diverse challenges, many of which are still unknown. Smart Grids can be realised by adding intelligence throughout the power grid. This intelligence can be provided through suitable ICT networks. ICT can be utilised to effectively monitor and control energy production, consumption and management of the grid. In this chapter we will summarise the conclusions offered by each chapter within this thesis independently and, finally, suggest future work.

7.1.1 ICT Architecture for the NAN level

It is believed that ICT systems themselves have played a huge role in accelerating the consumption of electricity globally. However, the same ICTs also offer systems which enable the monitoring and control of electricity; thus they can play a role in efficiently producing and consuming this energy. In this research we have firstly identified the current gap in the proposals for ICT networks for Smart Grids. Accordingly, we have designed an ICT architecture based on the established architectural principles for the NAN level. This research has shown that the architectural principles can very flexibly be applied to the development of ICT for the NAN level. Our designed ICT architecture is component-based within a layered architecture that is independent of the choice of communication technologies for transmitting data. This architecture comprises five layers.
that cooperate together to provide the main functions of monitoring, data movement, data storage and control. The control function itself is divided into the three classes of control of environment, control of the power grid, and control of the entire individual NAN. Additionally, this architecture is a scalable architecture which can cope with the future developments of the grid.

Another important aspect of this architecture is that, unlike the architectures discussed in the literature review, the important parts of it have been implemented in a real environment, rather than being only a suggestion or being implemented by simulation tools. This implementation is unique, to the best of our knowledge, and provides a basis for future analysis and development of the grid.

The research significance of our proposed ICT architecture for the NAN level of the electrical grid is that it enables electrical engineers to gather sufficient data from a level of the grid whose detailed behaviour had been unknown up to now. These data are sufficiently rich so as to be able to help them to understand what is going on in the sub-Grid. These data will then be used for the next step which is to move beyond monitoring to controlling the NAN. This ICT architecture is vital for this step because electrical engineers cannot start performing controls until they know how the grid is behaving and under what conditions this behaviour starts to change. Since we have developed a working realisation of an ICT for the NAN, we can provide real data for future researchers.

### 7.1.2 Energy Aware Topology

One of the factors that influenced the design decisions of our proposed ICT architecture is its relationship to some networking issues and environmental considerations, namely, energy awareness. The monitoring devices deployed in our architecture perform various tasks such as sensing, processing, and transmitting the gathered data to a more powerful computation unit. Since the greatest amount of energy is used for the transmission rather than the sensing or the computation, it is necessary to decrease the transmission energy required by the whole sensor network. Therefore, we can enhance the energy awareness of our ICT architecture.

Considering the fact that transmission distance and the number of transmitted bits are the two main parameters affecting the energy dissipation of the data transmission, we have followed two approaches. The first approach will be discussed in this section and the
second approach will be discussed in the following section. The first approach was to apply cluster-based communication in a WSN and find the optimised number of clusters for that network which will result in minimum energy consumption by the WSN.

The findings of this research suggest that network engineers cannot simply rely on the analytical formula proposed in the literature review to find the optimal number of clusters in a WSN. It is not always possible to feed the network parameters as an input into these formula and find the appropriate answer for the optimal number of clusters. The results presented in this thesis reveal some limitations which have not been discussed in other papers. We have presented two of these papers and discussed the restrictions of the formula they use as a justification that they cannot perform correctly in all situations.

In this research we have analysed the topology of a WSN which is part of our designed ICT architecture in terms of offering energy awareness. We have considered two WSNs, a small scale WSN and a medium scale WSN, to find the optimal number of clusters in each case. We have analysed the total energy consumption of each network by considering the energy spent on sensing, sending, receiving, processing and starting up the sender and receiver circuitry. We consider that the energy for processing which involves data reduction can change from case to case. We did not consider full data reduction as it is not applicable for Smart Grids’ applications at this stage. Therefore, we have considered a compression ratio which can also change from case to case. For the small scale WSN we have utilised the free space model both for communications within the clusters and between the CHs and the base station. For the medium scale WSN we have utilised the free space model for communication within clusters and a multi-path fading model for communications from the CHs to the base station.

To better understand the effect of the shape and location of the clusters on the total energy consumption in such networks we have undertaken experiments with over 450 different cases. We have manually engineered these cluster shapes and the number of nodes in each cluster to evaluate each of these scenarios individually. Accordingly, our observations and analysis of these cases, with regard to the total energy consumption of a WSN via simulating a number of different topologies for each specific cluster count, reveal that there exists a range of ideal cluster counts which result in a range of minimum energy consumption. Our result shows that we might achieve a minimum energy consumption
in a system with a particular cluster count, and specific network topology, while, on average, that particular cluster count might not result in the least energy consumption. This is due to the fact that we are not able to deploy the sensors in their most energy-efficient topology because of the layout of the environment; thus we have to introduce a range of numbers of cluster count that produce results close to the optimal and, with regard to the layout of the network, choose the optimal one for that particular network. Moreover, we find that the existence of relatively big clusters in a network will result in more energy dissipation. Furthermore, the existence of smaller clusters near the base station, and bigger clusters farther away from the base station, will improve energy efficiency.

Although we have considered this analysis for a section of the second layer of our ICT architecture for the Smart Grid (we thus assume our environment is a grid shaped area) a similar analysis can be applied to other WSNs in other domains. Analysis can be performed on networks with various sizes, and assumptions, such as randomly deployed nodes, to identify the range of the optimised number of clusters.

### 7.1.3 Data Reduction

The second approach which has been considered to offer energy awareness is to develop a data reduction algorithm suitable for the NAN level of the Smart Grid. Energy consumption in a sensor network is application specific. As an example, for an application that can tolerate data loss, we can use lossy data reduction which results in a higher compression ratio. This will ultimately lead to more reduction in energy dissipation from the network during data transmission when compared with applications that cannot tolerate data loss.

In this research we have designed a practical data reduction algorithm called the DRACO for Smart Grid applications in the NAN. The compression efficiency of the DRACO depends on the degree of correlation between data. This is interesting because the higher the sampling rate is, the higher data correlation there will be, and the DRACO performs better when data correlation is higher. This is useful in terms of identifying the key changes in behaviour of electrical systems. Initially, the DRACO was tested against synthesised data of the third layer of the architecture which is substation monitoring. More importantly, later on, it was been tested against real data collected from the third layer with a high sampling rate (every 1 second). In all these experiments the DRACO shows
a good compression ratio. Additionally, the DRACO has been tested against real data collected for the first layer of our ICT architecture which is the building monitoring level. In this case it shows an acceptable compression ratio; this is due to the fact that the sampling rate of these data was very low (every 30 minutes). Moreover, the DRACO has been evaluated against a number of different data collecting regimes and has shown how it can cope with such variety.

Although initially, the DRACO was designed and tested for data collection at the NAN level of the grid, it can be applied to other data collection environments with a high data sampling rate.

7.1.4 Summary

In conclusion, the novelty of this research is the proposal, design and implementation of an ICT architecture for the NAN level of the Smart Grid and the techniques used to offer energy awareness to the architecture at this level. Additionally, the fact that we have been able to check our designs against a real test bed, using real equipment producing real data that has been confirmed by experts in the power engineering industry, adds to the significance of this research. This research was started with the aim of contributing to a specific domain, namely the NAN level of the Smart Grid, but we have also observed that some of these design ideas can be utilised in different areas. Therefore, although this research is a contribution to a particular area, some of the issues raised and solutions proposed can be more generalised.

7.2 Future Work

Integration of ICT with the power grid is an emerging topic with many gaps, uncertainties, ambiguities and a huge potential for future research, as many domains are still unexplored. Since the aim of this research was to develop an ICT architecture for the NAN level of the grid, whilst taking into account energy-aware considerations, naturally, it was not possible to cover all aspects of the problem. Generally, more research needs to take place in order to refine and extend the proposed ICT architecture. The following are some suggestions for future work with regards to our designed ICT architecture:
Conclusion and Future Work

1. To implement the second layer of the architecture which comprises WSNs in a real environment and investigate the real challenges and requirements of such an implementation.

2. To add more monitoring and control options such as SCADA and AMI systems to our proposed architecture and, then, to further analyse the behaviour of the grid. These new additions, which can be integrated into our designed architecture, will be additions to the implementation side of the architecture, while the design logic can remain the same.

3. To check how this ICT proposal can fit in other situations and be extended to other scenarios. We have designed this architecture for a particular NAN in an urban area. Future work can take this further and apply it to other NANs in suburban or rural areas; it might be, for example, that different NANs have different characteristics and requirements which need further investigation.

4. To investigate how NANs should join up in a city and how they should communicate, for example, to investigate if a peer-to-peer communication between NANs in a city is appropriate, or if a hierarchical communication system for NANs would be more applicable, or even if a centralised approach might be able to bring more benefits to the grid. This future work can be accomplished when electrical engineers have thoroughly analysed the behaviour of each NAN individually and subsequently have analysed the behaviour of a city-wide electrical grid; then future researchers can investigate the best method of communication for a number of these NANs in a wider context such as a city.

5. To investigate control aspects for an entire NAN, to identify its challenges and requirements and, finally, to propose control strategies.

6. To investigate at each layer what type of control has to be embedded in this architecture. Currently, each of the first 3 layers transmit their data to the database layer. Then, transmitted data will be extracted by the NCU (NAN control unit) to provide control over the entire NAN area. However, in future, we might reach the point where each of the first three layers will transmit their data to the database layer as well as to the layer above them. For example, layer 1 (building level monitoring) will transmit its data to layer 2 (environmental level monitoring and
control). Then layer 2 can offer control on environmental issues based on the input from environmental level data (layer 2) as well as from the building level data (layer 1). As such, the amount of power usage by buildings situated in a NAN area might affect the street lighting system of that area. Moreover, layer 2 (environmental monitoring and control) can transmit data to layer 3 (substation monitoring and control). Then layer 3 can offer control over the power grid based on input from instrumentation within the power grid itself (layer 3) as well as from environmental data (layer 2). Applying these kind of controls on this system will depend on the decisions of policy makers and will require thorough investigation. However, our proposed ICT architecture is able to adopt and integrate these kinds of future controls within these layers.

7. To investigate security requirements for the NAN level. Since substations reveal information about power grids, this would require techniques to prevent malicious activities such as denial of service, eavesdropping and false data injection which would cause disruption to the network operations. Security would be a very broad area of research but would certainly provide an interesting topic for further investigation.

8. To investigate the database optimisation techniques. With the growing volume of real-time data and historical data, this topic might be interesting for future researchers.

9. To investigate the possibility of using cloud computing for layers four and five of the architecture. For example, the effect of moving the data storage and processing to a cloud environment, as against localised data storage and processing units, can be studied.

10. To investigate the applicability of utilising multi-hop routing instead of direct communication for providing communication from cluster members to the CHs, as well as from the CHs to the base station. Multi-hop routing should be investigated for large scale WSNs. Past experiences, findings and discussions which were presented in an international conference on sensor networks (Sensornets 2013, Barcelona) show that, while multi-hop routing might be more efficient in theory, in a real world environment direct communications are more practical. However, having access to the real WSNs that can expand through a real NAN
would be a good test bed for comparing these theories against a real practical situation.

11. To investigate the applicability of genetic algorithms in order to find an optimal topology of the WSN and to check their validity against simulation results.

12. To extend the data reduction algorithm, according to new comprehension of the behaviour of the grid, and enable it to adapt to the behavioural changes of the electricity grid. The DRACO is a pragmatic algorithm which we have designed by looking at the structure of the data. It was constrained by the fact that it has to be lossless and also by the fact that down sampling was not an option. Therefore, it is possible that, in future, when electrical engineers gain a better understanding of how the grid operates at this level, future researchers might develop other versions of the DRACO. However, it will be along the principles that the data are correlated in order to do the compression.
Appendix A. Extension to the Query Processing System

In the proposed ICT architecture, different types of sensors can be deployed in the second layer of the architecture in order to apply monitoring over this layer. Since the sensors located in the second layer of the architecture (which are responsible for monitoring environmental data) are not yet available we have used simulated sensors and data for this level of the Smart Grid. These environmental data are important for understanding the response of the system to such attributes. We chose TinyOS (Levis et al., 2005) sensors to be used as a prototype to evaluate the architectural proposal. Accordingly, TOSSIM (Levis and Lee, 2003), the WSN simulator for the TinyOS sensors, has been selected to simulate these sensors. The advantage of TOSSIM is that it enables users to take their implementation and run it on the actual sensor. Thus we can test our prototype network in a laboratory-based environment and in a real physical environment. Furthermore, TinyDB (Madden et al., 2005), which is a WSN query processing system, has been extended to extract the environmental data from our test bed and feed them to another source of computation for monitoring and visualisation purposes and thus will gain a predictive timely-manner system control in the future. The difference between TinyDB and traditional DB is that when we post a query to the sensors with the TinyDB installation we receive real-time data, instead of receiving archived data, in reply. Given that sensors are battery-powered devices, we try to reduce power consumption in the system as much as possible. It is believed that TinyDB will reduce power consumption because it not only contains the same features of traditional query processing (such as join, select, project and aggregate information) but also provides functionality for minimising power consumption by utilising Acquisitional query processing techniques. These techniques
focus on when, where, and how often, data are sampled and sent to a query-processing operator.

As mentioned, to achieve our goal, TinyDB has been extended by the addition of a Smart-Grid component for electrical network applications. The SmartGrid component is simulated and the results of the queries on this component are saved in a table created in the database for later use.

At the hardware level, in order to add a new sensor, the sensor board should be plugged into an I/O interface available on a mote platform. Furthermore, a software device driver, which presents the virtualisation and abstraction of sensors for a tailored application, should be executed in TinyOS. If an application requires reading of the data from the sensor, it accesses the specific attributes that call on device driver functions in order to extract hardware information. Since there is no hardware board available for us, we have developed a device driver by developing a configuration and module file called AttrSmartGrid.nc and AttrSMartGridM.nc. The role of the configuration file and the module file is as follows: the configuration file links the components together and the module file implements the executable logic. SmartGrid attributes are added to the TinyOS attributes’ list through the module files.

After developing the required module and configuration files, we have to log the query results in a database called PostgreSQL. Then we can check the query result and its graph; also, we can check the logged query results in the database. We can either check the logging data while the simulation is running (real-time data) or stop the query and check the logged data (historical data). As the query results are saved in a database we are now able to extract environmental information about the electrical network from the database and feed them to another source of computation in order to predict the impact of a course of actions in future.

To illustrate that the developed SmartGrid component is working we select a sample query such as “SELECT current FROM sensor WHERE nodeid=>5 SAMPLE PERIOD 2048”, then we log it to the database and then send the query via the GUI. This query will fetch “current” value from the sensors whose node ids are greater or equal to 5 and get these values every 2048 milliseconds. Figure A.1 depicts the query result with its related graph. It has three columns of data. Epoch is the time between each sampling and the other two columns show the values of current and node id which should not be less
than 5. The graph shows that we have used a periodic number generator in AttrSmart-GridM.nc for producing attribute current values. The generated data at this stage can be accessed and visualised via the visualisation tool that we have developed for the NCU.

Figure A.1: Result of a sample query.
Appendix B. Data to Knowledge (Visualisation Tool)

B.1 Literature Review on Visualisation for Smart Grids

B.1.1 Introduction

Data visualisation is an effective technique to deal with large data sets. It not only depict the raw data but also will produce useful information derived from the raw data. Since visualised information is easier to comprehend, data visualisation is used to communicate information clearly and effectively to the user via graphical means (Kang and Park, 2010). It has been argued that visualisation is one of the key elements in energy management systems that enables system operators to accelerate their decision-making and improve the quality of their decisions. Visualisation is becoming more important in Smart Electrical Grids than it is in traditional electrical networks, as these grids are in need of effective methods of communicating and comprehending large volumes of data (Ekanayake et al., 2012).

B.1.2 Other Geographically Based Visualisation Tools

As discussed above visualisation is a powerful method for managing and displaying data. It has been employed in different fields. In this subsection we will present some works that have investigated visualisation in other areas of research that have similar visualisation needs. As an example, in 2012 (Jablonowski et al., 2012) a scientific 3D visualisation system was provided for managing electric vehicles charging in the roads. Such a system
Appendix B. Data to Knowledge (Visualisation Tool)

could help researchers investigate the charging management scheme by visually exploring, experimenting with, and assessing important features of the system.

In the area of water distribution grids, visualisation has been used to provide a graphical user interface that enables the display of dynamic information and predictions on the future state of the grid. As an example, a study (Stoianov et al., 2007) on water networks uses Google Maps to visualise the data related to a water network. This study enables its users to choose a desired sensor and extract the related data from the water grid. Additionally, the work by Haines et al. (2009) considers a Google Maps based graphical user interface as a significant tool for water engineers which allows them to run ‘What if’ simulations and to visualise the results of their simulations. They show how dynamic information and predictions on the state of the network can be accessed using lightweight devices and visualised in user friendly Google Maps based web interfaces.

Data visualisation via Google Maps is not only valuable for engineering disciplines; it is also becoming a useful technique for handling and managing data in other industries. As an example, it has been used in the real estate industry (Hwang, 2008) to manage property and display the results of the queries of customers. Moreover, data visualisation through Google Maps has been investigated and proved to be an effective technique for supporting public health service planning (Gibin et al., 2009).

Google Map visualisation techniques can also be applied to networked systems, such as the Smart Electrical Grid. These techniques are used to retrieve the data and help the users to better understand the network conditions. Having defined what visualisation is intended to do, and its application in various industries, in the next section we will present a number of studies that investigate visualisation in Smart Electrical Networks.

B.1.3 Visualisation Tools for Smart Grids

In the decade following 2000, some preliminary work on visualisation in the traditional power grid was undertaken by the research group of Professor Thomas Jeffrey Overbye in the University of Illinois (Overbye, 2000; Overbye and Weber, 2000; Klump et al., 2002), and James D. Weber from Power World Corporation (Klump and Weber, 2002). In order to represent large volumes of data in an energy management system, they introduced a number of visualisation techniques to be used in such networks. These techniques included animation, contouring, data aggregation, and virtual environments.
These visualisation techniques were developed for traditional power networks for the purpose of monitoring transmission grids.

Since traditional electrical grids are migrating towards Smart Grids, where the complexity of the electrical network modelling and operation is increasing, the need for new visualisation tools to enhance the comprehension of such systems is becoming imperative.

In recent years, there has been an increasing amount of literature investigating visualisation in Smart Grids. While most of this research has addressed the need for visualisation in transmission grids, there has been relatively little research that has investigated the development of such tools in the distribution grid. It is worth mentioning that most of this literature has been published after we have introduced and published the first version of our visualisation tool.

The two most common techniques used for visualisation in the Smart Grid are one-line diagrams and geographic visualisation. One-line (Lendak et al., 2013) diagrams use several levels of detail to visualise the power grid. They can visualise the substation diagrams and the transmission and distribution system diagrams. Substation diagrams present the internal structure of the substations. Transmission and substation diagrams comprise numerous substations, cables and pole switches. Traditionally one-line diagrams are created manually, a process that is error prone. Moreover, since electrical grids are now changing more frequently, these kinds of diagrams necessitate extensive manual labour. Therefore, a recent study in 2013 (Lendak et al., 2013) introduced an algorithm that automatically generates a one-line diagram by utilising a mathematical graph in order to present the distribution network of the Smart Grid. The second technique is to map the network to a geographical map, which we have used to develop our visualisation tool. We have used the Google Maps API and have overlaid distribution network information on it. The rest of this section will only present literature that has investigated geographic visualisation in Smart Grids.

In 2009, Overbye (2009) discussed the use of visualisation for the transmission system of the Smart Grid. These visualisation methods include the use of coloured contours to provide insight into load control, the use of animated arrows to depict line flow direction, and 3D mapping. Moreover, in a complementary approach, he developed visualisation by integrating information on the electrical grid model and geographic information. Nevertheless, it is likely that 3D mapping is a challenging technique for electrical engineers.
to use because the display is confusing and it is more difficult to navigate through compared with a 2D map (e.g. by confusing north and south on the map).

In 2011, Tang (2011) proposed a smart power management system that facilitated both grid management and visualisation to form an effective system for the new Smart Electrical Grid. He stated that this system could incorporate real-time monitoring information and historic information to detect weaknesses in the grid. This system also offered fault analysis, troubleshooting and repair, and support for other applications. His paper mainly focused on the management side of the systems and fewer details were presented regarding the visualisation side. Tang’s recommended system seems to be a good proposal for managing and visualising the electrical grid, but this system has not been realised and implemented. Additionally, Tang proposed the use of power grid data such as SCADA, power quality, geographic information systems and other types of information related to the power grid. However, we propose the integration and visualisation of power grid data with other types of environmental data to offer an information-rich view suitable for operators who need to control the grid.

In 2012, other research by Chopade et al. (2012) presented a geographic-based visualisation methodology for the wide area network in the Smart Grid via visualisation software offered as a commercial package. They used AVS Express 7.3 as the visualisation software in order to monitor and plan the American Electricity Infrastructure. They discussed some of the features of their tool such as a 3D viewer, and a Graphical User Interface (GUI). Finally, Chopade et al. (2012) anticipated that, in future, visualisation techniques will integrate real-time activities with information and data transfer from different sections of the grid; these are similar considerations as those we have proposed for our developed visualisation tool. Our proposed visualisation tool is able to incorporate real-time and historical data, and to integrate power related data with environmental data at the distribution section of the Smart Grid.

Another study in 2012 by Yan et al. (2012) investigated an integrated visualisation system to examine Smart Grid behaviour under a security attack. They used a commercial software package called ESRI ArcGIS as the GIS platform, which presents geospatial data such that it can be easily comprehensible and customisable. In order to better comprehend how the system would behave under attack and to propose a new defence plan, they developed an interface so that the visualisation platform can communicate with the
MATLAB platform. In this case the geospatial data provided by the commercial software can be processed in MATLAB which simulates the attack and defence scenarios. This integrated methodology offers a useful technique to comprehend the behaviour of the electrical grid, supplemented with geographical detail, in case of attack. They concluded that their developed system enables power engineers to model and simulate various attack scenarios and to comprehend the behaviour of the grid under such attacks. Finally they have developed defence tactics to increase the security and reliability of the power network.

Additionally, in 2012, Bo et al. (2012) proposed a framework for a Wide Area Measurement System (WAMS) of the power systems. Figure B.1 depicts their proposed visualisation framework for such systems. As is shown, they have integrated different types of information within the visualisation platform. These data concern; the dynamical operation of the grid, fault information from the grid disturbances, and low frequency oscillations. This information is divided into two classes. The first class presents a summary and a visual display of information about dynamic alarms, and the second one presents a visual display of non-alarm application information. The first class presents essential information on situations where warnings are required within current applications. It comprises limit violation, on-line disturbance identification, and low frequency oscillation. The second class encompasses a display of performance observations of the units connected to the grid. The similarity between these two works is their use of a geographical map and the deployment of alarms. However, the alarm system introduced in this work by Bo et al. (2012) is only able to report an alarm by changing the colour of the screen; in this case only the grid operator behind the screen will be notified about the alarm. The alarm system implemented in our visualisation tool goes beyond that and reports the alarm not only by changing the colour of the screen but also by sending text messages and offering web services to the subscribed workforce.

A more recent study by Datta and Mohanty (2013) has argued that visualisation is required in new smart electrical networks and has outlined the benefits that a visualisation tool can offer. Although this work has discussed the architecture of the enterprise GIS (Graphical Information System) in general, it has not discussed each of the comprising components or the implementation issues. Figure B.2 depicts this study’s proposed enterprise GIS architecture for visualising the smart electrical grid. A similarity between
this architecture and our developed architecture lies in the consideration of various sources of data (internal and external to the power grid) as an input to the tool. A difference between this architecture and ours, is that we have adopted the concept of a separation of concerns where data source, data storage and data processing are deployed in different layers of the architecture, while in Datta and Mohanty’s architecture it seems that these functionalities are happening in the same layer. They have not clarified if they have considered infrastructure, storage and computation in different layers.

Figure B.1: Visualisation framework for power system monitoring by Bo et al. (2012).
Another investigation in 2013 by Liu et al. (2013) discussed whether, by utilising visualisation tools, the safety and economy of a power grid can be ensured. They developed a visual platform showing real-time power network status and visualising the early warning of internal and external risks on the screen. They proposed a 3-layered structure which is depicted in Figure B.3. The first layer of this architecture is an overview panel that provides information from the power grid applications. The second layer comprises multi-theme windows; this helps in the interpretation of applications and assists in making decisions. The final layer is a geographical map which enables a vivid expression of key information. This system has been implemented for a real-time power network in East China. The authors claimed that results from the real implementation proved their hypothesis that visualisation systems are able to improve safety and the economy of the power grid.
Appendix B. Data to Knowledge (Visualisation Tool)

Figure B.3: 3-layered information display frame by Liu et al. (2013).

Finally, a study by Nga et al. (2012a; 2012b) proposed a visualisation system for the distribution network of the Smart Grid by exploiting Geographical Information System and two other visualisation techniques to display data at such level. They used Quantum GIS (QGIS), which is an open source GIS application, and Google Earth as visualisation tools. The research mentioned above has provided a tool for monitoring the AMI and SCADA devices.

B.1.4 Summary

Collectively, the studies mentioned in this Appendix outline the critical role of visualisation in the Smart Electrical Grid. The studies presented thus far provide visualisation tools and techniques for wide area monitoring or for transmission grids which are useful for large scale infrastructure monitoring and control. A small portion of the literature available today has explored visualisation in the distribution grid. Our literature review shows that other researchers have not examined visualisation at the NAN level of the distribution grid. In this thesis we have used standard techniques of visualisation to investigate the monitoring and control of the NAN area in the distribution grid where no such monitoring and visualisation has been previously deployed. According to the nature of the grid at this level, we have provided some additional functionality based on the requirements of the system which will be discussed later in this Appendix.

To summarise, Table B.1 depicts some of the functionalities that are provided by our visualisation tool. It shows that some of these functionalities are provided by the research discussed above, such as having a GIS interface, incorporating real-time data and incor-
porating data that are internal to a power grid. In the Table B.1, + means that the functionality is provided, - means the functionality is not provided, and n/a means the information about the functionality is not provided in the literature.

Table B.1: Summary of functionalities of visualisation tools.

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Our tool</th>
<th>(Overbye, 2009)</th>
<th>(Tang, 2011)</th>
<th>(Chopade et al., 2012)</th>
<th>(Yan et al., 2012)</th>
<th>(Bo et al., 2012)</th>
<th>(Datta and Mohanty, 2013)</th>
<th>(Liu et al., 2013)</th>
<th>(Nga et al., 2012b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIS interface</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Incorporate real-time data</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Incorporate data external to electric grid</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Incorporate data internal to electric grid</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Database access</td>
<td>+</td>
<td>n/a</td>
<td>+</td>
<td>+</td>
<td>n/a</td>
<td>+</td>
<td>n/a</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Report component failure</td>
<td>+</td>
<td>n/a</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>n/a</td>
<td>+</td>
</tr>
<tr>
<td>Authorisation</td>
<td>+</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Access</td>
<td>+</td>
<td>n/a</td>
<td>n/a</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Open source</td>
<td>+</td>
<td>-</td>
<td>n/a</td>
<td>-</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>+</td>
</tr>
</tbody>
</table>

B.2 Data to Knowledge (Developed Visualisation Tool)

In this thesis we have introduced our ICT architecture for monitoring, collecting, and transmitting data. Here in this Appendix we present the software architecture aspect of our proposed ICT architecture and how we can convert collected data into information by using the tool we have developed.

The lack of automatic control in the electrical grid makes human intervention inevitable for monitoring and controlling the system. Field engineers currently deal with emergencies in a grid based on their personal understanding of the problem, previous experience and training (Han et al., 2010). Electrical engineering requires the development of an ICT architecture that provides for the collection of data at a sufficiently rich level of coverage to support tools that convert data into knowledge concerning the functioning of the NAN. Therefore a software design is required whereby the operators can extract
knowledge from data. One of the techniques used to convert data to knowledge is visualisation. In this Appendix we will discuss the tool we have developed which is an interface for the human operator with the grid. To illustrate the concept, we have developed an in-house visualisation tool as a prototype. The focus of this Appendix is on the monitoring tasks undertaken by our visualisation tool which will, in the future, be supplemented by control tasks that will be designed by electrical engineers. This is because the control aspects will be decided by electrical engineers based on their analysis aided by our software. After they have decided on the control algorithms the software architecture will be able to integrate them. However, for ease of readability we have described this software tool purely as a visualisation tool.

**B.2.1 Developed Visualisation Tool**

Visualisation tools are employed in many engineering fields, such as water distribution grids, because there is an increasing need to display and manage large volumes of data. The literature review shows that there have not been many studies undertaken on applying visualisation to power grids. Thus, in this research we have developed a visualisation tool that makes the real data and the network topology of a power grid comprehensible by network operators and engineers in the field. Our visualisation tool overlays the electrical grid information and the environmental information on a map using the Google Maps API (Application Programming Interface). As discussed earlier, this research is being implemented on the medium voltage power network of the University of Manchester campus test bed, thus enabling the visualisation tool to be developed using real equipment, real data, and with feedback from professionals in the field. We are now at the stage where this system is going live. Considering that, currently, there is less information available in this area below 33 kV, our research is valuable since it will deliver the collected data to the experts and visualises what is happening in the lower voltage network that will consequently offer a better control over the grid. This test bed consists of smart meters and WSNs. It also contains eleven 6.6 kV substations that are equipped with sixteen monitoring systems called cRIO which collect the data from the network and process them. The substations with one transformer are equipped with one cRIO, whereas substations with two transformers are supplied with two cRIOS. Given that better monitoring will result in a more efficient control over the system, a graphical display
of the network is provided for electrical engineers. It is helpful for them to utilise the visualisation technology in order to track the behaviour of the grid, discover the faulty part(s) of the grid, and even sometimes prevent catastrophic failure and take remedial actions.

In addition to the above considerations, asset management is becoming more important to companies as costs rise and there is a requirement to keep prices to the consumer low. Our visualisation tool enables the workforce to manage the assets of the electrical network more efficiently. By combining geographical information about the location of the assets with sensed information about their state, this helps a peripatetic work force to ensure that they are performing the correct operation at the correct location.

**B.2.2 Requirements**

Our developed visualisation tool enables the human operator to monitor the operation of the Smart Grid at NAN level and enhances their understanding of the performance of such electrical networks. This tool operates at the application layer of our architecture and provides a basis for the development of Decision Support Tools (DSTs) for planning for, and operating, the Grid at the mentioned level. It overlays the information from the sensors, and the measurements of the electrical performance of the NAN, on a map-based view of the geographical area in which the electrical grid is deployed.

The first step in designing our visualisation tool was to identify its requirements. In software engineering, functional requirements are defined as the concrete functionalities of a software system. However, non-functional requirements are described as the qualitative characteristics of a system (IEEE-Standards-Board, 1993). We now outline the functional and non-functional requirements of our visualisation system.

Regarding the functional requirements we have two requirement categories: User Interface (UI) related requirements, and data related requirements. UI related requirements are the ones that are used to visualise the characteristics of our test bed such as location and information of the monitoring devices. Data related requirements are the ones that are used to analyse retrieved data.
UI related functionalities are divided into four sub-requirements. The first UI sub-requirement related functionality in our system is to locate the position of each metering device on the map, since their data may vary according to their location. The second UI-related sub-requirement is to present the flow of retrieved data via tables. In addition there is a requirement to show the flow of data via graphs, which will greatly assist in understanding the characteristics and behaviour of the sensing environment. The final UI-related sub-requirement is to illustrate the schematic view of our test bed and to locate the selected device on the schematic map.

Data related functionalities are divided into four sub-requirements. The first sub-requirement in this category is to generate the environmental data via a simulation tool. These simulated data have been realised by TinyDB, which is briefly discussed in the Appendix A. The second data-related sub-requirement is to identify unexpected events. This sub-requirement itself is divided into three groups. The first group is to identify the sensor (monitoring devices’) failure. The second group is to identify the DB failure. The third group is to identify the over-threshold data. The extracted data related to each monitoring device should be in a certain range whose extent is controlled by a human operator and can change according to circumstances. It is important to determine if any single retrieved datum has exceeded the defined threshold, because this may cause abnormality in the system. The third data-related sub-requirement is to announce data that are over a threshold, because monitoring needs to be combined with the ability to alert users about unusual events or conditions and also the locations of such events in the sub-Grid. The final (fourth) data-related sub-requirement is the ability to incorporate near real-time data.

Regarding the non-functional requirements, the following five issues have been considered in the design of our system. The first non-functional requirement is accessibility. Accessibility implies that this system can be accessed via different devices and platforms also from different location, for example via different PCs and portable devices such as PDAs and mobile devices. The second one is backup, which enables the tool to store data that belongs to the previous week in another database inside the tool, in order to have a backup system when required. The third requirement is that the tool is built on Open Source software. Therefore, our system is released under the GNU LGPL 2.1 license. The fourth requirement is security, whereby our system requirements dictate that users
need to be authorised to gain the required read permission of the database in order to access the data in its current state. However, is only one aspect of the security. Finally, the fifth is usability and the visualisation tool has been checked in this respect by end users. These end users are professional electrical engineers working on the Smart Grid project in the University of Manchester.

B.2.3 Software Architecture

As discussed earlier, our research project requires us to design the software architecture aspect of our proposed ICT architecture. Therefore, based on the requirements discussed above, a software architecture has been developed to support operations on the NAN test bed. Software architecture describes techniques on how to divide a system into partitions and on how to identify the components and enable them to communicate (Fielding, 2000). In other words, it is the style in which components are structured and integrated. In designing a software architecture for the ICT in the NAN sub-Grid, we chose to componentize the NAN system into interacting sub-systems. As discussed in chapter 3, a component-based architecture is created by dividing the system into distinct functional or logical components (Fielding, 2000). Our system comprises different components. Some examples of these components are: the database component, the WSN simulator component, the GIS component such as Google Maps, and an alarming component such as IntelliSMS. Componentized architectures are known to offer reusability, replaceability, extensibility and independence of the components (Fielding, 2000). Additionally, utilising cluster-based communication and componentizing the ICT network monitoring of the NAN results in a scalable architecture that can cope with future implementations and additions to the system.

Figure B.4 depicts our developed software architecture which is a client-server style architecture. This architecture comprises a distinct client and server and a connecting network. As defined by the National Communications System Technology and Standards Division in the US (1996), a client-server architecture is referred to as the software systems by which clients make requests of a specific service, and servers react to the request and provide the service. Generally, storing data in a central repository on the server side offers more security than distributing them in different local repositories on the client
Appendix B. Data to Knowledge (Visualisation Tool)

sides. Moreover, client-server architecture is appropriate when the application has to support different types of client and different devices (Fielding, 2000). Accordingly, our architecture contains a server side and a client side. The server side itself has 3 layers, namely an infrastructure layer, a persistence layer, and an application layer, as shown in Figure B.4. The infrastructure layer is itself componentized into three monitoring levels, each relating to a specific section of the NAN in the distribution sub-Grid including building level, street level, and substation level monitoring as described earlier. As far as possible we have designed the software using similar principles to the ICT architecture described earlier since the two support each other in providing the functionality for the engineer to understand and control the NAN of the Smart Grid.

The persistence layer provides for stable storage of data allowing historical as well as current data to be used. It is currently implemented via a local database, which stores all the data received from the infrastructure layer, and a database connectivity module that uses an interface to connect to the next layer which is the application layer. The backup strategy embedded in this level (the application level) will enhance the preservation of the data. Moreover, it can manage to accommodate the ever-increasing volume of data produced by the infrastructure layer. The application layer is a .NET application that is able to connect to the outside world and send HTTP requests and respond to the client side. On the client side we have used technologies such as ASPX, CSS, JavaScript, and Google Maps API to visualise the collected data which can then be viewed by the Grid operator.

The client side of the architecture, and also the application layer and persistence layer of the server side, have been implemented. The monitoring systems at the building level and at the substation level in the infrastructure layer are also installed and the software system has been implemented. Therefore, the persistence layer is receiving real data from these two monitoring levels. The street level monitoring sensors are not yet available; hence we have extended the TinyDB and used TOSSIM, the WSN simulator associated with TinyDB, to simulate the environmental data being monitored by this level. Although TOSSIM is a more complex simulation compared to abstract sensor node simulations, it enables users to take their implementation and run it on an actual mote. Therefore, we
will be able to run and test our prototype implementation on the real physical environment as it becomes available as well as in a laboratory-based environment. Thus, at the moment the persistence layer is receiving simulated data from the street level monitoring.

Figure B.4: Software Architecture for the ICT infrastructure of the Neighbourhood Area Network.
Appendix B. Data to Knowledge (Visualisation Tool)

B.2.4 Analysis and Design

This section presents the analysis undertaken and design decisions made for our developed visualisation tool. These design decisions are made in order to meet the requirements that are mentioned in the previous section and to realise the architecture discussed earlier. For this purpose, we first illustrate our use case diagram in order to depict the functionalities and actors of our system. Then, we illustrate the data flow diagram in order to depict the flow of information that passes within our system.

B.2.4.1 Use Case Diagram

The referenced functional requirements allow us to identify some use cases for the proposed tool. The title of each use case is selected as an action-verb which refers to the primary goal of the functional requirements. The internal-actors of this system can be divided into two categories: unauthorised and authorised user. The system starts with the first use case, called ‘Show Map’. This use case is based on the Google Maps API and is able to locate the metering devices on the map. ‘Select Device’ use case is identified as the second use case. This use case can be called by authorised and unauthorised users and it is employed to present the information regarding a specific metering device on the map as well as showing its position according to its longitude and latitude (geo-position). In addition, users can request to observe the schematic location of each selected device that is located according to its schematic view.

However, the data demonstration functionalities that are realised by the ‘Show Data Graph’ and ‘Show Data Table’ use cases require a prerequisite function which is realised by the ‘Login’ use case that changes the status of the user from unauthorised to authorised user. Data, which are presented by the mentioned demonstration functionalities, can be provided either by the real data provider or by a simulator tool and they can also be filtered according to their desired date. The data provider is an actor in our use case diagram that retrieves the data from the cIROs and smart meters, stores the retrieved data in a database, and enables our system to receive the retrieved data via a data connector. The simulator tool is an actor in our use case diagram that generates environmental data since this type of data is not provided by our available metering devices.
The last use case describes how the system informs its users that a single unit of data exceeds a predefined threshold. These over-threshold data will be announced by three different methods. First, the over threshold unit of data will be highlighted in the web user interface of an authorised user. Second, these data will be sent to engineers (whose mobile numbers are registered in our system) via a text message. Third, these data will also be published via a web service. In order to receive this service, an engineer needs to subscribe to the published service. The ‘Alert Over-Threshold’ use case does not only say that something has failed, but it also says that something is about to fail. Sometimes this function gives engineers enough time to prevent the failure. Figure B.5 illustrates the use case diagram for the proposed visualisation tool.

Figure B.5: Use Case Diagram.

B.2.4.2 Data Flow Diagram

Figure B.6 illustrates the first level of the Data Flow Diagram (DFD) that depicts the flow of data and highlights the main functions carried out by the system.

When the application is started, the map will be loaded, which is based on the Google Maps server, and the programme will show the map view of our test bed. Then the user can follow three actions as is shown in Figure B.6: (i) request to visualise the schematic
map; (ii) request to visualise the real data from metering devices located in the substations (e.g. cIROs) and devices located in the campus buildings (e.g. smart meters); and (iii) request to visualise the simulated environmental data.

For the first action, the user selects a metering device and, consequently, s/he can check the schematic map of the test bed and the actual location of the selected metering devices (Figure B.6).

For the second action, similar to the first action, the user selects a metering device. However, s/he needs to be authorised by the system in order to retrieve the real data from the selected device. To this end, the credential of the user should be approved by the database. Therefore, after entering the login information the user can extract the data from the database and select the data table of interest. In addition, it is possible for the user to limit the period of time over which s/he wants an overview and then view the data. It is also possible to plot the data to a graph. This action enhances a better comprehension of the behaviour of the data. After visualising the data, the tool will determine if any of these data are over the predefined threshold. If the threshold is exceeded then the tool will send an alert to any operators who have subscribed to it. In order to send the alert it will follow three main actions. Firstly, in order to send the passive alert it will highlight the over threshold data for the operator behind the screen. Secondly, in order to send the active alert it will send text messages to the engineers in the field by using the IntelliSMS component. It will inform them about the actual fault and the time and location of it. Likewise, an interested engineer can subscribe to receive an over threshold service which is a web service containing the same information as the afore-mentioned text message (Figure B.6).

For the third action, the user starts the data generator in order to simulate the environmental data. This data is stored in a TinyDB database. Then the user can retrieve the generated data via the visualisation tool. This data retrieval is performed via the Open Database Connectivity (ODBC) (Microsoft, 2010) middleware. Finally, the user can select the WSN simulator in the visualisation tool and visualise the environmental data. All this collected data can now be used by electrical engineers as input for the control algorithms of the grid (Figure B.6).
B.2.5 Evaluation

The work by Fielding (2000) has indicated that it is difficult to evaluate and compare architectures in an objective manner. He stated that, in order to evaluate an architecture, one has to consider the functional requirements of the system and the degree to which each architecture meets the non-functional properties. For example, it is not legitimate to evaluate the design of one architecture against the requirements of another architecture, since each architecture focuses on different requirements and uses different methods and technologies for implementation. Therefore, we have considered a qualitative evaluation with respect to the purpose of our prototype system and on the bases of its functional requirements; from this we have presented a table to check if our developed tool does meet these requirements.
Our visualisation tool has been evaluated based on a real implementation. A walkthrough of the actual implementation of this design is currently being installed in the sub-Grid supplying the University of Manchester, is presented below. In order to evaluate our prototype with respect to requirements of our system, we conducted tests on the developed tool. To start with, we demonstrated the results of running our GIS-based tool over a web interface to validate our GIS interface and its accessibility and independence of the platform.

B.2.5.1 A Walkthrough of the Implemented Visualisation Tool

We tested the performance of different components of the system. Each component was expected to perform the functions that it was intended to undertake. The first component to be evaluated was the database component. This component has been realised by PostgreSQL and is responsible for storing data received from the infrastructure level. Next we evaluated the database connectivity component which is an interface between the database and the application layer. The other component that we tested was the WSN simulator. This component has been realised by TOSSIM and is responsible for generating environmental data. Furthermore, the authorisation system and the backup database were also tested. Finally, in order to specify the openness of this tool, we have released our tool under the GNU LGPL 2.1 license available in GitHub (http://j.mp/ManchesterSmartGrid).

Table B.2 summarises the simplified qualitative evaluation of our prototype system and other existing prototypes. These existing prototypes are the ones which have been discussed in the literature review of this thesis. This table indicates that our developed prototype system meets each individual criterion required by our system. The plus sign shows that the specific criteria has been met, the minus sign shows that the criteria has not been met, and plus-minus sign shows that some of the existing tools meet the requirement and some do not, and n/a means the information is not available.

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Type of requirement</th>
<th>Existing prototypes</th>
<th>Our prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIS interface</td>
<td>Functional</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Data flow via table and graph</td>
<td>Functional</td>
<td>±</td>
<td>+</td>
</tr>
<tr>
<td>Incorporate near real-time data</td>
<td>Functional</td>
<td>±</td>
<td>+</td>
</tr>
</tbody>
</table>
Appendix B. Data to Knowledge (Visualisation Tool)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Functional</th>
<th>±</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incorporate external data to the power grid</td>
<td>Functional</td>
<td>±</td>
<td>+</td>
</tr>
<tr>
<td>Incorporate internal data of the power grid</td>
<td>Functional</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Identify unexpected events</td>
<td>Functional</td>
<td>±</td>
<td>+</td>
</tr>
<tr>
<td>Actively announcing unexpected events</td>
<td>Functional</td>
<td>±</td>
<td>+</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Non Functional</td>
<td>±</td>
<td>+</td>
</tr>
<tr>
<td>Backup</td>
<td>Non Functional</td>
<td>n/a</td>
<td>+</td>
</tr>
<tr>
<td>Authorisation access</td>
<td>Non Functional</td>
<td>n/a</td>
<td>+</td>
</tr>
<tr>
<td>Open source</td>
<td>Non Functional</td>
<td>±</td>
<td>+</td>
</tr>
</tbody>
</table>

Now we will present a walkthrough of the actual implementation of this design which has been installed in the sub-Grid supplying the University of Manchester. This description is aided by screenshots.

The screenshots below present a scenario in which a user, in this case a supposed electrical engineer, needs to check the status of a specific part of the sub-Grid. Data shown in this scenario are real data captured from working the sub-Grid and also simulated data generated by TinyDB.

1- The user launches the application (Figure B.7)

![Figure B.7: Interface of the main page of the visualisation tool.](image)

2- The user can:
   - View the desired section of the sub-Grid via:
     - Map view (Figure B.8)
Appendix B. Data to Knowledge (Visualisation Tool)

- Terrain view (Figure B.9)
- Satellite view (labels can be added or removed from satellite view) (Figure B.10)
  - Zoom in and out by pressing + and - on the map respectively
  - Navigate through the map with the help of the control navigation button provided on the map
  - Drag and drop the icon provided on the top right corner of the map and have a closer view of the area where monitoring devices are installed

Notice: The actions described above have been provided by Google Maps (Google).

Figure B.8: Interface of the terrain view of the University of Manchester campus
Appendix B. Data to Knowledge (Visualisation Tool)

Figure B.9: Interface of the satellite view of the University of Manchester campus.

3- The user can select the desired monitoring devices. There are three different types of devices which the user can select.

- The first type of monitoring device is the cRIOs located in the substations in the sub-Grid. The user can select each of these 16 cRIOs from the right side of the tool.
- The second type of monitoring device is the smart meters located in the sub-Grid buildings. In this case, the smart meters installed in the Kilburn building have been selected (visible on the right hand side of the tool).
- The third type of monitoring devices is wireless sensors located in the environment (street level). Since we do not have real sensors for this level, we have used simulated data. The simulation button is provided on the right side of the tool.

4- Selecting each of these devices will result in flying into each location of the device on the map according to its coordinates (latitude and longitude) and will also result in displaying information of the selected device. In this case cRIO number 2 has been selected (Figure B.10).
Appendix B. Data to Knowledge (Visualisation Tool)

Figure B.10: The user has selected cRIO number 2 (which is located at the University of Manchester museum) from the right panel. Its location and related information are shown on the map.

5- The user can check the schematic view of the selected cRIO (Figure B.11). In this case cRIO number 1 has been selected (Figure B.12).

Figure B.11: The user has selected cRIO number 1 which results in opening another page, as is shown in this picture. Now the user can choose to view the schematic view of cRIO number 1, or return to the main page.
Figure B.12: The user has selected to view the schematic view of cRIO number 1.

6- The user can also select the “Drop Markers” option on the right hand side of the tool and locate all the cRIOs on the map (Figure B.13).

Figure B.13: The user has selected the drop markers to locate all the cRIO devices on the map.

7- By selecting smart meters (Kilburn_meters) the tool will guide the user to a new page asking for the credentials of the user in order to connect to the database and extract the desired data (Figure B.14).
Appendix B. Data to Knowledge (Visualisation Tool)

Figure B.14: The user has selected the Kilburn-meters from the main page which result in opening this page. Now the user is asked to enter her/his credentials.

8- After entering the correct credentials the application extracts data related to the selected device from the database (Figure B.15). The over threshold data are highlighted.

Figure B.15: The user has entered the correct credentials which results in opening this page. This page shows data that are extracted from the selected smart meter. The over threshold data are highlighted.

9- The user can also check data which belongs to a desired period of time and can view historic data.

10- The user can also check these data on a graph to better comprehend the behaviour of the grid (Figures B.16 and B.17). The figures below display data over a period of one week. The x-axis presents the time (here the days of a week) and the y-axis represents
the power consumed by the selected smart meter. Peak (week days) and off-peak (week-end) sections are illustrated.

Figure B.16: The user has selected to view data which belongs to the period of one week from 21\textsuperscript{st} November 2012 to 28\textsuperscript{th} November 2012. The result of real data captured from the Kilburn-meters are shown on the graph.

Figure B.17: The user has checked the off-peak period against the calendar and realised that it was the weekend which results in low usage.

11- The subscribed user receives a text message reporting over threshold data and the location of it (Figure B.18).
Appendix B. Data to Knowledge (Visualisation Tool)

Figure B.18: The user has received a text message regarding the over threshold data of the area being monitored.

12- The subscribed user receives a web service reporting the over threshold data. Any further information can be added if required. Figure B.19 shows the test client application of the web service that subscribers receive over threshold data.

![This is the Test Web Service GUI](image1.png)

In the following you can find the result of the web service:

- Size is 22
- Time stamp: 14-4-2014 8:30:00
- Data: 23,665
- Threshold: 23
- Time stamp: 14-4-2014 9:00:00
- Data: 27,149
- Threshold: 23
- Time stamp: 14-4-2014 9:30:00
- Data: 33,6
- Threshold: 23
- Time stamp: 14-4-2014 10:00:00
- Data: 38,861
- Threshold: 25
- Time stamp: 14-4-2014 10:30:00
- Data: 37,85
- Threshold: 23
- Time stamp: 14-4-2014 11:00:00
- Data: 39,821
- Threshold: 23
- Time stamp: 14-4-2014 11:30:00
- Data: 41,6

Figure B.19: The user has received a web service reporting the over threshold data.

13- A backup database is provided inside the visualisation tool that stores data which belong to the past one week (Figure B.20).
Appendix B. Data to Knowledge (Visualisation Tool)

Figure B.20: The backup database storing data for the past one week.

14- In order to check the simulated data, the user first needs to run a simulation. Figures B.21 and B.22 depict the data generated by the simulation on another machine.

Figure B.21: The user has run the simulation tool on another machine to generate the simulated data.
Appendix B. Data to Knowledge (Visualisation Tool)

Figure B.22: Results of simulated data on another machine.

15- Now the visualisation tool needs to connect to the simulation which is on another machine and extract the generated data. This process happens through ODBC (Microsoft, 2010). ODBC is a middleware API which enables access to different database systems regardless of the database type and operating systems.

16- The user enters the database connectivity information such as IP address, port number, database name and database user name and password (Figure B.23).

Figure B.23: The user has entered correct information through ODBC in order to connect to the machine upon which the simulation is running.
17- Finally, the user can check the simulated data in the visualisation tool (Figure B.24).

![Figure B.24](image.png)

Figure B.24: The user has extracted simulated data from the simulation tool on another machine and viewed it on the visualisation tool.

### B.2.5.2 Qualitative Evaluation of the Design of our Visualisation Tool Architecture

In this section we will evaluate the architectural design of our visualisation tool according to the selected qualitative metrics given in Fielding (2000).

- **Network Efficiency**: The first metric to evaluate is network efficiency. It has been identified that the best application performance can be achieved by minimising the use of network (Fielding, 2000). As an example software systems that hold both data and software in a single device are considered to be more efficient in terms of network efficiency. However, a distributed architecture requires network. When the architecture is physically distributed like the electrical grid, we cannot provide efficiency by locating data source and data computation unit in a single device. For example, we have to use network bandwidth for performing different tasks such as sending a HTTP request and a response from client side to the server side, extracting data from the database, using the Google Maps component, and connecting to the WSN simulator for visualising environmental data (Fielding, 2000).
Appendix B. Data to Knowledge (Visualisation Tool)

- **Scalability:** Scalability indicates that the architecture can support a number of components and interactions between components. The simplification of components and the distribution of services across them can lead to a better scalability of the system (Fielding, 2000). Our designed architecture is almost a scalable architecture as it comprises various components and each of them is responsible for providing a specified service. It is a scalable architecture because the component comprising the architecture can be replicated easily. For example, we can have more cRIOs or bigger data storage if required. Additionally, our designed architecture is not only componentized in terms of its comprising components but it is also componentized geographically. Thus, for example, a city-wide area has been divided into several NAN, each with a hierarchical architecture, while we assume a peer-to-peer layer can be provided above them. In this case, if the electricity grid requires more NAN, it can be added to the overall system without affecting the other NANS.

- **Simplicity:** In order to induce simplicity into a system, the architecture should consider the concept of the separation of concerns by breaking the system into distinct functionalities (Fielding, 2000). Each of these functionalities can represent a layer or a component in the system. The separation of concerns can reduce the level of complexity of components and simplify the ability to understand and implement them. Moreover, when concerns are separated, this will simplify the reasoning of the whole architecture. Since our designed architecture is a combination of layered and componentized architecture, this system, thus, is an embodiment of the separation of concerns which will automatically lead to the simplicity of the system.

- **Modifiability:** This metric indicates how easy it is to make a change to an architecture (Fielding, 2000). Each architecture should be ready for gradual change over time, as the user requirements may change. Bearing this concept in mind, our designed architecture has been divided into the following two sub-categories.
  - **Extensibility:** This metric presents the ability to add more functionality to the architecture without affecting the whole system. As an example, minimising the coupling between the components of an architecture can result in extensibility of that architecture (Fielding, 2000).
Appendix B. Data to Knowledge (Visualisation Tool)

- **Reusability:** This metric indicates the ability of the components, connectors, and data elements in a system to be reused in another system without modification (Fielding, 2000).

  The level of coupling across components in the system can support the degree of extensibility, and reusability, of that system. Our designed system supports modifiability since our prototype architecture has been designed based on an appropriate level of abstraction, loose coupling and separation of concerns.

- **Portability:** This metric indicates that the system can run in various environments (Fielding, 2000). Our prototype architecture supports portability on the client side because we provide web interfaces that can run on different devices and platforms.

- **Reliability:** This metric indicates the degree of vulnerability of the architecture to failures. Therefore, in order to support reliability in the system, a single point of failure should be avoided and recoverable actions should support the architecture in case of failure (Fielding, 2000). Our architecture design supports reliability in the sense that it can deal with persistence layer failure by providing a backup database in the application layer. Moreover, our system can deal with failures by announcing over threshold data and by offering redundancy for such action to cover the failure. As such, three methods of alerting such events have been provided. The first method is passive alerting such as alerts on the user screen, the second is active alerting such as sending text messages, and the third is web services for the subscribed users. Additionally, preventing unauthorised access to the data collected from the instrumentation of the power grid and the environment will improve both the reliability of the software system and the reliability of the neighbourhood area in the Smart Grid.

**B.2.5.3 Identifying Emergency Scenarios**

Handling the emergency scenarios in the NAN plays an important role in preventing the catastrophic failure of the larger area. To show how the architecture can respond we have identified three possible emergency scenarios and proposed a solution for each of them. This is not intended to be an exhaustive list but to show the principles of the software design.
Appendix B. Data to Knowledge (Visualisation Tool)

The first emergency scenario is when individual monitoring devices fail. In this case, the application can identify the failure and alert users if it is not receiving data from the DB relating to the specific sensor for a defined period of time. This has been implemented for the sensors at the substation level and the building level. In most cases, the sensor failure might affect the routing of the system. In the server side of our proposed architecture, if the individual sensor in each of monitoring system goes down, it will not affect the routing of the whole system because each individual sensor has direct communication instead of multi-hop communication. This will prevent other sensors from being affected by the failed sensor.

A second scenario (see Figure B.25) is to lose the persistence layer. The application will alert the user if it is not receiving data from the DB for a specific time. In such a case, we are losing both the historical data stored in the DB and the live data. To recover the historical data we have built a temporary DB in the application layer to save data for the past week. The oldest data start deleting as the new data come in. Therefore, if the persistence layer is down, the application layer can cover it. To recover the live data we are able to change the destination of the programme that is extracting data from the sensors. Therefore, instead of transmitting data to the DB, we can set the destination to the developed application. Thus we can receive live data in the application and then visualise them even if the DB or the links to the DB is down.

A third emergency scenario (see Figure B.26) is when the values of the monitored electrical data exceed a warning threshold. In this case, our application can alert the operator of the Grid who is behind the screen in the control room by highlighting over threshold data. The application will also use a component to send an SMS to the subscribing engineers in the field. Moreover, it will use the web services to send an alert to the engineers and other neighbouring areas. This will inform the other areas of the fault happening in a specific area and will prevent conflicting actions. The other advantages of using both the SMS service and the web service is that, in critical times when the network is busy, using another system can assure the alarm is spotted in a reasonable amount of time.

In summary, the idea behind the construction of these emergency scenarios is that it enables us to work out how to utilise the architecture so that it can cope with key failure situations in a timely manner and prevent cascades of failure throughout the wider regions of the Grid.
Figure B.25: The persistence layer is down.
B.2.6 Summary

A data stream can be converted to knowledge by various tools. Here, we use a visualisation tool in order to extract information out of data. The primary aim of the visualisation is to express information vividly and effectively via graphical tools in order to provide insights into a complex system. The Smart Grid will cause more complex power system modelling and operations, resulting in an increased need for visualisations to enhance understanding. Therefore, in this Appendix we have discussed our developed visualisation tool which facilitates a better comprehension of the behaviour of the NAN in a Smart Grid.
Appendix B. Data to Knowledge (Visualisation Tool)

This tool enables information to be gathered and visualised from the working of a real system operating a sub-Grid level where monitoring has not previously been deployed and the detailed behaviour of the NAN level Grid has remained unknown until now. In this Appendix we have outlined the requirements of the developed visualisation tool. We have presented the software architecture and its components. Furthermore, we have discussed the design decisions and the selection of technology used to implement the architecture. In brief, we have realised this visualisation tool by using standard technologies such as .Net application, ASPX, CSS, JavaScript, and Google Maps API. We employed Visual Studio Integrated Development Tool as a basic development environment. This IDE was selected since Microsoft provides an academic license for this software. At the beginning of this project, we used VS 2010 and, over the time, we migrated the developed tool to be compatible with VS 2012 and finally VS 2013.

We have described the implementation of the tool we have developed in that it is working with simulated and real data in an actual working sub-Grid level of a university campus test bed. For the building level and the substation level devices our tool connects to the real data that are stored in the PostgreSQL database. However, for the street level devices, our tool needs to be connected to a simulation tool that generates data and stores them in the TinyDB database. Therefore, two different database connector modules have been employed for the data retrieval process.

We have tested our tool based on the fact that it is working in a real environment and it is being tested by professionals in the field. In the near future this tool is going to be used by several groups of people. The first group consists of students who are going to use it as a learning tool. The second group consists of researchers in Smart Grid projects. As an example, this tool can help these researchers understand how the pattern of weather data corresponds to the pattern of electricity usage. Eventually, this tool will be used by grid operators who will be trying to control the grid at this level.

We have evaluated our tool based on the functional criteria of our system. Additionally, we have evaluated the architectural design of our prototype system based on the qualitative metrics specified in (Fielding, 2000). Finally emergency scenarios have been identified and implemented. For this purpose, an external module IntelliSMS has been employed in order to facilitate the text messaging when an emergency scenario has happened. Additionally, a web service is also provided for the same purpose. Therefore, a client can
register to receive the service interface via its address (url). This service interface has been automatically generated via the Visual Studio.

According to our knowledge, this is the first tool that has been introduced and implemented for the monitoring and the control of the NAN in the distribution sub-Grid. It can integrate various levels of monitoring from the building level to the street level and, finally, to the substation level, and can apply monitoring and control over the collected data at such levels. There is no previously designed tool that can integrate all the information as a whole system for this level of the electrical Grid and present it via a visualisation tool. This tool is customisable and more functionality can be designed and implemented if required. For example, in future more sources of data such as SCADA and AMI data can be integrated. As a result, the tool acts as an essential component in the operation and planning of the system.

To summarise, in this tool, we have integrated software, hardware and data in order to extract, organise, analyse and display information which we believe to be useful in monitoring fieldwork, raising situational awareness of the state of the grid, identifying vulnerabilities, and preventing failures.

In future, power engineers will integrate this tool with various programmes, such as power network simulations, in order to lead to better management of the grid. It is believed that, by integrating this tool with electrical grid simulation, this tool will enable prediction(s) on the future state of the grid and the developing of an action plan.

As a final point, to generalise our visualisation tool, although it has been implemented as a prototype for the smart electrical grid, but it is able to be used in other smart networks which require similar functionalities to visualise information in order to better comprehend the behaviour of their networks. To close, with small modifications, all the functionalities provided in this tool can be used for other smart networks.


References


214


References


References


References


