Modeling and analysis of network protocols for automatic meter reading systems using power line communications

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Modeling and Analysis of Network Protocols for Automatic Meter Reading Systems Using Power Line Communications

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SUMMARY

Utilities now look at the deployment of automatic meter reading (AMR) systems to reduce the operating costs, improve meter reading accuracy, eliminate man-made errors and improve efficiency through demand management. The inherent communication infrastructure presented by power line communications (PLC), which significantly reduces the cost of building a new communication network, makes PLC a favorable solution for AMR communication networks. Power supply networks, however, are not designed for communication because the PLC channel is characterized by large, and frequency-dependant attenuation, changing impedance and fading as well as unfavorable noise conditions. Therefore it is important to develop a robust and stable network protocol that meets the working conditions and requirements for PLC channels in order to make PLC network systems competitive with other access technologies. The objective of this thesis is to investigate suitable network protocols for use in PLC based AMR systems and to study their performances using narrowband and broadband PLC technologies.

One of the typical problems associated with PLC-based AMR systems is the “hidden node” problem. A “hidden node” is a meter unit that cannot communicate directly with the data concentrator (DC). The “hidden node” problem is not caused by a meter’s own malfunction but because of the significant signal attenuation along cables, the noisy power line environment and the varying in-home impedance. These affect the efficiency and reliability of PLC-based AMR systems. Furthermore, the impulsive noise interference on the PLC channel also considerably influences the performance of the AMR system.

Over the years, much research has been done on the mitigation of impulsive noise interference through physical (PHY) layer or PHY/MAC cross-layer designs. There also has been some research on the fundamentals of AMR systems using PLC. There is, however, no significant research on the effect of impulsive noise interference on AMR system performance. Phase 1 of this research seeks to develop analytical models to analyze the performances of the two AMR protocols, namely clustered simple polling (CSP) and neighbor relay polling (NRP), under impulsive noise interference. The

performance analyses show that the NRP protocol performs better than the CSP protocol in terms of throughput but requires longer data collection delay to cater for re-polling of failed meter units. Both the CSP and NRP protocols do not perform well under heavy impulsive noise interference, resulting in a drop to 0.2% of successful metering data collection. However, high throughput can be achieved for moderate and heavy impulsive noise interference environments by reduction of the packet size of the AMR system.

Phase 1 of the research demonstrates that the delay associated with the polling-based protocol is generally higher and increases with the number of nodes connected to the DC. Furthermore, polling-based protocols lack the important capability for automatic association of new devices to the system. Therefore, Phase 2 of the research proposes a new and effective communication protocol for implementation in PLC-based AMR systems and presents analytical models to study its performance. The protocol utilizes a novel packet routing system which combines “Request” and “Data” packets that enable meter units to send their metering data to the DC and at the same time re-broadcast the “Request” to other meter units. The protocol ensures significantly lower data collection delay than the NRP protocol. It will be able to achieve 100% throughput for light and moderate impulsive noise interference environments and 75% throughput for a heavy impulsive noise interference environment using broadband PLC with a cluster size larger than 60. The protocol does not require a central controller to initiate all data transmission unlike polling based protocols and can be applied to PLC systems with unstructured networks.

Finally, with AMR being part of an advanced metering infrastructure (AMI) in smart grid technology, Phase 3 of the research proposes a communication infrastructure for implementation of AMI in the Intelligent Energy System pilot project at Nanyang Technological University, Singapore and presents analytical models to study its performance. The proposed AMI communication infrastructure utilizes a hybrid PLC and Worldwide Interoperability for Microwave Access (WiMAX) technology for the last mile and backhaul communications respectively. The PLC-based communication employs the packet routing protocol developed in Phase 2 of this research. The WiMAX-based communication operates on the 3.5GHz licensed band satisfying the Stanford University Interim (SUI) model for path loss prediction. The proposed AMI

completes the data collection of 1250 meter units in less than 205 seconds. The proposed AMI achieves 100% throughput for $P_g > 0.5$ in environment without impulsive noise interference, where P_g is the probability that a meter unit can directly communicate with the DC or a relay meter unit. It is also able to achieve less than 5% drop in throughput for light and moderate impulsive noise environments.

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Lists of Acronyms and Notations

A. List of Acronyms

PLC	-	Power Line Communications
BPLC	-	Broadband Power Line Communications
AC	-	Alternating Current
CENELEC	-	European Committee for Electrotechnical Standardization
RF	-	Radio Frequency
CISPR	-	International Committee for Radio Interferences
IEC	-	International Electrotechnical Commission
FCC	-	Federal Communications Commission
ITU-T	-	International Telecommunication Union - Telecommunication Standardization Sector
IEEE	-	Institute of Electrical and Electronics Engineers
iDA	-	Infocomm Development Authority
TSTC	-	Telecommunications Standards Technical Committee
UPA	-	Universal Power Line Association
ETSI	-	European Telecommunications Standards Institute
PSCC	-	Power System Communications Committee
PES	-	Power Engineering Society
EMA	-	Energy Market Authority
SGCC	-	State Grid Corporation of China
IES	-	Intelligent Energy System
NTU	-	Nanyang Technological University
TVWS	-	Television white space
WiMAX	-	Worldwide Interoperability for Microwave Access
GSM	-	Global System for Mobile Communications
PSTN	-	Public Switched Telephone Network
AMI	-	Advanced Metering Infrastructure
AMR	-	Automatic Meter Reading
DC	-	Data Concentrator
LV	-	Low Voltage

MV	-	Medium Voltage
LVDN	-	Low Voltage Distribution Network
AWGN	-	Additive White Gaussian Noise
CSP	-	Clustered Simple Polling
NRP	-	Neighbor Relay Polling
PHY	-	Physical
MAC	-	Medium Access Control
ASK	-	Amplitude Shift Keying
FSK	-	Frequency Shift Keying
PSK	-	Phase Shift Keying
QAM	-	Quadrature Amplitude Modulation
BPSK	-	Binary Phase Shift Keying
QPSK	-	Quadrature Phase Shift Keying
OFDM	-	Orthogonal Frequency Division Multiplexing
DSSS	-	Direct Sequence Spread Spectrum
FHSS	-	Frequency Hopping Spread Spectrum
BW	-	Bandwidth
LAN	-	Local Area Network
ISMA	-	Inhibit Sense Multiple Access
QoS	-	Quality of Service
KERI	-	Korea Electrotechnology Research Institute
VoIP	-	Voice over Internet Protocol
ISI	-	Inter Symbol Interference
ICI	-	Inter-Carrier Interference
ACK	-	Acknowledgement
HCU	-	Home Concentration Unit
DCU	-	Data Concentration Unit
DLMS	-	Device Language Message Specification
FEC	-	Forward Error Correction
NRC	-	Non-Recursive Convolutional
RSC	-	Recursive Systematic Convolutional
D-TDMA	-	Dynamic Time-Division Multiple Access
PRMA	-	Packet Reservation Multiple Access
CDMA	-	Code Division Multiple Access

NC-PRMA	-	Non-Collision Packet Reservation Multiple Access
CSI	-	Channel State Information
HPAV	-	HomePlug AV
HDB	-	Housing Development Board
EMC	-	Electromagnetic Compatibility
CSMA/CA	-	Carrier Sense Multiple Access with Collision Avoidance
SUI	-	Stanford University Interim
NLOS	-	Non-line-of-sight
DER	-	Distributed Energy Resources

B. List of Notations

$A(f, d)$	-	Attenuation
f	-	Carrier frequency
f_c	-	Centre frequency
d	-	Length of the dedicated path
k	-	Exponent of the attenuation factor
τ_i	-	Propagation delay for the path i
c_0	-	Speed of light
A	-	Signal amplitude
t_{IAT}	-	Impulsive noise interference inter-arrival time
t_w	-	Impulsive noise interference width or duration time
t_d	-	Distance between impulsive noise interferences
T	-	Signal time period
$s(t)$	-	Transmitted signal
$d(t)$	-	Data signal
P_g	-	Probability for a meter unit with “Good” status
P_b	-	Probability for a meter unit with “Bad” status
P_{gg}	-	Probability that a “Good” meter unit remains “Good”
P_{gb}	-	Probability that a “Good” meter unit changes to “Bad”
P_{bb}	-	Probability that a “Bad” meter unit remains “Bad”
P_{bg}	-	Probability that a “Bad” meter unit changes to “Good”
P_T	-	Transition probability matrix

P	-	Meter status probability matrix
$P_k(t)$	-	Probability distribution of impulsive noise interference arrival
λ'	-	Impulsive noise interference arrival rate
P_{NFail}	-	Probability of “Near” cluster failure
P_{MFail}	-	Probability of “Medium” cluster failure
P_{FFail}	-	Probability of “Far” cluster failure
P_{FPoll}	-	Probability that meter units in the “Far” cluster can be polled
$P_{AllPoll}$	-	Probability that all meter units in the sub-network can be polled
t_{tx}	-	One-way transmission delay for a packet
t_{proc}	-	Message processing delay
$t_{S\ell}$	-	Delay for one meter's successful data collection where $\ell=1, 2, 3$
$t_{TO\ell}$	-	Time-out period for different clusters where $\ell=1, 2, 3$
$t_{RP\ell}$	-	Delay for one “hidden node” re-polling where $\ell=1, 2, 3$
$t'_{CSP\ell}$	-	Data packet vulnerable time for CSP where $\ell=1, 2, 3$
$t'_{NRP\ell}$	-	Data packet vulnerable time for NRP where $\ell=1, 2, 3$
$P_{k=0,CSP\ell}$	-	Probability that no impulsive noise interference occurs during CSP data packet vulnerable time
$P_{k=0,NRP\ell}$	-	Probability that no impulsive noise interference occurs during NRP data packet vulnerable time
$T_{S\ell}$	-	Successful data collection delay for ℓ level cluster where $\ell=1, 2, 3$
$T_{F\ell}$	-	Unsuccessful data collection delay for ℓ level cluster where $\ell=1, 2, 3$
$N_{S\ell}$	-	Number of successful data collections for ℓ level cluster where $\ell=1, 2, 3$
$T_{NRP,\ell}$	-	Total data collection delay for ℓ level cluster re-polling procedure where $\ell=1, 2, 3$
$T_{CSP}(t)$	-	Data collection time for CSP
$S_{CSP}(t)$	-	Throughput for CSP
$T_{NRP}(t)$	-	Data collection time for NRP
$S_{NRP}(t)$	-	Throughput for NRPP

$P_{ClusterFailure}$	-	Probability of cluster failure
P_{L1Fail}	-	Probability of “Level 1” cluster failure
P_{L2Fail}	-	Probability of “Level 2” cluster failure
P_{L3Fail}	-	Probability of “Level 3” cluster failure
$P_{AllGood}$	-	Probability that all meter units can transmit their data
$T_{backoff}$	-	Additional back-off interval where $\ell=1, 2, 3, 4$
W_{CW}	-	Pseudo-random integer variable uniformly distributed over an interval $[0, D_{Win}]$
D_{Win}	-	Size of the contention window
$R_{max\ell}$	-	Maximum random back-off period generated for all meter units in a particular hop level where $\ell=1, 2, 3, 4$
$t_{C,\ell}$	-	Routing protocol’s data collection delay for each hop level where $\ell=1, 2, 3, 4$
T_{wait}	-	Transmission waiting interval
W_{CR}	-	Pseudo-random integer variable uniformly distributed over an interval $[0, D_{backoff}]$
$D_{backoff}$	-	Size of the internal back-off window
$K_{max\omega}$	-	Longest waiting interval for each transmission round
$t_{K,\omega}$	-	Routing protocol’s data collection delay for each transmission round
PL_{SUI}	-	SUI model path loss
Γ	-	Number of transmission rounds required
T_{PLC}	-	Data collection delay for one last mile PLC network
T_{WiMAX}	-	Data collection time for backhaul WiMAX network

CHAPTER 1 INTRODUCTION

This chapter presents an introduction to power line communications (PLC) and smart grid technology including its applications, advantages, challenges and recent developments. The research motivations, objectives, contributions and organization of this thesis are also discussed in this chapter.

1.1 Introduction to Power Line Communications (PLC)

PLC is the method of transmitting communication signals on the same pair of wires that are used to supply alternating current (AC) power carrying large currents at high voltages alternating at 50 or 60 Hz. PLC systems operate by superimposing a high frequency signal (ranging from several kHz up to even 100's of MHz) at low energy levels over the 50 or 60 Hz electrical signal. This signal is transmitted via the power infrastructure and can be received and decoded remotely. The amplitude of the analog carrier signal is usually less than 10Vp-p. The analog carrier signal is coupled onto the 50 or 60 Hz AC signal and a high voltage (110V – 240V AC) power line network, through dedicated coupling circuits and signal amplifiers.

Power line communications utilizes the electrical power supply networks for communication purposes. The main idea in the deployment of PLC is the reduction of cost and expenditure in the realization of new communication networks. The high voltage (HV) (110 – 380 kV) networks usually span very long distances to connect the power stations with large supply regions. The medium voltage (MV) (10 – 30 kV) networks with serves a shorter distance compared to HV networks supply to larger areas or cities. The HV or MV networks can be used to bridge longer distances to avoid building an extra communication network. The low voltage (LV) (230/400 V) networks serves individual customers and their transmission length are usually up to a few hundred meters. The LV network is connected to a very large number of households and can be used for the realization of PLC access networks or last mile communication network. The in-home electrical installations also falls on the LV network level. In-home networks make it possible to achieve PLC local area networks (LAN) within

homes or buildings to connect devices through the power socket while avoiding high cabling cost. Each of these HV, MV, LV and in-home PLC mediums has different noise and propagation characteristics that could affect the performance of the communication system.

Figure 1-1 shows a typical distribution system in Singapore where the outdoor low voltage distribution network (LVDN) connects about 5 to 6 high-rise buildings, each having around 100 households, in a ring configuration. The PLC access network implemented at the LV output of the distribution transformer transforms the LVDN into a large-scale local area network (LAN). In such system, the local distribution transformer substation is connected to the telecommunication network via conventional communications infrastructure. The PLC system is also implemented as a ‘last mile’ solution where the PLC range will be limited to the indoor LVDN from the main distribution board of any residential or industrial building.

Figure 1-1: Simplified structure of the LVDN in Singapore.

Access networks provide the essential connection between a large number of end-users and the back-bone communication network. The access network design and development is the most critical process in the development of a communication infrastructure. This is because the cost of realization, installation, and maintenance of the access network represent more than 50% of the investment in the network [1]. Therefore, it is important for network providers to realize a cost-effective access network technology in order to increase their competitiveness in a deregulated

telecommunication industry. PLC provides an alternative cost-effective solution for the realization of the access network utilizing power supply grids for communications.

PLC technology can be classified into two categories, narrowband PLC and broadband PLC. Narrowband PLC operates on frequencies in the range of 3kHz to 148.5kHz in Europe under European Committee for Electrotechnical Standardization (CENELEC) and 45 to 450 kHz in the United States (US) [2]. Narrowband PLC operates at low data rate and power requirement. It is most widely used in the area of automatic meter reading, building/home automation and electrical load management. Broadband PLC operates at high frequencies in the range of 1 to 30 MHz [3]. It can achieve data rate ranging from several hundred kbps to hundreds of Mbps or even higher. Broadband PLC is usually employed for high speed applications, such as Internet access, home networking and home entertainment systems.

This thesis aims to investigate suitable network protocols for use in PLC based AMR systems and to study their performances using narrowband and broadband PLC technologies. The main advantage of PLC arises from its ability to eliminate the rewiring challenge by taking advantage of the near universal presence of power line infrastructure. Data can be transmitted to any location over the power line network, as long as they are supplied with power. This offers PLC a unique feature over other means of data transmission with significant cost advantages. It does not require high installation costs and provide users the flexibility to access the network from multiple access points across a wide range of locations. The users would only need to plug their computers or data devices through a PLC modem into any electrical outlet in the building to gain access to the PLC network. It has significant advantages in particular, over wireless communications channels which suffer from high attenuation due to obstruction by signal blocking mechanism within buildings such as concrete walls and steel doors. Furthermore, wireless network operators need to consider enabling security protocols to protect their subscribers and the network. Compared to wireless systems, PLC systems similar to other wired communication systems have lower security risk.

The power supply networks were not originally designed for communications but for the transmission of electric power. Therefore, they do not present a favorable transmission medium. This is because power lines are typically unshielded thus act

almost like antennas, producing electromagnetic radiation in their environment causing interference to other radio communications. Therefore, regulatory bodies often specify very strong limits regarding the electromagnetic radiation from PLC networks. Furthermore, broadband PLC operates in the frequency spectrum of up to 30MHz, which is also used by various other services such as amateur and short wave radio. The International Committee for Radio Interferences (CISPR) was set up by the International Electrotechnical Commission (IEC) to produce standards to protect the reception of radio transmission. CISPR 22 defines limits for the conducted and radiated emissions from PLC equipments and serves as the basis for other major national standards such as United States's Federal Communications Commission (FCC) part 15 regulation and Europe's CENELEC Standard EN50065 [1]. These regulations require the PLC equipments to operate with a limited signal power hence reducing transmission distance and data rate.

Internationally, PLC is receiving wide attention as a solution for smart grid communication and home networking. This can be seen from the G.hn standard developed by the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) which provides an integrated approach for several broadband transmission media including power lines for home networking [4]. The Institute of Electrical and Electronics Engineers (IEEE) has also developed the IEEE P1901 Standards for broadband over power lines to address the importance of standardization in the PLC context [5]. In Singapore, the acceptance and push for PLC solution for home networking can be seen from the Infocomm Development Authority (IDA) Telecommunications Standards Technical Committee (TSTC) Working Group which facilitates the evolvement to the Connected Digital Home concept using coaxial, fiber optic, wireless and PLC technologies. Since the idea of PLC was first developed, several standards have evolved including X10 which was a front runner in the early stages. Current standards include HomePlug 1.0 and Home Plug AV from HomePlug Power Line Alliance [6], [7], Digital Home Specification V1.0 from Universal Power Line Association (UPA) [8], the European Telecommunications Standards Institute (ETSI) standards [9] and the working standard from Power System Communications Committee (PSCC), IEEE Power Engineering Society (IEEE PES) [10].

A market research conducted by BMP telecommunications consultant in 2003 reported that with chipset production costs getting lower and growing data transfer rates, PLC faces a bright future especially for in-home networking [11]. Figure 1-2 shows the broadband penetration and the projected market share of PLC over other media. In 2009, a market review conducted by BMP showed that in parallel to the significant efforts related to standardization, a growing number of PLC projects are up surging around the world, as a platform for providing broadband services. The number of worldwide passed homes has constantly increased (1.5 million in 2009) as shown in Figure 1-3, showing a growing interest for the PLC technology. The number of passed homes is projected to reach 9 million in 2011. This significant increase is mainly due to the new market segment created by the smart grid initiatives around the world. Broadband PLC technology has been chosen by numerous utilities as its performance and characteristics are enticing and demonstrate a viable solution for the future.

Figure 1-2: Projected PLC market share versus broadband penetration [11].

Figure 1-3: PLC passed homes evolution [11].

1.2 Introduction to Smart Grid Technology

The exploding global demand for electricity especially in developing countries such as China and India, require practical and clean electric generating options, and significant increase in efficiency throughout the entire energy chain. The energy chain must incorporate information technology in revolutionary ways that use real-time information, distributed energy resources, e-business platform and market efficiencies to minimize the need for inventory and infrastructure and to maximize productivity, efficiency, and reliability. The smart grid technology is the creation of a distributed, yet integrated, system that will automate the energy chain and empower consumers to participate directly or indirectly in the generation and consumption of energy. In other words, smart grid is the transformation of the electric industry from a centralized, producer-controlled network to one that is less centralized and more consumer-interactive.

The basic concept of smart grid technology is to integrate monitoring, control, analysis and two-way real-time communication to the electric transmission and distribution

system to improve efficiency of the system while reducing the energy consumption [12]. The smart grid will allow utilities to distribute electricity around the system as efficiently and economically as possible. It will also allow and encourage the consumers to use electricity as economically as possible while reducing consumption. The smart grid actually builds on many of the technologies currently employed by utilities but includes communication and control capabilities that will optimize the operation of the entire electrical grid. The smart grid is also positioned to take advantage of new technologies, such as distributed generation technologies, plug-in hybrid electric vehicles, demand side management, home/building energy management systems, and many more.

There are a few notable projects completed or on-going around the world on the development of smart grid. The Energy Market Authority (EMA) of Singapore announced on 19 November 2009 that it has spearheaded a pilot project for an “Intelligent Energy System (IES)” [13]. The IES pilot will involve around 4,500 consumers in various residential, commercial and industrial locations, including the Nanyang Technological University (NTU) campus and the CleanTech Park at Jalan Bahar. The IES pilot project seeks to test and evaluate new applications and technologies around a smart grid. Communication infrastructure will be established within NTU, linking up to 1250 smart meters at various locations around the campus to the data concentrators and the NTU Central Host. Communication infrastructure such as broadband PLC, RF mesh, TV white space (TVWS), Wi-Fi, Worldwide Interoperability for Microwave Access (WiMAX) and fiber optics will be explored. This clearly shows that the PLC technology has a wide commercial potential in Singapore both for smart grid communication and home networking.

In Italy, Telegestore project was launched in October 1999 by an Italian energy provider, ENEL. The project completed in 2006 was the first and largest smart grid installed with a budget of US\$2.87 billion over a five-year period [14]. At the end of December 2006, about 30 million smart meters and 350 thousand data concentrators were installed over three continents to exploits LV distribution network between data concentrators, smart meters, the public Global System for Mobile Communication (GSM), Public Switched Telephone Network (PSTN) and acquisition centre (Automatic Meter Management). Different communication technologies such as PLC

and RF were tested and evaluated. ENEL chose PLC over RF after it examined the reliability of each and concluded that PLC is more suitable as it provides a more reliable and secure communication link between the smart meters and data concentrators. As of September 2008, the project covered 31.3 million customers, using 350 thousand data concentrators. The Telegestore project is saving ENEL about US\$680 million/year [15].

Another smart grid development is on-going in the city of Austin, Texas, USA. The project which started in 2003 is divided into two phases. The first phase focuses on system integration, communication, safety, reliability and improved customer service. The first phase of the project was completed in August 2008. It includes 500 thousand devices (smart meters, smart thermostats, and sensors across its service area) servicing 1 million customers and 43 thousand businesses [16]. The second phase of the project which is currently on-going includes initiatives to improve operations and procurement, ensure quicker outage restoration, enhance better planning and management of load distribution and reduce the need for extra generation and transmission capacity.

The State Grid Corporation of China (SGCC) embarked on a large-scale project from 2007 for the development of a smart grid system [17]. The project is divided into 3 phases. The first phase, which ended in 2010, focused on planning Smart Grid construction by outlining technical standards, developing technology and equipment, and implementing pilot projects. The second phase will last until 2015 and will see the construction of a reliable nationwide transmission grid, including operational Smart Grid management systems, wide spread deployment of smart meters, and enough electric vehicle (EV) charging stations to accommodate the use of EVs. The final phase will last from 2016 to 2020 and complete China's nationwide grid by connecting all planned coal, hydroelectric, nuclear and wind power generation facilities to areas of high demand in a reliable, intelligently managed transmission network.

Advanced Metering Infrastructure (AMI) is the fundamental building block of a complete smart grid system. AMI is the integration of many technologies, such as smart metering, home area networks, integrated communications, data management applications, and standardized software interfaces, which creates an essential link between the grid, utilities, consumers and their loads, system operators, and generation

and storage resources. Data collected through AMI enables system operators to greatly improve consumer service by refining utility operating and asset management processes. In addition, AMI gives consumers the information they need to make intelligent decisions on their energy consumption and the ability to execute various energy efficiency programmes that lead to substantial benefits [18].

AMI includes automatic meter reading (AMR) system which is the technology of automatically collecting consumption, diagnostic, and status data from energy metering devices or smart meters and transferring that data to a central database for billing, troubleshooting, and analyzing. AMR was first conceptualized to reduce the utilities' cost in the expense of time-consuming periodic trips to each physical location for visual inspection of meters. Furthermore, visual inspection of metering devices is often difficult where accessibility is a problem and susceptible to man-made errors. Another advantage of AMR is that billing can be based on near real time consumption rather than on estimates based on previous or predicted consumption. This timely information coupled with analysis facilitates other functions within the smart grid system to better control and manage the production and consumption of electric energy. The specifications of the AMR system consider in this research work are tabulated in Table 1-1.

Table 1-1: AMR System Specifications

Feature	Specification
Metering data packet size	24 bytes (192 bits)
Link data rate	2.4 kbps (narrowband) 1 Mbps (broadband)
Message processing time	1 s
Polling time-out period	1.5 s (Near/Level 1 cluster) 2.5 s (Medium/Level 2 cluster) 4.5 s (Far/Level 3 cluster)
Number of meter units under a DC	504
Number of sub-networks under a DC	21
Number of meter units per sub-network	24
Communication data flow	Two-way
Data collection cycle period	1800 s

The shift from manual to automatic meter reading requires a change from the conventional electromechanical meters to digital meters or smart meters. Smart meters are solid state programmable devices that perform many functions, including real-time consumption data recording, power quality monitoring, net metering and loss of power (and restoration) notification. The AMR communications infrastructure supports continuous interaction between the system operator, central database and smart meters. It employs open bi-directional real-time communication standards that are highly secure. There are various architectures that can be employed for AMR systems, with the most common being local data concentrators (DC) collecting data from groups of meters within the same vicinity and transmitting that data to the central database via a backhaul network. Many communication medium can be considered to provide part or all of this architecture including coaxial cables, optical fiber, PLC and wireless technologies. However, of all available transmission medium, only PLC, in particular at low-voltage (LV) level, offers significant reduction in investment costs due to the already present communication infrastructures.

The urgency to drive an overhaul of grid infrastructure has seen governments, industries, and electric utilities around the world coming together to stimulate the development of the smart grid technology. These initiatives are designed to integrate clean energy technologies, improve the reliability of the electrical grid, reduce costs through increased operating efficiency for utilities, improve energy efficiency through consumer participation and prepare the grid for the integration electric vehicles. Pike Research forecasts that smart grid infrastructure, including grid automation upgrades as well as smart metering, represents a huge market opportunity and will attract \$200 billion in worldwide investment between 2008 and 2015 [19].

1.3 Research Motivations

The concept of “smart grid” has received wide attention in the past few years. Worldwide, utilities and governments are looking at utilizing advanced monitoring, control and communication technologies to achieve improvements in grid automation. The ultimate aim is to enhance the capabilities of the power grid to achieve greater efficiency and reliability. Advanced metering infrastructure (AMI) has been the most common smart grid implementation worldwide. AMI implementation is recognized to

be the fundamental step in the move towards smart grid [18]. AMI gives utilities and consumers the information they need to make intelligent decisions in the control and management of energy. The key aspect in realizing the vision of AMI is to establish a two-way seamless communication infrastructure to provide an essential link between the utility, consumers, and generation and storage resources.

The deregulation of the power supply industry to separate generation, transmission and distribution of electric power has created a new environment which allows a healthier competitive business environment to benefit the consumers. Apart from the commercial aspect on compelling generators and transmission grids to be more efficient and cost conscious, it has set the stage of more requirements for timely information on consumption, load profile and power quality [20]. Furthermore, the rapid growth of population and technology has increased the number of power consumers and electric power consumption. The current metering trend of manual data recording and account-based billing is manpower intensive and expensive to operate. Utilities now look at the deployment of AMR systems to reduce the operating costs, improve meter reading accuracy, eliminate man-made errors and improve energy efficiency through demand management. AMR is a part of a larger AMI for smart grid systems.

Power lines were originally developed for transmission of AC power to electrical loads, but the use of the electrical supply networks for communication purposes began as early as in the 20th century [21]. PLC is a method of using power line wires or cables as a medium to transmit data. In the development of communication network infrastructures, access network design is very important considering the high cost investments required for the realization of direct access networks to the end users. The inherent communication infrastructure presented by PLC, which significantly reduces the cost of building a new access network, makes PLC a favorable solution for “last mile” communication networks. One of the major applications for “last-mile” PLC access network is the AMR system. The low-voltage power supply network which is also the PLC access network is built on various network topologies, with a tree-like structure as shown in Figure 1-4. There are generally several network sections from a distribution transformer to the meters with different network topologies. This random PLC access network structure poses a potential challenge in designing an effective and efficient network protocol for AMR applications.

Figure 1-4: PLC access network.

PLC especially broadband PLC (BPLC) is increasingly being deployed to meet utility needs for high-speed data applications on the system side. Next-generation PLC systems now under development promise lower cost, improved performance, higher speed, and utility applicability. Utilities prefer PLC technology for AMR due to the already present communication infrastructures. PLC-based AMR systems, however, face some challenges that need to be addressed in order to provide a viable, reliable and efficient AMR system. These challenges are mainly due to the fact that low-voltage power supply networks are not designed for communications; they are therefore not favorable for data communication. Power supply networks operate on standard electrical wirings which consist of a variety of conductor types and interconnections joined almost at random. This will give a variety of characteristic impedances in the network. Also, the network terminal impedance will vary with communication signal frequency and with time as the consumer load pattern varies [22]. This impedance mismatch results in a multi-path effect causing significant attenuation on the power lines especially with longer transmission distance. Furthermore, PLC systems have to operate within limited signal power in order to ensure low electromagnetic interference. These physical characteristics will affect the efficiency and reliability of upper layer services such as AMR. In PLC-based AMR systems, this is typically categorized as the

“hidden node” problem where a meter unit cannot directly communicate with the data concentrator to receive signals or send metering data which results in unreliable metering data acquisition and additional data collection delay.

Besides signal distortion due to cable losses and multi-path propagation, the power line channel is considered unreliable because of the higher noise levels present especially at lower frequencies. The noise in a power line channel is represented by a non-Additive White Gaussian Noise (non-AWGN) [23]. This is because the power line noise at a power socket outlet corresponds to the sum of noise waveforms produced and emitted to the lines from the appliances connected to the power line network. The power line noises are characterized by two main types: background noise and impulsive noise interference. The background noise is of lower power spectral density and remains stationary throughout the transmission while impulsive noise interference occurs for a short period with high power spectral density. Impulsive noise interference is considered as the key source of packet error in PLC based data transmission [24].

These are significant challenges, and there have been some research on PLC-based AMR systems that study the impact of the challenges. Comprehensive studies on the fundamentals of PLC-based AMR systems can be found in [25]-[28]. A few field tests or pilot projects on AMR systems have also been conducted such as in [29] and [30]. In [31] and [32], PLC modules for AMR have been developed with noise suppression elements. An analytical modeling of polling in PLC-based AMR systems was done in [33] and a simulation based study on AMR systems with consideration of various network parameters including noise was done in [34]. There is, however, no significant research on the effect of impulsive noise interference on PLC-based AMR system performance.

In [35], two AMR protocols were introduced to overcome the “hidden node” problem in AMR systems, namely clustered simple polling (CSP) and neighbor relay polling (NRP). The performances of the AMR protocols were analyzed in simulation models. The network “clustering” concept introduced, where the meter units in a sub-network are divided into three-level clusters, namely, “Near”, “Medium” and “Far”, respective to their distance to the DC, increases the data collection success rate as cluster head meter units are physically closer to meter units in the next cluster, thus reducing the

effect of signal attenuation. This thesis aims to extend previously mentioned research work on the “hidden node” problem and focus on developing effective and efficient network protocols that meet the working conditions and requirements of automatic meter reading systems using narrowband or broadband PLC. The developed protocols must be relatively robust under the multipath effect and also noise interference, especially the impulsive noise interference. The performances of the developed protocols for smart grid application will be analyzed under impulsive noise interference to determine the theoretical competency of the developed protocols.

1.4 Objectives of This Research Work

In line with the above motivations, the primary objective of this research is to develop analytical models to analyze the performances of the two AMR network protocols introduced in [35] when they are subject to the signal attenuation suffered in PLC systems due to the multipath effect. The performances of the AMR network protocols in terms of data collection delay and throughput will be studied under impulsive noise interference. The effect of the access network topology on the performances of the two protocols will also be analyzed. The models will be used to study the optimum packet size and data rate to mitigate the effect of impulsive noise interference on the AMR system performance. The analytical models and performance analyses of the two AMR network protocols will be helpful in designing a robust and efficient network protocol for PLC-based AMR systems, determining the optimum packet size of the metering data, determining the optimum data rate of the PLC system and determining the optimum number of meter units in a typical impulsive noised PLC network.

The secondary objective is to design a new protocol that will overcome the limitations of PLC based AMR systems discussed earlier and develop generic analytical models to study their performances using narrowband or broadband PLC. The performance of the developed protocol in terms of data collection delay and throughput under impulsive noise interference will be analyzed and compared with that of the Neighbor Relay Polling (NRP) protocol to evaluate its effectiveness and efficiency. The research will also focus on finding the optimum cluster size and data rate to mitigate the effect of attenuation and impulsive noise interference on AMR system performance.

Finally, the third objective of the thesis is to study the theoretical competency of the developed protocol for smart grid application. The developed protocol will be used in the implementation of an AMI in the Intelligent Energy System pilot project at Nanyang Technological University, Singapore. Analytical models will be developed to study the performance of the proposed protocol and the overall AMI in terms of data collection delay and throughput under impulsive noise interference.

1.5 Contributions of This Research Work

The main contributions of this research are as follows:

- i. Generic analytical models is developed to study the performances of the two AMR network protocols introduced in [35] under impulsive noise interference. The generic models developed can be applied to study the performance of the AMR system employing CSP or NRP protocol in various network conditions, e.g., different cluster sizes or different numbers of sub-networks. The models also present analysis of two different topological structures, radial and tree, of the PLC access network. It was found that the NRP protocol performs better than the CSP protocol in terms of throughput but required longer data collection delay to cater for re-polling of failed meter units. It was also found that the AMR protocols based on narrowband PLC cannot perform well under heavy impulsive noise interference. A drop in throughput of almost 99% is observed for the network under heavy impulsive noise interference. The developed models and performance analyses are helpful in designing a new network protocol that addresses the shortcomings of the CSP and NRP protocols.
- ii. The research proposes a new and effective communication protocol for implementation of an AMR system using PLC and presents analytical models to study its performance. The performance of the proposed protocol in terms of data collection delay and throughput under impulsive noise interference is analyzed and compared with that of the NRP protocol. The proposed protocol does not require a central controller to initiate all data transmission unlike polling based protocols and can be applied to PLC systems with unstructured networks. The proposed protocol ensures significantly lower data collection delay than the NRP protocol. It will be able to achieve 100% throughput for light and moderate impulsive noise interference environments and 75% throughput for a heavy

- impulsive noise interference environment using broadband PLC with a cluster size larger than 60.
- iii. The research proposes a communication infrastructure for implementation of an AMI in the Intelligent Energy System pilot project at Nanyang Technological University, Singapore and presents analytical models to study its performance. The performance of the proposed AMI in terms of data collection delay and throughput under impulsive noise interference is analyzed. The proposed AMI completes the data collection of 1,250 meter units in less than 205 seconds. The proposed AMI achieves 100% throughput for $P_g > 0.5$ in an environment without impulsive noise interference. It is also able to achieve less than 5% drop in throughput for light and moderate impulsive noise interference environments.

1.6 Organization of This Thesis

This thesis consists of seven chapters as follows:

Chapter 1: Introduction

This chapter provides background information to power line communications and smart grid technology including its applications, advantages, challenges and recent developments. It also discusses the motivations, objectives and contributions of this research work, as well as the organization of this thesis.

Chapter 2: Literature Review

In this chapter, a review of previous research works on power line channels is presented. The ideology of AMR systems and the use of power line communications for AMR systems are also discussed. The signal attenuation due to the multipath effect and the noise interference over power line channel is reviewed.

Chapter 3: AMR System Model

The unfavorable multipath effect and noise interference introduced in Chapter 2 raise a number of challenges for PLC-based AMR systems. In order to develop a more robust network protocol to handle the multipath effect and noise interference, and to achieve better performance, the fundamental blocks of the AMR system need to be modeled. In this chapter, the analytical modeling of the “hidden node” problem, impulsive noise interference and PLC network topology is presented. The two AMR network protocols introduced in [35] are also discussed in detail in this chapter.

Chapter 4: Modeling and Performance Analysis of CSP and NRP Protocols

In this chapter, generic analytical models are developed to study the performances of the CSP and NRP protocols for AMR systems using narrowband or broadband PLC under impulsive noise interference environment. The effect of the access network topology on the performances of the two protocols is also analyzed. Optimal data rate and packet size for PLC-based AMR systems under impulsive noise interference are also discussed in this chapter.

Chapter 5: A New Routing Protocol for PLC-based AMR systems

A new and effective communication protocol which addresses the key limitation of polling-based AMR systems is introduced in this chapter. Analytical models are developed to study the performance of the proposed protocol in terms of data collection delay and throughput under impulsive noise interference. The optimum cluster size and data rate to mitigate the effect of attenuation and impulsive noise interference on the AMR system performance are evaluated.

Chapter 6: A PLC-WiMAX based AMI System for Smart Grid

In this chapter, a communication infrastructure for implementation of an AMI, utilizing PLC for last mile communication and Worldwide Interoperability for Microwave Access (WiMAX) for backhaul communication, in the Intelligent Energy System pilot project at Nanyang Technological University, Singapore is proposed. Analytical

models to study its performance in terms of data collection delay and throughput under impulsive noise interference are presented.

Chapter 7: Conclusions and Recommendations for Future Research.

An overall assessment of the research work is discussed in this chapter. Areas for further research are proposed as well.

CHAPTER 2 LITERATURE REVIEW

2.1 Power Line Communications

The idea of sending communication signals on the same pair of wires that are used to supply AC power is as old as the telegraph itself. An information signal with a frequency far above the mains frequency of 50 or 60 Hz is injected into the power supply network. The power supply network, however, was not designed to convey high frequency signals. Furthermore, the electrical and frequency response requirements of power lines are not as critical as data network cabling. Similar to wireless channel, power line channel suffers from noise, fading, multi-path and interference.

Many researches have been conducted to study the technologies and challenges of PLC. Most notably, [22] describes the PLC and the HomePlug 1.0 protocol with performance results from ideal laboratory measurements and actual field tests in residential buildings. It also reviews the various power line technologies and modulation techniques as well as the power line medium and its associated problems. The field test results showed that the power line network has full connectivity; however, varying channel characteristics such as the varying terminal impedances or the mismatch between the varieties of characteristic impedances with the terminal impedances cause different performance results. Furthermore, it also highlights the effect of transmission distance on the performance of PLC systems due to signal attenuation.

A comprehensive review of the sources of attenuation, noise and distortion encountered when communicating over AC power wiring is provided in [36]. It also examines various technologies which have been used to address these challenges, such as spread spectrum and digital signal processing. It concludes that digital signal processing is the key in overcoming the harsh conditions of the power line environment. It was also found that spread spectrum technology is detrimental rather than a benefit in overcoming these challenges.

Suitable and efficient medium access control (MAC) protocol is an important issue to consider for PLC systems as there are a possibly large number of access points, especially in the low-voltage or “last-mile” network, sharing the transmission capacity

of the PLC system. Design and performance evaluation of MAC protocols for PLC systems are presented in some research. An investigation on several polling based reservation MAC protocols for application in PLC access networks is presented in [37]. A two-step reservation procedure is introduced to improve the performance of polling based solutions. A fundamental review of various MAC protocols for PLC is provided in [38]. It proposes the use of reservation MAC protocols typically ALOHA random access to be applied to the PLC access networks. [39] presents analytical models to study Inhibit Sense Multiple Access (ISMA) MAC protocol for broadband PLC. It proposes a protocol that adaptively changes the packet length in order to minimize the effect of impulsive noise interference. A hybrid reservation-polling MAC protocol which is able to effectively deal with the PLC channel disturbances is proposed in [40]. The simulation results obtained shows that the system efficiency is virtually not affected by lightly to moderately disturbed PLC channels.

A comparative performance study of wireless and power line networks are discussed in [41]. It presents a practical and theoretical performance comparison of the 802.11 a/b and the Home-Plug 1.0 PLC protocol. It addresses the issues related to coverage, channel stability, reliability and capability to provide quality of service (QoS) support especially for multimedia services. From the field test results, it was found that PLC offers better coverage, greater link stability and provides higher data rate performance.

A trial PLC network and its deployment in Korea including the design and implementation of the PLC network management system are presented in [42]. Korea Electrotechnology Research Institute (KERI) deployed the PLC network using medium-voltage (MV) and LV power lines over a distance of approximately 5km. The PLC network provides services, such as broadband Internet, automatic metering and Voice over Internet Protocol (VoIP), to 20 household subscribers. The experience from the development of the PLC network indicates that Internet access and VoIP service through PLC is viable and as effective as the existing broadband Internet access technologies.

The challenge for PLC is to overcome the harsh and unpredictable characteristics of the power line environment. The key issues are: a) significant signal attenuation caused by

frequency-dependent cable losses and multipath signal propagation in the power line network and b) the effect of the noise generated in the power line network.

2.1.1 Signal Attenuation

As a PLC signal travels from the transmitter to the receiver, it suffers from attenuation caused by the characteristics of the power lines, reflection at the junctions of power lines due to the mismatch of impedances at the connections, and propagation delay between the multiple paths of the signal which can result in the cancellation of the signal or inter symbol interference (ISI). The signal attenuation due to reflection and propagation delay as well as the complex power line structure makes power line channels complicated and difficult to model. Despite its complexity, many research have been conducted to study and further develop the modulation and network protocols for PLC. Most notably [43] and [44] developed the multipath model for power line channels. The accuracy of their multipath model is verified by experiments and practical measurements. This model is widely accepted and used in the modeling and analysis of PLC [45]-[47].

The attenuation of signals transmitted through the power lines is closely related to the length of the dedicated path it takes to reach the receiver. The relationship between signal attenuation, length and frequency is given by

$$A(f, d) = e^{-(a_0 + a_1 f^k)d} \quad (2.1)$$

where f is the carrier frequency, d is the length of the dedicated path, a_0 and a_1 are the attenuation parameters, and k is the exponent of the attenuation factor (typical values are between 0.5 and 1). The parameters of a_0 , a_1 and k are related to the characteristics of the power line, which can be derived from the measured transfer function for the network [43].

When a transmitter sends a PLC signal through the power line channel, the signal reflects back and forth at the branches and cable junctions due to the mismatch in

impedances. The signal will then propagate along multiple paths to reach the receiver. Each path i that the signal takes has a weighting factor g_i which is the product of the reflection and transmission factors of the path. When the signal reaches a joint in the network, it faces parallel branches of the cables. The impedances of these parallel cables can be of lower impedance than that of the cable which the signal is coming through. In this case, the reflection and transmission factors at such joint of the power line are less than one. In the case where the impedances of the parallel cables are equal to that of the cable which the signal is coming through then the reflection and transmission factors are equal to one. Correspondingly, the weighting factor g_i of such path is less than or equal to one [43]. There could be infinite number of paths that a PLC signal eventually takes before it reaches the receiver because transitions and reflections occur throughout the path. These transitions and reflections make the attenuation for each path larger, therefore the signals transmitted in these highly attenuated paths contribute much less to the overall signal at the receiving end.

The propagation delay τ_i for the path i can be calculated from the dielectric constant ε of the insulation material of the power line, the speed of light c_0 and the length d_i of the path i , which can be represented as [43]

$$\tau_i = d_i \sqrt{\varepsilon} / c_0 \quad (2.2)$$

Figure 2.1 provides a simple illustration on the signal attenuation created by the multipath effect. The signal transmitted from the transmitter to the receiver is assumed to be a sine signal with a frequency f and amplitude A , and the signal can be represented as

$$s(t) = A \sin(2\pi ft) \quad (2.3)$$

Figure 2-1: An illustration on the signal attenuation created by the multipath effect.

The signal propagates through a power line with the speed c as determined by the characteristics of the power line [43]. Suppose there are two paths, a direct path and a second path, for the signal to propagate from the transmitter to the receiver. Due to the propagation delay, the signal that goes through the direct path with distance d_1 can be represented as

$$s_1(t) = A' \sin[2\pi f(t - d_1 / c)] \quad (2.4)$$

The delayed signal which goes through the second path with distance d_2 can be represented as

$$s_2(t) = A'' \sin[2\pi f(t - d_2 / c)] \quad (2.5)$$

The delayed signal lags behind the signal that takes the direct path by $d = d_2 - d_1$ over a time lag of d / c . If d / c is half of a sinusoid cycle $T = 1 / f$, the lagged signal is 180 degrees behind the direct path signal. This degree of lag brings about the cancellation of the two signals when they reach the receiver. This cancellation will greatly attenuate the signal with carrier frequency, f .

A typical PLC-based AMR system with an access link between a substation and a consumer consists of distribution cables and branching house connection cables. The house connection cables end at a house distribution box, followed by the indoor wiring. Numerous reflections are caused by the joints of house connection cables, house

distribution boxes, and the joints at series connections of cables with different characteristic impedances. Furthermore, signal propagation does not only take place along a direct path between the transmitter and the receiver, but additional paths (echoes) must also be considered. The result is a multipath scenario with frequency selective fading [43]. The overall attenuation suffered in PLC systems is typically categorized as the “hidden node” problem in PLC-based AMR systems where a meter unit cannot directly communicate with the base station to receive signals or send metering data which results in unreliable metering data acquisition and additional data collection delay. In this thesis, the hidden node problem is represented by a two-state transition Markov model.

2.1.2 Noise Interference

The performance of the PLC system is also affected by the noise and distortion characteristics of the power line channel. In contrast to other “well designed” communication channels, power lines do not represent additive white Gaussian noise (AWGN) channels. The noise scenario is rather complicated, as not only colored broadband noise, but also narrowband noise and different types of impulsive disturbance occur. This is especially because power lines were not designed specifically for communications. Furthermore, many types of electrical equipments are commonly connected to the residential and commercial power lines. These electrical equipments are likely to introduce various types of noises to the power lines. These noises are either in-band (within the signal frequency) or out-of-band (different from the signal frequency) noises. While the source of noise in power line communications is widely distributed, the noise scenario can be roughly separated into five classes [24], namely:

1) Colored background noise

Colored background noise is made of relatively low power spectral density that decreases with frequency. It is mainly caused by the superposition of many noise sources of lower power. Unlike white noise, which has a continuous and uniform spectral density independent of the signal frequency, the colored noise is strongly dependent on the signal frequency and varies over time.

2) Narrowband noise

Narrowband noise usually has a sinusoidal form with modulated amplitude. It is caused mainly by the ingress of broadcast stations over medium- and shortwave- broadcast bands. Its amplitude usually varies during the days and tends to be higher at night due to stronger reflection properties of the atmosphere.

3) Periodic impulsive noise interference asynchronous to the mains frequency

This kind of noise interference has a repetition rate of between 50 and 200kHz which has a discrete line spectrum space that varies according to the impulse repetition rate. It is mainly caused by the switching modes of the power supplies used in various types of electrical equipment. This noise interference occupies frequencies that are close to each other due to its repetition rate and therefore builds frequency bundles that are usually approximated by narrowband.

4) Periodic impulsive noise interference synchronous to the mains frequency

This kind of noise has a repetition rate of between 50 and 100Hz and is synchronous with the mains. It has a short duration and a power spectral density that decreases with frequency. It is primarily caused by power supplies operating synchronously with the mains frequency.

5) Asynchronous impulsive noise interference

Asynchronous impulsive noise interference, whose impulses are generally caused by switching transients in the power line network, have durations of several microseconds up to a few milliseconds with random inter-arrival time. The power spectrum density of asynchronous impulsive noise interference can reach values of more than 50dB above background noise.

Noise types 1, 2 and 3 usually remain stationary over long periods thus can be summarized into one noise class called “generalized background noise”. On the other hand, noise types 4 and 5 vary in time and can be summarized as one noise class called “impulsive noise interference”. The most common and detrimental noise source in PLC systems is the impulsive noise interference due to its relatively higher amplitude which is the main cause of burst error occurrence in digital communication over power lines. In references [48]-[52], modeling and analysis of the impulsive noise interference on power line communications has been conducted. All the results show that the impulsive noise interference considerably influences the quality and reliability of the PLC system.

The width, inter-arrival time and power of impulsive noise interference typically reach values which will very likely cause numerous bit or even burst errors in the transmitted data.

The typical impulsive noise interference wave is shown in Figure 2-2, where $A = \max(A_i^+, A_i^-)$ is the impulsive noise interference amplitude, t_w is the impulsive noise interference width or duration time, and t_d is the distance between impulsive noise interferences. The arrival time is expressed as $t_{arr,i}$. The distance between two impulsive noise interferences is the inter-arrival time t_{IAT} given as

$$t_{IAT} = t_w + t_d = t_{arr,i+1} - t_{arr,i} \quad (2.6)$$

Figure 2-2: Time-domain impulsive noise interference representation.

The impulsive noise interference in power line channel will definitely interfere with the performance of the AMR system. Theoretically, it will decrease the throughput of the AMR system because of the destroyed metering data packets due to bit or burst errors. It will also increase the average time required to perform overall meter data collection caused by the additional retransmission needed for the destroyed data packets. There are many researches done on the fundamentals of AMR systems using PLC as

discussed earlier. However, there are no significant researches on the effect of impulsive noise interference on the AMR system performance. This thesis aims to be the benchmark and reference to future researches on the effect of impulsive noise interference typically on AMR systems and PLC applications in general.

2.1.3 Modulation Techniques

Many research works have been conducted on modulation techniques to overcome the multipath effect and noise interference in order to improve the performance of PLC systems. Early PLC modulation techniques were based on signal carrier systems such as amplitude shift keying (ASK), phase shift keying (PSK) and quadrature amplitude modulation (QAM).

ASK represents digital data as variations in the amplitude of a carrier signal while keeping frequency and phase constant. The levels of amplitude relate to the number of levels adopted by the digital message. However, ASK is rarely used in PLC due to the high level of attenuation and the noisy power line channel which severely affect its performance.

PSK represents digital data as variations in the phase of a carrier signal while keeping amplitude and frequency constant. It includes binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and other levels of modulation. Among the variations, BPSK is the simplest single carrier modulation system. This form of modulation is illustrated in Figure 2-3.

Figure 2-3: BPSK single carrier modulation system.

Figure 2-3 shows a unique carrier signal with frequency $f_c = \frac{1}{T}$. The carrier signal is transmitted with a 0° phase shift and a 180° phase shift to represent data “1” and “0” respectively. The transmitted signal of the BPSK system can be described by

$$S(t) = A \sin(2\pi f_c t + d_i \pi) \quad (2.7)$$

where A is the amplitude of the sinusoid signal, and d_i are the bits of information to be transmitted. Various types of PSK systems hold the same unique carrier. The only difference among the systems is the type of phase variance used to transmit information.

In the case of QAM, data is transmitted by changing the amplitudes and phases of two sinusoid carriers that have the same frequency but are out of phase with each other by 90° and thus called quadrature carriers. The difference among the variations of QAM modulation is that they use different amplitude and phase variances to transmit data. Signal of the single carrier system is represented by a Sinc function with center frequency f_c , and bandwidth $BW = \frac{2}{T}$, as shown in Figure 2-4.

Figure 2-4: Spectrum of the single carrier modulation system.

Frequency shift keying (FSK) is a method of modulation that transmits data using two sinusoid carrier signals at different frequencies. It can be represented as

$$S(t) = A \sin(2\pi f_i t + \varphi) \quad (2.8)$$

where A is the amplitude of the carriers, φ is the phase of the carriers usually having a value either as 0° or 90° , and f_i ($i = 0, 1$) is the frequency of the two carriers. As shown in Figure 2-5, data “0” and “1” are transmitted on carrier signal with frequency f_0 and f_1 respectively.

Figure 2-5: FSK modulation.

The relationship between the two FSK frequencies needs to fulfill the orthogonal requirements as follows:

$$f_1 - f_0 = N \frac{1}{T} \quad (2.9)$$

where N is an integer larger than or equal to 1. In the frequency domain, the FSK signal spectrum is the two frequency tones of Sinc function centered at f_1 and f_0 respectively, as shown in Figure 2-6, where the two frequency distance is $\frac{1}{T}$. In order to ensure that the two carrier signals do not interfere with each other, the peak of one carrier signal is located at the zero of the other carrier signal.

Figure 2-6: Spectrum of FSK signal.

However, as simple FSK does not have enough noise immunity, several good modulation techniques have been derived by using multiple orthogonal carrier signals to transmit digital data. Among these, the most notable is introduced in [53]. This modulation technique uses four orthogonal frequencies and a transmission sequence. The four orthogonal carriers f_1 , f_2 , f_3 and f_4 , and the transmission sequence of $f_1 \rightarrow f_2 \rightarrow f_3 \rightarrow f_4$ represents two bits 00, $f_2 \rightarrow f_3 \rightarrow f_4 \rightarrow f_1$ represents 01, $f_3 \rightarrow f_4 \rightarrow f_1 \rightarrow f_2$ represents 10, and $f_4 \rightarrow f_1 \rightarrow f_2 \rightarrow f_3$ represents 11. This increases the noise immunity of the system and achieves greater performance as shown by the experimental results. Another modulation technique, called Chirp modulation introduced and detailed in [54] and [55], shows significant improvement on FSK noise immunity. The signal spectrums of these modulation techniques are similar to those of the simple FSK, except that these systems have spectrums consisting of multiple frequency tones instead of just two.

Due to the limitations of single carrier systems, the use of multiple carriers is a growing practice in PLC. The FSK-based modulation techniques achieve noise immunity by varying the carrier frequency over time such that multiple carrier signals are not transmitted simultaneously.

One widely used modulation technique in PLC systems is the Orthogonal Frequency Division Multiplexing (OFDM) technique which is a multi-carrier system that functions differently from the techniques introduced earlier. In an OFDM system,

multiple bits of information are modulated on all the sub-carriers within a symbol period and multiple sub-carriers are simultaneously transmitted. This difference can be clearly observed from Figure 2-7 (a), (b) and (c). In the figure, (a) is the BPSK signal where logic “1” is represented with a sine wave at 0° phase shift, and logic “0” is represented with a sine wave at 180° phase shift; (b) is the FSK signal where logic “1” is represented by a sine wave with frequency $3/T$, and logic “0” is represented by a sine wave with frequency $2/T$; and (c) is the OFDM signal with 32 carriers, each with BPSK modulation.

(a) Single carrier BPSK signal in the time-frequency domain.

(b) FSK signal in the time-frequency domain.

(c) OFDM signal in the time-frequency domain.

Figure 2-7: Comparison of the BPSK, FSK and OFDM system signals.

The fact that the OFDM system transmits multiple bits of information simultaneously gives it an important advantage over single carrier PSK and FSK systems. The OFDM system allows for the transmission of more bits of information if the symbol duration time T is the same. The system signals illustrated in Figure 2-7 indicate that the OFDM system is 32 times faster than the BPSK or FSK system. Furthermore, OFDM system can be seen to have a longer symbol time that provides higher resistance to inter symbol interference (ISI) caused by the multiple paths of transmission in power lines.

However, time and frequency synchronizations are two key problems which affect OFDM communication system, particularly in PLC systems. Time synchronization error in OFDM system leads to the inter symbol interference (ISI) problem while frequency synchronization error leads to inter-carrier interferences (ICI) [56]. Therefore, different techniques need to be applied to provide reliable synchronization between the power line communication devices. OFDM time synchronization method is divided into generally two categories: (i) based on circulation prefix method, which uses circulation prefix correlation characteristic to estimate time synchronization such as maximum likelihood estimation [57] and differences method [58], and (ii) based on pilot method where pilot symbol is thrust in transmission symbol [58].

Another type of modulation technique used in PLC is spread spectrum modulation which spreads the data across the entire available frequency band. Spread spectrum

technique is widely used in wireless digital communication specifically to overcome the jamming situation. Advantages of spread spectrum technique include inherent transmission security, resistance to interference from other systems, redundancy, and resistance to multipath and fading effects.

One of the most applied forms of spread spectrum technique is the direct sequence spread spectrum (DSSS) which modulates the data signal by a high rate pseudorandom sequence of phase modulated pulses before mixing the signal up to the carrier frequency of the transmission system. The transmitted signal $s(t)$ is given as

$$s(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t) b(t) c(t) \quad (2.10)$$

where the data signal $b(t)$ is defined as

$$b(t) = \sum_{n=-\infty}^{\infty} b[n] \prod_{T_b} (t - nT_b) \quad (2.11)$$

Besides DSSS, frequency hopping spread spectrum (FHSS) technique is also employed in PLC systems. In FHSS, the available band is divided into non-overlapping frequency “bins” and the data signal occupies one bin for a specific duration and hops to another bin afterward. FHSS can be categorized as either “fast-hop” or “slow-hop” based on whether the frequency hopping takes place at a rate higher or lower than the message bit rate. Due to practical difficulty in building coherent frequency synthesizers, modulation schemes such as M-ary FSK are usually employed for the data signals [59]. The data signal for M-ary FSK is given as

$$b(t) = \sqrt{2P} \cdot \sum_{n=-\infty}^{\infty} \prod_{T_b} (t - nT_b) \cos(2\pi f_n t + \phi_n) \quad (2.12)$$

The main advantage of spread spectrum technique is its electromagnetic compatibility. However, the main disadvantage of spread spectrum technique is the relative lower realizable bit rate compared to OFDM technique. OFDM technique also shows better

robustness against channel distortions, flexibility to avoid affected channels and optimum bandwidth utilization through bit-loading procedure.

2.1.4 Channel Coding Methods

Many researchers choose OFDM as the modulation technique for PLC systems [60 - 62]. OFDM can perform better than single carrier modulation in the presence of impulsive noise interference, because it spreads the effect of impulsive noise interference over multiple subcarriers. Similar to other communications systems, channel coding can improve the OFDM system performance. Channel coding is a technique used for controlling errors in data transmission over unreliable or noisy communication channels such as PLC. Forward error correction (FEC) is a widely used channel coding method which adds a certain amount of redundancy to the transmitted information that will be exploited by the receiver for transmission error correction due to channel distortion and noise. FEC methods such as block codes, convolution codes and turbo codes have been investigated for application within OFDM systems [56].

Figure 2-8 illustrates the general model of a block coded communication system [56]. In block code method, the original data is segmented into blocks of a fixed length k . A certain amount of parity bits are added to each block of the information vector U . The information bits and parity bits together form the codeword V of length n . This codeword is then submitted for modulation and transmission. At the receiving end, because the channel is usually subject to noise disturbance, the channel output may differ from the channel input. The demodulator performs an inverse operation and produces a received vector R which may be different from V . Upon receiving R , the decoder will first determine whether R contains transmission errors. If the presence of errors is detected, the decoder will either take action to locate the errors and correct them or request for a retransmission. Some of the commonly used block codes are Hamming codes, Golay codes, BCH codes, and Reed Solomon codes with non-binary symbols.

Figure 2-8: General model of a block coded communication system [56].

A convolution code is one of the most widely used channel codes in practical communications systems. As opposed to the block code, a convolution encoder does not separate the data streams into blocks. Convolution codes encode the data continuously via the trellis till the end of the data stream. A convolution code is a linear trellis code described by three integers, n , k , and K . A convolution encoder, at each clock cycle, takes one message symbol of k bits and produces one code symbol of n code bits. Integer k is the number of input bits and n is the number of output bits. Hence, the code rate is k/n . Typically, k and n are small integers of less than 5, with $k < n$. K is the constraint length which defines the number of A -tuple inputs in the shift register portion of the encoder. The encoded bits depend not only on the current k input bits but also on past input bits. Hence, the convolution encoder is a finite state machine. An example of convolution encoder is shown in Figure 2-9. In this convolution code, the outputs of the modulo-2 adders are sampled in succession to provide the output of the encoder.

Figure 2-9: Convolution encoder.

The decoding of the convolution code is much more difficult than encoding. The major methods available in the literature are maximum likelihood decoding, sequential decoding and threshold decoding as discussed in [63]. Maximum likelihood decoding is performed by the Viterbi algorithm and its implementation in PLC systems was investigated in [64]. All the three approaches differ in decoding complexity, delay and performance. A maximum a posteriori (MAP) decoding was also proposed and discussed as an alternative approach based on minimizing the probability of a message bit error [65].

Turbo coding introduced in [66] provides impressive results in coding long data frames that is approaching Shannon channel capacity limit. Turbo encoders are based on either Non-Recursive Convolutional (NRC) or Recursive Systematic Convolutional (RSC) encoders as illustrated in Figure 2-10. The NRC output is formed by linear combinations of the current and past values in a nonsystematic manner. The RSC encoder contains a systematic output and a feedback loop. The output stream is obtained by multiplexing a_i , $c_i^{(1)}$ and $c_i^{(2)}$ at each cycle i of the clock.

Figure 2-10: General structure of NRC and RSC encoders.

Interleaving is another common method in reducing the ‘burstiness’ of the channel error. It can be applied to single bit or symbol to a given number of bits. Interleaving is a procedure of shuffling source symbols across several code words before transmitting them over the physical medium, thereby creating a more uniform distribution of errors. The symbols are de-interleaved at the receiver side and if any error burst occurred during the data transmission, the subsequent erroneous symbols will be spread out over several code words. The operation of a simple interleaving strategy is shown in Figure 2-11.

Figure 2-11: Operation of a simple interleaving strategy.

2.1.5 PHY/MAC Cross-Layer Techniques

Protocol architectures that consider cross-layer interactions will be able to counter problems such as the poor performance of PLC links and dynamic networks environment. Most of the recent works in PLC consider OFDM systems because they allows separation of the overall transmitted data in several parallel independent subcarriers. The modern design methodologies of resource allocation are based on the demand assignment access control scheme [67]. Several multiple-access protocols pertaining to the demand assignment catalog have been proposed to implement flexible resource management strategies in order to cope with PLC channel impairments, including dynamic time division multiple access (D-TDMA), packet reservation multiple access (PRMA), carrier sense multiple access (CSMA) and its variants, and hybrid of TDMA and other promising multiple access schemes such as code division multiple access (CDMA). Considering that the employed modulation schemes at the transmitter end can be reconfigured on a burst-by-burst basis depending on the instantaneous perceived channel quality, leading to the investigation of exploiting a variable throughput MAC protocol that works closely with the underlying physical layer. The development of cross-layer designs involve several research areas such as signal processing, adaptive coding and modulation, channel modeling, traffic modeling, queuing theory, network protocol design and optimization techniques. In [68], a centralized MAC protocol, named non-collision packet reservation multiple access (NC-PRMA) introduced in [12] that can efficiently increases channel throughput, is adopted as the TDMA access architecture with adaptive OFDM transmissions for broadband PLC networks. Channel-aware scheduling strategies were proposed in [69] to adaptively transmit data and dynamically assign resources based on Channel State Information (CSI). The key idea in packet transmission is to choose users with better channel conditions in order to ensure a higher performance. An opportunistic CSMA protocol was introduced in [70] exploits the cyclo-stationarity of the noise in home PLC networks to improve the throughput of low-priority users while ensuring high throughput for Quality of Service (QoS) sensitive high priority users.

2.1.6 Smart Meter PHY Layer Characteristics

HomePlug is an industry alliance consisting of major industry players at every level of the value chain. HomePlug Alliance members bring necessary capabilities and a financial commitment to the successful launch of the PLC technology. HomePlug AV (HPAV) represents the next generation of technology from the HomePlug Powerline Alliance. Its purpose is to provide high-quality, multi-stream, entertainment oriented networking over existing AC wiring, while addressing interoperability with HomePlug 1.0. HPAV employs advanced PHY and MAC technologies that provide a 200 Mbps class power line network for video, audio and data. The PHY layer utilizes this 200 Mbps channel rate to provide a 150 Mbps information rate with robust, near-capacity communications over noisy power line channels [7]. The MAC layer is designed to be highly efficient, supporting both TDMA and CSMA based access with AC line cycle synchronization. The TDMA access provides QoS guarantees including guaranteed bandwidth reservation, high reliability and tight control of latency and jitter. The CSMA access provides four priority levels. AC line cycle synchronization provides superior channel adaptation in the face of common line cycle-synchronized noise. The central coordinator controls the activities of the network, allocating time for CSMA use and scheduling TDMA use.

The INT6400 chipset from Atheros is a third-generation HomePlug AV-based solution that delivers carrier-grade broadband communications over power lines. Many smart meters manufactures such as Grid Net uses the INT6400 chipset for their smart meters [71]. INT6400 technology enables fast, wired networking within a home using the home's existing electrical wiring and also in providing last-mile broadband access in multi-dwelling units. The INT6400 chip employs windowed OFDM modulation technique over a 2 – 30 MHz frequency band. Advanced turbo code is used as channel coding technique for forward error correction. The Atheros HPAV transceiver is optimized for multi-media streaming applications and is fully compliant with the HPAV standard to reliably deliver up to 200 Mbps PHY rate over power line.

2.2 Automatic Meter Reading (AMR) Systems

The rapid increase in power consumers and consumption in Singapore, has led to the establishment of the Energy Market Authority (EMA) which is intended to regulate the electricity and gas industries in Singapore. In [20], an insight on the growth and changes of the electricity market and metering trends in Singapore and how they shape each other is discussed. It reports that the demand for power has changed from reliability to quality and evolved the need to improve on metering, from collecting consumption to real-time power quality information as part of a complete energy management program. The high cost of about S\$55 million a year met by the utilities for the manpower intensive, manual meter reading and account-based billing has set a stage for the deployment of Automatic Meter Reading (AMR) technology.

AMR refers to the technology proposed to help utilities automatically collect the electricity meter readings and possibly send commands to the meters. AMR provides significant benefits to both the consumers and the utilities including reducing peak demand, supporting the time-of-use concept for billing, enabling consumers to make informed decisions regarding their energy usage, and reducing the cost of meter reading. The AMR system requires three basic components; 1) an electronic device that measures the amount of electrical energy supplied to the consumer and has an interface which allows data to be transmitted from the remote device to the central server, 2) a central server equipped with a system which includes receivers, data concentrators, modems, and computers that are able to store and process received information, and 3) a reliable and secure communication system to transmit data and to control the different signals between the remote device and the central server [72].

The AMR system requires the use of smart meters to enable transmission of power related information. The installation of the intelligent meter at consumer premises enables automatic reading, processing and feed back of consumption data. A smart meter has the following capabilities:

- a) Real-time or near-time measurement of electricity used and generated;
- b) Local and remote meter reading (on demand);
- c) Power quality measurement;

- d) Remote configuration of meter to connect and disconnect energy to certain consumers;
- e) Remote load management; and
- f) Outage notification.

In [73], the proposal to use smart meters by the United Kingdom government and its benefits is outlined. It states that besides eliminating the need to visit each house individually to read metering data and the need for estimated bills, smart meters will enable consumers to check their electricity consumption and cost at their convenience. This will create more energy conscious consumers as they can make informed choices on their daily energy consumption.

The most basic AMR system operates to collect and store consumer's consumption information. This is done in a sequence of transmitting a command to read the meter, receive and store the data at some central location. The system response time and the data throughput of the AMR system are shown to be highly dependent on the communication infrastructure and the operational characteristics of the system design [74]. The issues related to the deployment of AMR systems in terms of system architecture design, communication protocols and standardized modem development are discussed in [27], [28], [74], and [75].

In [76], the use of short- to mid-range wireless technology for AMR systems is introduced and discussed in detail. In fact, there are a few researches done on the use of wireless technology for AMR systems as in [77] and [78]. Even though, the wireless technology appears to be a technically feasible AMR model especially when the cost and the ease at which the wireless system can be installed and configured are important, the reliability of the wireless link, the capabilities of the wireless protocols, the ability to penetrate a wall in the garage or basement of a block of flats as well as the battery life of the wireless device also need to be carefully considered. The comparative performance study in terms of coverage, channel stability, and reliability of wireless and power line networks done in [41] shows that PLC network performs better than wireless network. It also emphasized that for nomadic users plugged into the power distribution system, PLC offers a robust, stable and speedy alternative compared to wireless system. This is typically the case for an AMR system where the meter units

are fixed to the power supply network. However, [20] and [79] discuss that PLC combined with wireless technology for AMR communication network could be the best solution to reduce the tariff price and enable service to more houses in India and Singapore.

The technical features and the available standards for PLC modems are discussed in [27]. It also proposes a combination of PLC network and data network such that every meter is connected to a PLC modem through RS232 data port. It suggests that a group of PLC modems, corresponding to meters under the same transformer, connect to a single concentrator which links the PLC network to the data network. The meters report their measurements when they are polled. The PLC modem buffers the frames until an acknowledgement (ACK) is received, or otherwise the frame is retransmitted. However, no evaluation of the system is provided.

The use of PLC for delivering the electricity, gas and water measurements to the utility providers is proposed in [80]. The system involves various devices and different communication technologies for water, gas, and electricity meters to transmit their measurements to a device called Home Concentration Unit (HCU). The HCU will then send the measurements to a device called Data Concentration Unit (DCU). The DCU eventually sends the aggregated metering data in Device Language Message Specification (DLMS) format via a PLC modem to the utility company. It only caters for one-way data transmission from the meters to the utility provider. Similarly, no evaluation or comparison with other system is provided.

The issues related to the commissioning of AMR systems based on PLC technology are discussed in [81]. These include design and construction issues such as multiple access method, channel coding method, topology and protocol of the communication channel. An advanced and innovated PLC AMR system for LV and MV lines of the distribution network are also proposed. The research also recommends solutions to tackle the constraints and difficulties faced by PLC systems typically on the collision and integrity of data transmission. There is, however, no simulation or analytical studies on the performance of the proposed system.

One key development of narrowband PLC for automatic metering infrastructure is the PoweRline Intelligent Metering Evolution (PRIME) system [82]. PRIME is a physical and MAC layer standard definition based on up-to-date technologies. PRIME operates on the CENELEC A band, which is defined in EN50065-1 and spans from 3 kHz to 95 kHz. The PRIME PHY layer, which is based on adaptively modulated Orthogonal Frequency Division Multiplexing (OFDM), along with forward error correction and data interleaving, is designed to transmit and receive metering data over power lines. Three different digital modulation schemes (BPSK, QPSK, 8PSK) and optionally a convolution code is adaptively used to transmit a total of 96 data subcarriers between 42 kHz and 89 kHz. The PRIME MAC layer employs CSMA/CA as the channel access scheme but also allows for contention free periods in every MAC frame. Frame synchronization is enabled by broadcasting of beacons from the base node and from various switch nodes within a tree-network. The MAC layer consist of an integral part called the repeating function for the purposes of scalability and range extension. PRIME uses flexible key management policies and 128 bit AES (advanced encryption standard) to provide privacy, authentication and data integrity. Some field test deployment of PRIME is reported in [83] and [84].

This thesis aims to provide in-depth performance studies through analytical modeling of protocols for PLC-based AMR systems and propose a new network protocol that can counter the challenges posed by PLC technology on AMR systems.

2.3 Medium Access Methods

All the devices on a communication network share the same physical medium. Techniques are required to prevent the devices from transmitting at the same time. These techniques are known as medium access methods or medium access control protocols, primarily designed to organize the access of multiple subscribers sharing the same transmission medium. The use of a suitable MAC protocol for a PLC-based AMR system is an important issue to consider. The access technology is necessary to ensure QoS control while providing good network utilization due to the possibly large number of meter units which share the transmission capacity. The organization of access in the downlink direction is easy as it is fully controlled by the base station. In this direction, only data packets from the base station are in transmission. However, in the uplink

direction, multiple subscribers have to compete for the access to the medium. Since all subscribers operate independently and can have data to transmit at any time, a MAC protocol will ensure avoidance of data collision and a fair network usage for all subscribers. There are three basic medium access methods, namely, polling, contention and token passing.

The polling system works based on the master-slave concept where the master station polls (sends a query to) each slave in the network individually to check whether it has data to transmit. If the particular subscriber has data to send, it is granted access to transmit its data. If that particular subscriber indicates that it has no data to send, the master station will move on and poll the next subscriber. The contention system, however, works opposite to the polling system. When a subscriber has data to send, it immediately transmits its data over the medium. MAC protocols developed based on carrier sense require transmitting subscribers to sense the carrier (listen to the medium) in order to ensure no other subscriber is transmitting before starting to transmit its data. It is possible for two subscribers to transmit at the same time when both sense the carrier at the same time and conclude that there is no other subscriber transmitting. This will result in collision. Latest generation of MAC protocols have introduced improvement to the carrier sense requirement by detecting collision and taking corrective actions. On the other hand, the token passing medium access method provides a fair transmission allocation for all subscribers in the network. It uses a token, in the form of a small frame of data, to grant the subscriber who holds the token the permission to transmit. When the subscriber has completed its data transmission, it releases the token and the next subscriber wanting to transmit acquires the token. The polling and contention systems represent total control and anarchy respectively while the token passing exists somewhere in the middle.

In general, many systems implemented with a central controller employ a general polling process as a centralized medium access method [21], [85]. The central controller sends a “polling message” to each node following a round-robin procedure or any other cyclic order. When a node receives the “polling message” and it has data to send back to the central controller, it can transmit immediately for a predefined time period. The node also transmits an ACK after it has sent out the last bit of the data stream to indicate end of transmission. If the node has no data to send upon receiving

the “polling message”, it just sends an ACK to inform that it has no data to send. Upon receipt of ACK, the central controller immediately polls the next node in the same cycle. If the central controller polls a node and does not hear anything from the node for a predefined time-out period, it polls the next node in the cycle. The two AMR protocols, clustered simple polling (CSP) and neighbor relay polling (NRP), introduced in [35] are developed on this basis.

In PLC-based AMR systems it is assume that, in every data collection cycle, each meter unit has metering data to be sent to the data concentrator (DC) or next nearest cluster relay meter and it does not need to send ACK to indicate completion of data transmission. Also that, the amount of metering data is comparatively small such that it can be included in one packet. The DC or the relay meter unit immediately polls the next meter unit after it receives the metering data from the currently polled meter unit or when no data is received within the time-out period.

CHAPTER 3 AMR SYSTEM MODEL

3.1 Meter Unit Model with Hidden Node Problem

One of the typical problems associated with PLC-based AMR systems is the “hidden node” problem. A “hidden node” is a meter unit which cannot directly receive signals from the DC or cannot directly send its metering data back to the DC. In this thesis, the “hidden node” problem arises not because of a meter’s malfunction but its inability to communicate with the data concentrator (DC) due to significant signal attenuation along cables, a noisy power line environment and varying in-home impedance in the PLC network. A meter unit can operate properly under favorable network conditions but becomes a “hidden node” when the network conditions worsen. A two-state Markov model is used to represent the status transition of a meter unit according to the network environment [86], [87], as shown in Figure 3-1.

Figure 3-1. Two-state transition Markov model for a meter unit.

In the two-state Markov model, the “Good” and “Bad” represent the two possible conditions of a meter unit. “Good” indicates that a meter unit can directly communicate with the DC or a relay meter unit whereas “Bad” indicates that the meter unit is currently a “hidden node”. P_g and P_b are the probabilities for a meter unit with “Good” and “Bad” status respectively in a specific network environment. P_{gg} and P_{gb} are the probabilities that a “Good” meter unit remains “Good” and changes to “Bad” as the network condition changes. Similarly, P_{bb} and P_{bg} are the probabilities that a “Bad” meter unit remains “Bad” and changes to “Good”. (3.1) - (3.3) represent the two-state probabilities quantitatively:

$$P_g + P_b = 1 \quad (3.1)$$

$$P_{gg} + P_{gb} = 1 \quad (3.2)$$

$$P_{bb} + P_{bg} = 1 \quad (3.3)$$

It is assumed that the period of time that a meter unit remains in “Good” or “Bad” state is one data collection cycle period [35]. In other words, status of a meter unit will not change during a data collection cycle. With regard to the network condition, however, a meter’s status may change after one data collection cycle according to the transition probability matrix P_T as denoted in (3.4). The transition probability matrix in (3.5) computes the probabilities P_{gg} , P_{gb} , P_{bb} and P_{bg} after n data collection cycles [86].

$$P_T = \begin{bmatrix} P_{bg} & P_{gb} \\ P_{bg} & P_{gb} \end{bmatrix} \quad (3.4)$$

$$P_T^{(n)} = \frac{1}{P_{gb} + P_{bg}} \begin{bmatrix} P_{bg} & P_{gb} \\ P_{bg} & P_{gb} \end{bmatrix} + \frac{(1 - P_{gb} - P_{bg})^n}{P_{gb} + P_{bg}} \begin{bmatrix} P_{gb} & -P_{gb} \\ -P_{bg} & P_{bg} \end{bmatrix} \quad (3.5)$$

By means of the transition probability matrix P_T and meter status probability matrix P ($P_g^{(n)}$ and $P_b^{(n)}$) for the n^{th} cycle, the $(n+1)^{\text{th}}$ cycle’s “Good” and “Bad” probabilities can be obtained from (3.6) [86].

$$P^{(n+1)} = P^{(n)} \times P_T^{(n)} \quad (3.6)$$

It can be seen that (3.5) is the sum of a constant matrix and one that decays to a null matrix exponentially. Thus, P_T reaches steady state depending on the initial state after a number of cycles where the Markov process is in equilibrium. This is defined as the local balance concept in [86] such that the probability flux from the “Good” state to the “Bad” state is equal to the probability flux from the “Bad” state to the “Good” state, as formulated in (3.7).

$$P_g P_{gb} = P_b P_{bg} \quad (3.7)$$

3.2 Impulsive Noise Interference Model

In a power line communications environment, impulsive noise interference is a major concern in network performance as it may cause bit or burst errors in the transmitted data signal. This is particularly critical in the deployment of AMR system as metering information is sent in data packets to the DC. Thus, the effects of impulsive noise interference need to be considered in the evaluation of the performances of the AMR protocols.

Impulsive noise interference is typically caused by a short duration disturbance or an event in the power line, such as the switching on/off of water heaters, washing machines, or air conditioners. A change in these appliances normally induces noise bursts in the frequency spectrum used for data transmission, ranging from a few hundred microseconds up to a few seconds [88]. Many technologies have been developed to counter the effects of impulsive noise interference on data transmission, typically categorized as retransmission mechanisms or forward error correction (FEC) mechanisms. In this thesis, only impulsive noise interference that causes uncorrectable error on the data packet will be modeled. It is assumed that the impulsive noise interference has enough amplitude and width to destroy the packet. The occurrence of impulsive noise interference during the period of packet transmission is shown in Figure 3-2. If the impulsive noise interference appears in the channel and overlaps in time with the data packet, the packet is considered to have been destroyed.

Figure 3-2: Impulsive noise interference during data transmission.

The arrival rate and power spectral density of impulsive noise interference were measured and modeled in [24] and results proved that the arrival of impulsive noise interference follows a Poisson distribution with a rate of λ' units per second. The occurrence of k arrivals in t seconds has the probability distribution

$$P_k(t) = e^{-\lambda't} (\lambda't)^k / k! \quad k = 0, 1, 2, \dots \quad (3.8)$$

The characteristics of the impulsive noise interference are described by two random variables, namely impulsive noise interference inter-arrival time t_{IAT} and impulsive noise interference duration time t_w . t_{IAT} is the reciprocal of the impulsive noise interference arrival rate λ' with an exponential distribution.

In order to evaluate the effect of impulsive noise interference, the two random variables, impulsive noise interference inter-arrival time and impulsive noise interference duration need to be defined. Most of the measurements show that both the inter-arrival time and noise duration always have exponential distribution, although their mean values depend on the locations where the measurements are made. For convenience of analysis, it is assumed that the impulsive noise interference within one period of data frame has enough amplitude and width to destroy the frame transmission. In reference [38], [40], three impulsive noise interference models are given to represent different PLC channel environments. The impulsive noise interference generation parameters are exponentially distributed, and are given in Table 3-1.

Table 3-1: Impulsive Noise Interference Parameters

Disturbance model	t_{IAT}	t_w
I: Lightly disturbed	1.903s	1.82ms
II: Moderately disturbed	0.476s	0.87ms
III: Heavily disturbed	0.015s	2.08ms

According to reference [24], the heavily disturbed scenario is the impulsive noise interference from “industrial area”, the moderately disturbed scenario is from

“residential area with detached and terraced houses” and the lightly disturbed scenario is from “apartment located in a large building in night time”.

3.3 PLC Access Network Model

The model for the PLC access network in this thesis is based on Housing Development Board (HDB) high-rise residential buildings of Singapore [35]. The residential buildings are supplied by a 3-phase 4-wire supply system as shown in Figure 3-3. Generally, about 300~600 meter units form one PLC access network, where the distance from the DC to the farthest meter unit in the network is less than 200 meters [1]. Each of the red, yellow and blue phases of the three-phase transformer is connected to the DC and sub-divided into many sub-networks as shown in Figure 3-4. These sub-networks connect every end user in the network to the DC. End users are represented as a meter unit that has power-related data for collection. For load balancing purposes, meter units in the same vicinity are connected to the three different phases of a distribution transformer.

Figure 3-3: 3-phase 4-wire supply system employed in Singapore.

Figure 3-4: PLC access network – “last mile” communication.

In a normal situation, a meter unit communicates directly with the DC to receive and send data, but this communication capability decreases with increasing distance between the meter unit and the DC. In a real situation, it is often found that for all the meter units connecting to the same DC it is possible that only a few meter units close to the DC can establish direct communication with the DC. This irregularity is because of the signal attenuation suffered in PLC networks with respect to cable length or transmission distance. Therefore, the common direct polling procedure where the DC directly polls and collects metering data from all the meter units in the sub-network may not prove to be an effective solution in the PLC-based AMR system because the data collection success rate may be adversely affected.

The PLC access network utilizing radial topological structure shown in Figure 3-5 exactly resembles the actual residential electrical power distribution network in Singapore [89]. It represents a more structured network deployment where power is tapped from a main power line connecting all other meter units in the sub-network. The three-level clustering concept applied to the radial sub-network groups all the meter

units into three clusters, namely “Near”, “Medium” and “Far” clusters, respective to their distance to the DC. In this thesis, one radial topological sub-network is represented by eight meter units in each “Near”, “Medium” and “Far” cluster.

Figure 3-5: Sub-network with radial topology.

Meanwhile, the access network in the tree topological structure shown in Figure 3-6 corresponds to a more unstructured network deployment such as that in rural areas. The clustering concept applied to this sub-network requires a combination of two three-level clustering mechanisms analogous to the branches of the tree, sub-dividing it into segments “A” and “B”. This concept can be further expanded to cater for more complex network structures. In this thesis, the tree topological sub-network is represented by 5 meter units in the “Near” cluster, 6 meter units in the “Medium A” cluster, 9 meter units in the “Medium B” cluster, 4 meter units in the “Far A” cluster, and 0 meter units in the “Far B” cluster.

Figure 3-6: Sub-network with tree topology.

In this clustered PLC access network model, meter units in the “Near” cluster can all directly communicate with the DC while the meter units in the “Medium” cluster need to communicate with the DC through some meter units in the “Near” cluster, as 1-hop relay. A similar procedure applies to the meter units in the “Far” cluster, in which it engages in 2-hop relay, one in “Medium” cluster and another in “Near” cluster for data transmission with the DC. In other words, metering data from the “Medium” cluster meter units are sent to a relay meter unit in the “Near” cluster and then to the DC. Similarly, metering data from a “Far” cluster meter unit are sent to a relay meter unit in the “Medium” cluster, subsequently to a relay meter unit in the “Near” cluster and finally to the DC.

Since successful data transmission in the three-level cluster model depends on the relays in order to transfer data to the next level or to the DC, it is important to insure that at least one meter unit in the “Near” or “Medium” cluster can communicate with the DC or “Near” cluster relay respectively. Therefore, cluster failure probabilities need

to be defined as the probability that there is no “Good” meter unit in a particular cluster during one data collection cycle. In this thesis, it is assumed that the probability of cluster failure depends on the probability for a meter unit with “Bad” status, the cluster size and the cluster failure probabilities of relay meter units. The “Near”, “Medium” and “Far” clusters are represented by subscripts 0, 1 and 2 respectively in the equations. The number of meter units in “Near”, “Medium” or “Far” clusters is denoted as n_0 , n_1 and n_2 respectively.

Let P_{NFail} be the probability of “Near” cluster failure, such that there is no one “Good” meter unit in the cluster.

$$P_{NFail} = (P_{b0})^{n_0} \quad (3.9)$$

The probability of “Medium” cluster failure P_{MFail} is given by the probability that the “Near” cluster has at least one “Good” meter unit and there is no “Good” meter unit in the “Medium” cluster.

$$P_{MFail} = (1 - P_{NFail})(P_{b1})^{n_1} \quad (3.10)$$

Similarly, the probability of “Far” cluster failure is given by the probability that the “Near” and “Medium” clusters have at least one “Good” meter unit to serve as relays and there is no “Good” meter unit in the “Far” cluster.

$$P_{FFail} = (1 - P_{NFail})(1 - P_{MFail})(P_{b2})^{n_2} \quad (3.11)$$

The probability that meter units in the “Far” cluster can be polled depends, however, on the probability that there is at least one “Good” meter unit in the “Near” and “Medium” clusters

$$P_{FPoll} = 1 - P_{NFail} - P_{MFail} \quad (3.12)$$

Similarly, the probability that all meter units in the sub-network can be polled is given by the probability that there are no cluster failures. Hence,

$$P_{AllPoll} = 1 - P_{NFail} - P_{MFail} - P_{FFail} \quad (3.13)$$

Equations (3.9) - (3.13) can be applied directly to the radial sub-network utilizing one three-level clustering mechanism but some modifications are needed for the tree sub-network as it utilizes a combination of two three-level clustering mechanisms. Since there is only one “Near” cluster in the tree sub-network, the “Near” cluster failure probability remains the same. Consequently, there are two mutually independent “Medium” level clusters in the sub-network. The data collection from meter units in the two “Medium” level clusters depends on the relay meter unit in the common “Near” level cluster. Therefore, the cluster failure probabilities of the two “Medium” level clusters depend on the “Near” cluster failure probability.

$$P_{M_AFail} = (1 - P_{NFail})(P_{b1_A})^{n_{1A}} \quad (3.14)$$

$$P_{M_BFail} = (1 - P_{NFail})(P_{b1_B})^{n_{1B}} \quad (3.15)$$

The “Far” cluster failure probability can be obtained for branch “A” by use of its “Medium” cluster failure probability.

$$P_{F_AFail} = (1 - P_{NFail})(1 - P_{M_AFail})(P_{b2_A})^{n_{2A}} \quad (3.16)$$

If there is any meter located further than the current last meter in branch “B”, the analytical model can be extended to include a “Far” cluster on branch “B”. Then, the “Far” cluster failure probability is defined as

$$P_{F_BFail} = (1 - P_{NFail})(1 - P_{M_BFail})(P_{b2_B})^{n_{2B}} \quad (3.17)$$

Similarly, the probability that meter units in the “Far” cluster can be polled is given as follows:

$$P_{F_APoll} = 1 - P_{NFail} - P_{M_AFail} \quad (3.18)$$

$$P_{F_B Poll} = 1 - P_{NFail} - P_{M_B Fail} \quad (3.19)$$

The probability that all meter units in the sub-network can be polled is given by the probability that there are no cluster failures.

$$P_{AllPoll_A} = 1 - P_{NFail} - P_{M_A Fail} - P_{F_A Fail} \quad (3.20)$$

$$P_{AllPoll_B} = 1 - P_{NFail} - P_{M_B Fail} - P_{F_B Fail} \quad (3.21)$$

3.4 Existing Network Protocols for Hidden Node Problem

In order to overcome the hidden node problem, a network “clustering” concept is introduced in AMR protocols [35], where the meter units in a sub-network are divided into three-level clusters, namely, “Near”, “Medium” and “Far”, respective to its distance to the DC. A few meter units which can directly communicate with the DC are assigned as cluster heads responsible for collecting metering data from all other meter units in another cluster. This method significantly increases the data collection success rate as cluster head meter units are physically closer to meter units in the next cluster, thus reducing the effect of signal attenuation.

3.4.1 Clustered Simple Polling (CSP) Protocol

The Clustered Simple Polling (CSP) protocol is the transformed version of the above reviewed general polling procedure into the *clustered* PLC access network. The clustering concept divides the PLC network into 3-level clusters, namely, “Near”, “Medium” and “Far”, respective to their distance to the DC. A few meter units which can directly communicate with the DC are assigned as cluster heads to be responsible for collecting metering data from all other meter units in adjacent clusters.

In the CSP protocol, each meter unit is polled only once during one data collection cycle. When a meter unit cannot receive a polling message from the DC/relay meter and/or send its metering data to the DC/relay meter due to “hidden node” problem, the

data collection of this particular meter unit is deemed as “failed” subject to a time-out period. Figure 3-7 shows the polling procedure for meter units in different clusters. In one data collection cycle, the DC first directly polls all the meter units in the “Near” cluster one by one. The metering data of “Good” meter units are received and stored in the database by the DC, while “Bad” meter units will be marked as “failed” after time-out period. Then, the DC will select one of the “Good” meter units in the “Near” cluster as a relay meter unit. The DC will then send a command to this relay meter unit, and the relay meter unit will poll one of the meter units in the “Medium” cluster and forward the metering data to the DC. After receiving metering data of the meter unit in the “Medium” cluster or waiting for a predefined time-out period, the DC will send another command to the relay meter unit to poll another meter unit in the “Medium” cluster. The procedure continues until all meter units in the “Medium” cluster have been polled. Similar procedure follows for meter units in the “Far” cluster where the DC selects one “Good” meter unit in the “Near” cluster as a first relay meter unit and one “Good” meter unit in the “Medium” cluster as a second relay meter unit. The DC sends a command to the first relay meter unit and the first relay meter unit sends a polling message to the second relay meter unit which then polls one of the meter units in the “Far” cluster. The procedure is repeated until all the meter units in the “Far” cluster have been polled.

Figure 3-7: 3-level cluster polling procedure.

3.4.2 Neighbor Relay Polling (NRP) Protocol

The first step for the Neighbor Relay Polling (NRP) protocol in every data collection cycle is to execute the CSP procedure. Upon completion, if any meter unit is marked as “failed” and if time permits (less than the data collection cycle), the DC or relay meter

unit will attempt to poll a “Good” neighbor of the “failed” meter unit to serve as an additional relay to transfer data to the DC/relay meter unit. A “Good” neighbor meter refers to a meter unit that belongs to the same cluster, located geographically near and connected to the same phase of the transformer as the “hidden node”. This ensures that the physical distance between the “Bad” meter and the “Good” neighbor is comparatively small so that the signal attenuation is minimized. Furthermore, since this “Good” neighbor meter unit has successfully sent its metering data to the DC or relay meter unit earlier during the CSP procedure, the good communication link between it and the DC or relay meter unit should be highly maintained within the same data collection cycle.

Therefore, in the NRP protocol, after the CSP procedure, if there are any “Bad” meter units (indicated as N_b in Figure 3-8) in the “Near” cluster, the DC will send a command message to one of the “Good” neighbor meter units (indicated as N_g in Figure 3-8) and the “Good” neighbor meter unit will poll that “Bad” meter unit to collect the metering data. This procedure repeats until all “Bad” meter units in the “Near” cluster have been polled. For “Bad” meter units in the “Medium” cluster, the DC will send a command message to one of the “Good” meter unit in the “Near” cluster and then that “Good” relay meter unit will send a polling message to one of the “Good” neighbor meter units in the “Medium” cluster. Finally, that “Good” neighbor meter unit will poll the “Bad” meter unit in the “Medium” cluster. This procedure repeats until all “Bad” meter units in the “Medium” cluster have been polled. Similar procedure is performed for the “Bad” meter units in the “Far” cluster.

Figure 3-8: “Bad” meter unit polling procedure using “Good” neighbor.

The NRP protocol assumes that the communication link between neighbors within the same cluster is 100% successful. Thus, an improvement to the data collection success rate is expected with the NRP protocol. However, the only restriction that may adversely affect the throughput of the NRP protocol is when the data collection time exceeds the pre-defined data collection cycle period. The polling process will be stopped immediately when this condition is met and all “Bad” meter units which have not been polled will not be able to send their data to the DC.

CHAPTER 4 MODELING AND PERFORMANCE ANALYSIS OF AUTOMATIC METER READING SYSTEMS USING PLC UNDER IMPULSIVE NOISE INTERFERENCE

4.1 Introduction

In this chapter, analytical models to study the performances of two protocols for automatic meter reading (AMR) systems using power line communication (PLC) access networks are presented. The two protocols, namely clustered simple polling (CSP) and neighbor relay polling (NRP), are shown to be typically effective and efficient AMR protocols for overcoming the “hidden node” problem associated with AMR systems. The performances of the AMR protocols in terms of data collection delay and throughput are studied under impulsive noise interference. This chapter also analyzes two different topological structures of the PLC access network, radial topology and tree topology, and compares the two topologies and their significance with the performances of the AMR protocols. Optimal data rate and packet size for the PLC-based AMR system under impulsive noise interference are also discussed.

4.2 Analytical Modeling of AMR Systems

The analytical models for the performance analysis of the AMR protocols utilize probability theory to derive the network traffic model and the throughput of the AMR protocols. The data collection delay is defined as the average time taken to poll and collect data from all the meter units in the sub-network within one data collection cycle. The command message sent by the DC to the relay meters is not considered in the delay analysis as the time taken to transit the command message is relatively small compared with the metering data packet transmission time. Message processing delay t_{proc} is defined as the time taken to process a message at the meter unit. The message processing delay at the DC can be ignored because the DC can process the metering data collected from a meter unit during the polling and data collection period for the

next meter. The data rate for the narrowband PLC access network is taken as 2.4kbps. Then, the one-way transmission delay for a packet is given by

$$t_{tx} = \text{Packet Size} / \text{Link Data Rate} \quad (4.1)$$

The time taken for polling and receiving metering data from one meter unit in the “Near” cluster involves one processing time plus two-way transmission delays. Meanwhile, for meter units in the “Medium” cluster, data are sent to the DC through a relay meter unit from the “Near” cluster, after the relay meter unit first sends a polling message. Thus, time taken includes two processing times and three-way transmission delays. Similarly, a meter unit in the “Far” cluster sends back its data to the DC through two relay meter units in “Near” and “Medium” clusters consuming four processing times and five-way transmission delays. In any cluster, however, if the meter unit happens to be a “hidden node”, the DC will wait for the associated predefined time-out period before polling the next meter unit. Equation (4.2) gives the delay for one meter's successful data collection and (4.3) gives the time-out period for different clusters. In this thesis, ℓ takes the value 0, 1 or 2 for “Near”, “Medium” and “Far” respectively.

$$t_{S\ell} = (2^\ell + 1)t_{tx} + (2^\ell)t_{proc} \quad (4.2)$$

$$t_{TO\ell} = (2^\ell) + 0.5 \quad (4.3)$$

The re-poll mechanism in the NRP involves a neighbor meter unit as an additional relay for data collection. The delay associated with one “hidden node” re-polling is given by

$$t_{RP\ell} = (2^\ell + 3)t_{tx} + [2(2^\ell) - \ell]t_{proc} \quad (4.4)$$

In a PLC environment under impulsive noise interference, successful polling and transmission of data occur when no impulsive noise interference appears during the data packet vulnerable time. The data packet vulnerable time is the duration time when the data packet is at risk of being destroyed by impulsive noise interference. The data

packet vulnerable times t' are given as in (4.5) and (4.6) for CSP and NRP protocols respectively.

$$t'_{CSP\ell} = t_{S\ell} + t_w \quad (4.5)$$

$$t'_{NRP\ell} = t_{RP\ell} + t_w \quad (4.6)$$

The probability that no impulsive noise interference occurs during the data packet vulnerable time is given by

$$P_{k=0,CSP\ell} = e^{-\lambda' t'_{CSP\ell}} \quad (4.7)$$

$$P_{k=0,NRP\ell} = e^{-\lambda' t'_{NRP\ell}} \quad (4.8)$$

Analytical models have been developed to analyze the data collection time and throughput of the two AMR protocols under impulsive noise interference on radial and tree topological networks. There are three possible outcomes for each CSP data collection procedure. First is the successful data collection which occurs when the meter unit is a “Good” meter unit and there is no impulsive noise interference occurrence during the data packet vulnerable time. The successful data collection delay for ℓ level cluster CSP procedure is given by

$$T_{S\ell} = P_{g\ell} \times P_{k=0,CSP\ell} \times t_{S\ell} \quad (4.9)$$

$P_{g\ell}$ is the probability for a meter unit with “Good” status where $\ell = 1, 2$ or 3 depending on the associated cluster level of the meter unit. Second is the unsuccessful data collection due to impulsive noise interference. This occurs when the meter unit is a “Good” meter unit but there is impulsive noise interference occurrence during the data packet vulnerable time. The data collection delay for the unsuccessful data collection due to impulsive noise interference for ℓ level cluster CSP procedure is given by

$$T_{F\ell} = P_{g\ell} \times (1 - P_{k=0, CSP\ell}) \times t'_{CSP\ell} \quad (4.10)$$

Third is the data collection polling failure associated with “hidden node” or, in other words, the polled meter unit is a “Bad” meter unit. The data collection of that particular meter is deemed to have failed after the DC waits a certain time-out period. The delay associated with the failed data collection is given by

$$T_{TO\ell} = P_{b\ell} \times t_{TO\ell} \quad (4.11)$$

The polling and data collection of meter units in each cluster can result in any of the outcomes described earlier. The total data collection delay for ℓ level cluster CSP procedure is given by

$$T_{CSP,\ell} = n_{\ell} \times (T_{S\ell} + T_{F\ell} + T_{TO\ell}) \quad (4.12)$$

In the event of “Near” cluster failure, polling and data collection of meter units in the “Medium” and “Far” clusters cannot be performed as there will be no “Good” meter unit in the “Near” cluster to serve as a relay meter unit and hence data collection stops. Therefore, the data collection delay only involves the time for polling and data collection of meter units in the “Near” cluster. Similarly, in the event of “Medium” cluster failure, polling and data collection of meter units in the “Far” cluster cannot be performed as there will be no “Good” meter unit in the “Medium” cluster to serve as a relay meter unit. Thus, the data collection delay includes the time for polling and data collection of meter units in the “Near” and “Medium” clusters only. Meanwhile, all meter units in the sub-network can be polled unless “Near” or “Medium” cluster failure occurs. In other words, regardless of whether “Far” cluster failure occurs, all meter units in the sub-network can be polled for data collection. This is represented by P_{FPoll} . Therefore, the data collection delay will include the time for polling and data collection of all the meter units in the “Near”, “Medium” and “Far” clusters. The CSP data collection delay for one sub-network in radial topology is given by

$$T_{CSP(R)} = P_{NFail} \times T_{CSP,0} + P_{MFai}(T_{CSP,0} + T_{CSP,1}) \\ + P_{FPol}(T_{CSP,0} + T_{CSP,1} + T_{CSP,2}) \quad (4.13)$$

The throughput of the CSP protocol only includes successful data collection where the meter unit is a “Good” meter unit and there is no impulsive noise interference during the data packet vulnerable time. Similarly to the derivation of the CSP data collection delay, the CSP throughput is determined from the events of “Near” cluster failure, “Medium” cluster failure and the probability that all meter units in the sub-network can be polled. The number of successful data collections for ℓ level cluster CSP procedure is given by

$$N_{S\ell} = n_{\ell} \times P_{g\ell} \times P_{k=0,CSP\ell} \quad (4.14)$$

Then, the CSP throughput for one sub-network in radial topology is given by

$$S_{CSP(R)} = P_{NFail}(N_{S0}) + P_{MFai}(N_{S0} + N_{S1}) \\ + P_{FPol}(N_{S0} + N_{S1} + N_{S2}) \quad (4.15)$$

For the NRP protocol, besides the initial CSP procedure, re-polling is done for the meter units whose metering data were not collected in the initial CSP procedure but were subject to the availability of “Good” neighbor relay meter units in the same cluster as the failed meter units. The data collection failures in the CSP procedure are due to the “hidden node” problem and impulsive noise interference. Thus, re-polling will be performed on “Bad” meter units and also on “Good” meter units which failed during CSP procedure due to impulsive noise interference. The re-polling procedure is also susceptible to impulsive noise interference. In this thesis, 100% communication success between neighbor meter units is assumed. Therefore, the re-polling and data collection are always assumed to be successful unless impulsive noise interference occurs during the data packet vulnerable time. The data collection delay for ℓ level cluster successful re-polling and data collection is given by

$$T_{RP,S\ell} = [P_{g\ell} \times (1 - P_{k=0,CSP\ell}) \times P_{k=0,NRP\ell} \times t_{RP\ell}] \\ + (P_{b\ell} \times P_{k=0,NRP\ell} \times t_{RP\ell}) \quad (4.16)$$

Then, the data collection delay for ℓ level cluster failed data collection due to impulsive noise interference during re-polling data packet vulnerable period is given by

$$T_{RP,F\ell} = [P_{g\ell} \times (1 - P_{k=0,CSP\ell}) \times (1 - P_{k=0,NRP\ell}) \times t'_{NRP\ell}] + [P_{b\ell} \times (1 - P_{k=0,NRP\ell}) \times t'_{NRP\ell}] \quad (4.17)$$

The total data collection delay for ℓ level cluster re-polling procedure is

$$T_{NRP,\ell} = n_{\ell} \times (T_{RP,S\ell} + T_{RP,F\ell}) \quad (4.18)$$

Since the re-polling of failed meter units requires at least one “Good” neighbor meter unit in the same cluster as the failed meter unit, re-polling cannot be performed on any “Near”, “Medium” and “Far” cluster failures. Consequently, in the event of “Near” cluster failure, no re-polling can be performed. For “Medium” cluster failure only re-polling of failed meter units in the “Near” cluster can be performed. Similarly, re-polling of failed meter units in the “Near” and “Medium” clusters can be performed in the event of “Far” cluster failure. Re-polling of all failed meter units in the sub-network is only performed when there is no cluster failure in the sub-network. The NRP data collection delay for one sub-network in radial topology is given as

$$T_{NRP(R)} = T_{CSP(R)} + P_{MFail} \times T_{NRP,0} + P_{FFail} (T_{NRP,0} + T_{NRP,1}) + P_{AllPoll} (T_{NRP,0} + T_{NRP,1} + T_{NRP,2}) \quad (4.19)$$

The throughput of the NRP protocol includes the CSP throughput and the successful re-poll data collection of failed meter units in each “Near”, “Medium” and “Far” cluster. Similarly to the derivation of NRP data collection delay, the NRP throughput is determined from the possible re-polling that can be performed subject to the availability of “Good” neighbor relay meter units. Even though 100% successful communication is assumed between neighbors, the throughput is affected by the occurrence of impulsive noise interference which causes the data collection of the particular meter unit to be unsuccessful. The number of successful data collections for the ℓ level cluster re-polling procedure is given as

$$N_{RP,S\ell} = n_{\ell} \times \left\{ \begin{aligned} &[P_{g\ell} \times (1 - P_{k=0,CSP\ell}) \times P_{k=0,NRP\ell}] \\ &+ [P_{b\ell} \times P_{k=0,NRP\ell}] \end{aligned} \right\} \quad (4.20)$$

Then, the NRP throughput for one sub-network in radial topology is

$$\begin{aligned} S_{NRP(R)} = & S_{CSP(R)} + P_{MFai}(N_{RP,S0}) \\ & + P_{FFai}(N_{RP,S0} + N_{RP,S1}) \\ & + P_{AllPol}(N_{RP,S0} + N_{RP,S1} + N_{RP,S2}) \end{aligned} \quad (4.21)$$

Meanwhile, in the tree topological structure, a combination of two three-level clustering mechanisms is required to group all the meter units in the sub-network. In this configuration, the DC will start polling and collecting metering data from meter units in the “Near” cluster, followed by meter units in the “Medium” and “Far” clusters on branch “A” of the tree. Once the “A” branch is completed, the DC then continues to the “B” branch by polling and collecting metering data from the meter units in the “Medium” cluster via a “Good” meter unit in the “Near” cluster. The analytical model for the tree network requires small revision to the data collection time and throughput equations developed for the radial network, as it requires two three-level clustering mechanisms compared with just one for the radial topology. In this thesis, “Medium” and “Far” clusters of branches “A” and “B” are represented by sub-subscripts “A” and “B” respectively. The data collection time and throughput for CSP given in (4.22) and (4.23) respectively include a “Far” cluster on “B” branch but the number of meter units in this cluster n_{2_B} is set to zero for the performance analysis.

$$\begin{aligned} T_{CSP(T)} = & P_{NFai}(T_{CSP,0}) + P_{M_AFai}(T_{CSP,0} + T_{CSP,1_A}) \\ & + P_{M_BFai}(T_{CSP,1_B}) \\ & + P_{F_APoll}(T_{CSP,0} + T_{CSP,1_A} + T_{CSP,2_A}) \\ & + P_{F_BPoll}(T_{CSP,1_B} + T_{CSP,2_B}) \end{aligned} \quad (4.22)$$

$$\begin{aligned} S_{CSP(T)} = & P_{NFai}(N_{S0}) + P_{M_AFai}(N_{S0} + N_{S1_A}) \\ & + P_{M_BFai}(N_{S1_B}) + P_{F_APoll}(N_{S0} + N_{S1_A} + N_{S2_A}) \\ & + P_{F_BPoll}(N_{S1_B} + N_{S2_B}) \end{aligned} \quad (4.23)$$

Similarly to the NRP data collection delay and throughput derivation for the radial network, the NRP data collection delay and throughput for the tree network require slight modification to the equations analogous to the mutually independent branches of the tree. For the tree network, a core branch needs to be selected to enable a standard derivation of the re-polling procedure. In this thesis, branch “A” is chosen to be the core branch and the DC completes all the polling and data collection on this branch before moving to another branch. Thus, the re-polling of “Near” cluster meter units is related to the branch “A” cluster failure probabilities. The NRP data collection delay and throughput are given in (4.24) and (4.25) respectively for one sub-network in tree topology.

$$\begin{aligned}
 T_{NRP(T)} = & T_{CSP(T)} + P_{M_A Fail} \times T_{NRP,0} \\
 & + P_{F_A Fail} (T_{NRP,0} + T_{NRP,1_A}) + P_{F_B Fail} (T_{NRP,1_B}) \\
 & + P_{AllPol_A} (T_{NRP,0} + T_{NRP,1_A} + T_{NRP,2_A}) \\
 & + P_{AllPol_B} (T_{NRP,1_B} + T_{NRP,2_B})
 \end{aligned} \tag{4.24}$$

$$\begin{aligned}
 S_{NRP(T)} = & S_{CSP(T)} + P_{M Fail} (N_{RP,S0}) \\
 & + P_{F_A Fail} (N_{RP,S0} + N_{RP,S1_A}) + P_{F_B Fail} (N_{RP,S1_B}) \\
 & + P_{AllPol_A} (N_{RP,S0} + N_{RP,S1_A} + N_{RP,S2_A}) \\
 & + P_{AllPol_B} (N_{RP,S1_B} + N_{RP,S2_B})
 \end{aligned} \tag{4.25}$$

4.3 Performance Analysis of AMR Systems

In order to verify the developed models, the analytical models are compared with simulation models. The discrete event simulation of the data collection process is performed using Microsoft Visual C++ integrated development environment. In the simulation, the data packet size is set to 24 bytes. The link data rate of 2.4kbps is used. The message processing time t_{proc} is set to 1 second and time-out periods of 1.5, 2.5 and 4.5 seconds for “Near”, “Medium” and “Far” clusters are used [28]. The simulated AMR network consists of 21 sub-networks, each with a total of 24 meter units. The radial topology-based sub-network equally groups 8 meter units in each “Near”, “Medium” and “Far” cluster. Meanwhile, the tree topological sub-network is assumed to group 5 meter units in the “Near” cluster, 6 meter units in the “Medium A” cluster, 9

meter units in the “Medium B” cluster, 4 meter units in the “Far A” cluster and 0 meter units in the “Far B” cluster to illustrate an unstructured network arrangement.

In order to better illustrate the impact of impulsive noise interference on the AMR system performance, analysis without impulsive noise interference are presented first. This is obtained by setting the impulsive noise interference inter-arrival time to zero. The analytical and simulation results for CSP and NRP protocols are presented in Figure 4-1 and Figure 4-2. It can be seen that the analytical results correspond well with those from the simulations, which verify that the analytical model is accurately developed. Also, it can be observed in Figure 4-1 that the CSP data collection delay does not differ much for $P_g > 0.4$ but for $P_g \leq 0.4$, the data collection delay decreases significantly due to increasing cluster failure which limits the polling procedure. This is because there are no “Good” relay meter units in an intermediate cluster to enable data collection from meter units in the subsequent cluster. Theoretically, this can be seen as the probability of cluster failure, given in (4.26), decreases with increasing P_g .

$$P_{ClusterFailure} = (1 - P_g)^{ClusterSize} \quad (4.26)$$

Figure 4-1: Data collection delay without impulsive noise interference.

It is also observed that, an average of 14.8% reduction on CSP data collection delay can be achieved using a tree topological network as compared to a radial topological network. The major factor for this reduction is again due to the cluster failure probability. It can be seen from (4.26) that cluster failure probability also decreases with increasing cluster size. Since the “Near” cluster size of the tree network is smaller than the radial network, it gives the tree network higher probability of “Near” cluster failure compared to the radial network, which eventually reduces the data collection delay for the tree network as more polling of “Medium” and “Far” cluster meter units cannot be performed for the tree network. Furthermore, the “Medium A” cluster in the tree network has smaller cluster size compared to the “Medium” cluster in the radial network, this also eventually reduces the data collection delay for the tree network compared to the radial network as more meter units in the “Far” cluster cannot be polled. The average reduction of the CSP data collection delay in the tree network is an aggregated effect of higher cluster failures in the “Near” and “Medium” clusters due to smaller size as well as reduction in number of meter units in the “Far” cluster that requires the highest data collection time.

The data collection delay for the NRP protocol is much higher than that of the CSP protocol because of the additional time required to perform re-polling for the “hidden nodes”. This accounts to about 63.6% and 57.9% additional re-polling time taken by the NRP protocol for the radial and tree network respectively. It is also observed that, NRP data collection delay reduces significantly for $P_g > 0.4$. This is because as the P_g increases, the number of re-polling performed by the NRP protocol reduces as there are lesser “hidden nodes” present in the network. An average of 18.9% reduction on NRP data collection delay is also observed for the tree network as compared to the radial network. As discussed earlier, this is also the effect of the cluster size on the cluster failure probability and smaller “Far” cluster size in the tree network. In addition, the reduction is also caused by the smaller cluster size in the “Near” and “Medium A” clusters in the tree network as it limits the availability of a “Good” neighbor meter unit located in the same cluster of the “hidden node”. This is especially obvious for smaller P_g values where more meter units becomes “hidden node”.

The throughputs of the CSP and NRP protocols for both the radial and tree networks are given in Figure 4-2. Throughout this thesis, the throughput is the normalized value

of the successful data collection against the total number of meter units in the network. It can be seen that, for both the CSP and NRP protocols, the radial network performs better than the tree network for $P_g < 0.6$ but the performances of the two topologies are approximately equal for $P_g \geq 0.6$. This is because for $P_g \geq 0.6$ the number of “hidden nodes” in a cluster and the probability of cluster failure are significantly small. This can be verified from Figure 4-3 where the number of meter units that could not send its metering data to the DC reduces linearly with increasing P_g . These failed meter units are re-polled in the NRP only if a “Good” neighbor meter unit can be polled by the DC. In other words, if a “Near” cluster fails, any meter unit in the “Medium” or “Far” cluster cannot be polled even if it is a “Good” meter. This is why the NRP cannot achieve 100% throughput even though 100% communication success with neighbors is assumed. Throughput of 100% is only achievable when there are no cluster failures in the network. The NRP protocol achieves throughput of almost 100% for $P_g \geq 0.6$. This can be seen in Figure 4-3 where the probability of cluster failure is near zero for $P_g \geq 0.6$. This is when almost all “hidden nodes” can be re-polled successfully. However, it is noted that the analysis of different topology structures on the performances of the CSP and NRP protocols hold true only for the radial and tree topologies described in Chapter 3. Different cluster size or topology may yield different observation.

Figure 4-2: Throughput without impulsive noise interference.

Figure 4-3: Number of meter unit failure and cluster failure probability.

Next, the performances of the AMR protocols are analyzed in three impulsive noise interference models: lightly disturbed, moderately disturbed and heavily disturbed, as given in [32], [34]. Table 4-1 describes for each disturbance model the mean inter-arrival time t_{IAT} between two impulsive noise interferences and the mean duration of the impulsive noise interference t_w .

Table 4-1: Parameters of Impulsive Noise Interference

Interference model	t_{IAT}	t_w
I: Lightly disturbed	1.903s	1.82ms
II: Moderately disturbed	0.476s	0.87ms
III: Heavily disturbed	0.015s	2.08ms

The data collection delay and throughput for CSP are shown in Figure 4-4. For verification of the accuracy of the developed model, the analytical and simulation

results of the lightly disturbed model are given for the delay and throughput of CSP and NRP protocols. For the moderately and heavily disturbed models, only analytical results are given for the purpose of comparing the effect of impulsive noise interference on the performances of the CSP and NRP protocols based on radial as well as tree network topologies.

It can be seen that the analytical results correspond well with those from simulations, which verifies that the analytical model has been accurately developed. The impulsive noise interference occurrence in the power line environment does not affect the CSP data collection time, as can be seen from Figure 4-4(a). This is because the additional time due to the small duration impulsive noise interference t_w in the scale of milliseconds is not significant compared with the data transmission time. The throughput of the CSP is, however, affected by the impulsive noise interference as the number of failed meters is increased. This is because, even though a particular meter unit can establish “Good” communication with the DC or relay meter unit, it may not be able to send its metering data correctly as bit or burst error could occur during data transmission due to impulsive noise interference. This can be seen in Figure 4-4(b) as there are significant drops in the throughput of the CSP for radial topology, typically an average of 13%, 41.6% and 99.5% for lightly, moderately and heavily disturbed models respectively as compared with those without impulsive noise interference.

(a) Data collection delay

(b) Throughput

Figure 4-4: CSP throughput for radial and tree topological networks.

It can also be seen that the tree topology performs slightly better than the radial topology for $P_g > 0.5$, with an average drop of 12.3%, 40% and 99.6% for lightly, moderately and heavily disturbed models respectively. The reduction in throughput under impulsive noise interference is quite significant and corresponds to the probability that there are one or more impulsive noise interference occurrences during one meter unit's data transmission period. Table 4-2 reports the "Near", "Medium" and "Far" cluster failures for the three disturbance models under radial and tree topologies due to one or more impulsive noise interference occurrences during metering data transmission. These are obtained by multiplying the probability of one or more impulsive noise interference occurrences by the number of meter units in that particular cluster. It is clearly shown that the reduction in throughput is caused by the occurrence of impulsive noise interference during data transmission. It can also be concluded that the CSP protocol does not perform well in moderately and heavily disturbed impulsive noise interference environments with at least 40% to almost 99% reduction in throughput.

Table 4-2: CSP Data Collection Failure due to Impulsive Noise Interference

Network Scenario	Near	Medium	Far	Failure (%)
1: Radial – Model I	0.6522	0.95467	1.5228	13.04
2: Radial – Model II	2.2942	3.1769	4.5537	41.77
3: Radial – Model III	7.7444	7.9536	7.9985	98.74
4: Tree – Model I	0.4076	1.79	0.7614	12.33
5: Tree – Model II	1.4337	5.9567	2.2769	40.28
6: Tree – Model III	4.8403	14.913	3.9992	98.97

The NRP data collection delay and throughput are shown in Figure 4-5. It can be seen that the analytical results correspond well with the simulation results, which verify the accuracy of the developed model.

(a) Data collection delay

(b) Throughput

Figure 4-5: Performances of NRP protocol for radial and tree topological networks.

As expected, the NRP data collection delays shown in Figure 4-5(a) increase with the increasing impulsive noise interference. This is because the number of failed meter units increases with increasing impulsive noise interference, hence requiring more delay to perform re-polling. Average increases of 7.3%, 22.6% and 48.3% are recorded for the radial topology NRP delay in the lightly, moderately and heavily disturbed models respectively. The average increases of the NRP delay recorded for the tree topology are 6.7%, 21.6% and 46.7% in the lightly, moderately and heavily disturbed models respectively. Even though the average increase of the NRP delay should correspond to the average reduction of the CSP throughput as the failed meter units in the CSP are re-pollled by the NRP, it can be seen that the average increase in the NRP delay does not accurately match the average reduction of the CSP throughput. This is because the NRP re-poll meter units identified as failed whose metering data have not been stored. Therefore, when impulsive noise interference corrupts a data packet sent from a particular “Good” meter unit, the DC discards the data packet and identifies the meter unit as failed. This actually increases the possibility of cluster failure and hence more meter units cannot be re-pollled, as NRP requires a “Good” neighbor relay meter unit within the cluster of the failed meter unit. This eventually limits the NRP throughput, as shown in Figure 4-5(b). It can be seen that the average NRP throughput decreases with increasing impulsive noise interference, typically at 10.5%, 39.9%, and 99.7% for radial topology and 9.7%, 37.8%, and 99.8% for tree topology, under lightly, moderately and heavily disturbed models respectively. It can also be seen that, for $P_g > 0.6$, the NRP throughput of the tree topology performs slightly better than the radial topology because, at $P_g > 0.6$, the cluster failure probabilities and number of failed meter units are almost equal for the radial and tree topologies, as shown in Figure 4-6, but the slight advantage is that the tree topology has a smaller number of meter units in the “Far” cluster that may fail during re-polling due to impulsive noise interference. This is because meter units in the “Far” cluster require longer transmission time and hence are more susceptible to impulsive noise interference.

Figure 4-6: Number of meter unit failures and cluster failure probabilities.

4.4 Throughput Optimization

Since there are different scenarios of impulsive noise interference that have different effects on PLC-based AMR systems, it is desirable to find the optimal data rate and packet size for the AMR system. The throughputs of the CSP and NRP protocols for varying data rate and packet size are shown in Figure 4-7.

It can be clearly seen that the throughput for both protocols is greatly affected by the packet size, while changing the data rate does not change the throughput significantly. Hence, packet size will be the most important parameter to be considered for obtaining a high throughput AMR system. The data rates provided by PLC systems are limited because of the electromagnetic compatibility (EMC) requirements. Therefore, available PLC systems have maximum net data rates of 2 to 4 Mbps [1]. On the other hand, packet size depends on the amount of information that needs to be collected. A simple AMR system that only collects metering data without any concern for data security and improving data reliability requires small packet size of about $(7 + N)$ bytes, where N is the number of data bytes [18]. Since most domestic energy meters have a maximum reading of 99,999.9 kWh, if each digit is represented by a byte, the required data bytes

will be 6 bytes. Therefore, the minimum packet size for a simple AMR system is 13 bytes. The throughputs of the CSP and NRP protocols utilizing a data rate of 4Mbps and a packet size of 13 bytes are shown in Figure 4-8.

(a) CSP throughput for $P_g = 0.5$

(b) NRP throughput for $P_g = 0.5$

Figure 4-7: CSP and NRP throughputs with varying data rate and packet size.

(a) CSP throughput

(b) NRP throughput

Figure 4-8: CSP and NRP throughputs with fixed data rate and packet size.

The throughputs of the CSP and NRP protocols are significantly improved, especially for moderate and heavy impulsive noise interference models. It can be seen that, by utilizing smaller packet size, the NRP protocol can achieve 100% throughput for $P_g > 0.7$ under heavy impulsive noise interference. This is because smaller packet size will reduce the data packet's vulnerable time to impulsive noise interference and hence reduce the effect of impulsive noise interference on the AMR system.

4.5 Concluding Remarks

In this chapter, analytical models were developed to study the performances in terms of data collection delay and throughput of two AMR protocols, namely clustered simple polling (CSP) and neighbor relay polling (NRP). The models developed were verified by comparing the analytical results with those obtained from simulations. The generic models developed can be applied to study the performance of the AMR system employing CSP or NRP protocol in various network conditions, e.g., different cluster sizes or numbers of sub-networks. The performances of the two protocols were analyzed under impulsive noise interference based on radial and tree topological network structures. It was found that the NRP protocol performed better than the CSP protocol in terms of throughput but required longer data collection delay to cater for re-polling of failed meter units. It was also found that the tree topological network structure performed better than the radial topology for $P_g > 0.6$. The CSP and NRP protocols did not perform well under heavy impulsive noise interference, resulting in a drop of up to 99.8% in successful metering data collection. It was observed, however, that high throughput can be achieved for moderate and heavy impulsive noise interference environments by reduction of the packet size of the AMR system. Therefore, the use of smaller packet size or partitioning of larger data packets into smaller packets before transmission will significantly mitigate the effect of impulsive noise interference on the AMR system performance.

The analytical models of the AMR system developed in this chapter will be useful in understanding the shortcomings of the existing protocols and will form a foundation in developing a new improved network protocol for PLC-based AMR systems.

CHAPTER 5 A NEW ROUTING PROTOCOL FOR PLC-BASED AMR SYSTEMS

5.1 Introduction

This chapter proposes a new and effective communication protocol for implementation of an automatic meter reading (AMR) system using power line communications and presents analytical models to study its performance. The proposed protocol utilizes a novel packet routing system which combines “Request” and “Data” packets that enable meter units to send their metering data to the DC and at the same time re-broadcast the “Request” to other meter units. It employs a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) medium access control protocol for the contention-based data transmission. The performance of the proposed protocol in terms of data collection delay and throughput under impulsive noise interference is analyzed and compared with that of the Neighbor Relay Polling (NRP) protocol.

5.2 A Simple Routing Protocol

Initially, a simulation model was developed to evaluate the performance of a new and simple communication protocol for implementation in PLC-based AMR systems. The simple routing protocol uses an unconventional protocol system which combines “Request” and “Data” packet in one single packet as shown in Figure 5-1. Meter units send its metering data to the DC and at the same time re-broadcast the “Request” to other meter units.

Mode	Source Address	Destination Address	Request (Level)	Data
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Figure 5-1: Combined “Request” and “Data” packet.

The packet consists of a request flag that counts the packet’s depth level in the network hence giving the flexibility to stop broadcasting “Request” at the desired hop level. The

request flag also insures that meter units which have sent their data to the DC will not process the packet again. At the start of each data collection cycle, all meter units in the network will initialize their hop number (h) to 3 so that the “Request” broadcast will stop after 3 hops. The DC will start the data collection cycle by broadcasting (packet sent in broadcast (Br) mode) a “Request” packet (with request flag set to zero) to all meter units under its network. This broadcast packet, however, will be received by only a few meter units close to the DC due to the signal attenuation mentioned earlier. These Level 1 (L1) meter units in each sub-network, process the “Request” packet and re-broadcast the “Request” packet together with their metering data. The request flag on the outgoing packet is increased to 1 and the meter unit’s hop number is set equal to the request flag. These L1 packets will be received by the DC as well as “Good” meter units in level 2. Once DC receives the L1 packets, the metering data of the L1 meter units are recorded into the database. Concurrently, Level 2 (L2) “Good” meter units that received the L1 packet recognize the packet as a “Request” packet as the meter unit’s hop number is larger than the request flag in the incoming packet. The meter unit will then process the “Request” and re-broadcast the L1 packet together with its metering data while increasing the request flag and setting its hop number equal to the request flag. These L2 packets will be received by L1 meter units and meter units in level 3. Since the hop number of L1 meters will be smaller than the request flag of the incoming packet, it will re-transmit the packet according to the destination address in the packet. Level 3 (L3) meter units that received the L2 packets recognize the packet as a “Request” packet since the meter unit’s hop number is larger than the request flag in the incoming packet. It will process the “Request” and re-broadcast the L2 packet together with its metering data. The request flag will be increased to 3 and the meter unit’s hop number will be set to 3. These L3 packets will be received by L2 meter units which re-transmit the packets to L1 meter units and finally to the DC. Any meter unit that receives L3 packets will not recognize the packet as a “Request” packet because all meter units hop number was initialized to 3 at the start of data collection cycle. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol is employed in this protocol.

At the start of data collection, the DC broadcast a “Request” packet to all level 1 meter units. It is assumed that all “Good” level 1 meter unit process and start re-broadcast of L1 packets simultaneously. All meter units will start transmission at the same time

resulting in collision and all the meter units will immediately cease transmission and acquire a random number in multiple of the transmission time before attempting to transmit again. Due to a large window size of the random number, it is assumed that no meter units will have the same random back-off time. It is also assumed that only after the last meter unit in level 1 has completed its packet transmission, the level 2 meter units will start transmission. Meter units in level 2 will transmit their metering data to level 1 meter units and rebroadcast the “Request” packet to level 3 meter units. The last level 2 meter unit will transmit after the longest random back-off period. After the last level 2 meter unit has completed its transmission, level 1 meter units will re-transmit the level 2 meter unit’s data packet to the DC. Again, the last level 1 meter unit to re-transmit level 2 data packet to the DC will have the longest random back-off period. Finally, level 3 meter units will process the “Request” packet and broadcast their metering data to level 2 meter units, followed by level 2 meter units which re-transmit level 3 data packet to level 1 meter units and finally from level 1 meter units to the DC. The data collection delay is deduced from the longest random back-off period in each transmission level. This will cater for the worst case scenario of the AMR system.

The AMR packet creation and transmission using 3-hop broadcasting method is shown in Figure 5-2. The packet is created at each level and broadcast to the higher level for metering data transmission to the DC as well as to lower level as a metering data “Request” packet.

Figure 5-2: Packet creation and transmission using 3-hop broadcasting method.

The performance of the protocol was evaluated and compared with the CSP protocol. The data collection delay and throughput are obtained based on the network traffic model. In the simulation, the data packet size is set to 24 bytes. It is assumed that the metering data in each meter unit is ready when the meter unit receives the “Request” packet. The simulated AMR network consists of 21 sub-networks, each with a total of 24 meter units. The number of meter units in each level of the sub-networks is randomly assigned to illustrate an unstructured network configuration. The results are obtained based on a 1 year data collection period which is equal to 17,520 data collection cycles (1,800 seconds per cycle).

The performance of the AMR routing protocol is evaluated in terms of throughput and data collection delay. The throughput indicates the portion of meter units, whose metering data can be successfully collected by the DC within one data collection cycle of 1,800 seconds. The data collection delay indicates the maximum time taken to collect data from all meter units in one data collection cycle.

Figure 5-3 shows the throughputs of the routing and CSP protocols. The throughput or data collection success rate of the routing and CSP protocols increases linearly with P_g . In comparison, the proposed routing protocol performs similar to the CSP protocol in terms of throughput. This is because both the routing and CSP protocols are only able to collect metering data from “Good” meter units in the network which correspond to P_g . The metering data of “Bad” meter units or hidden nodes are not collected. In the proposed routing protocol, only “Good” meter units in each level of the sub-network respond to the metering data “Request” packet sent by the DC or higher level meter units.

Figure 5-3: Throughput of the proposed routing and CSP protocols.

The data collection delays of the routing and CSP protocols are shown in Figure 5-4. It can be seen that the proposed routing protocol performs significantly better than the CSP protocol with almost 200% reduction in data collection delay. This large improvement is due to the contention based approach employed in the proposed routing protocol as compared to time consuming polling based approach employed in CSP protocol. In the CSP protocol, the DC polls and collects the metering data of each meter unit in the network. This also applies to “Bad” meter units where the DC has to wait a predefined time-out period before polling the next meter unit. In the proposed routing protocol, however, the “Request” packet broadcasting method and the dual purpose packet transmission, which enable a particular meter unit to send its metering data to the DC as well as re-broadcast metering data “Request” packet to lower level meter units, insure shorter data collection time.

Figure 5-4: Data collection delay of the proposed routing and CSP protocols.

Through this research it is concluded that the new protocol achieves similar throughput as compared to the CSP protocol which is based on polling and clustering mechanism for metering data collection. The contention based protocol, however, shows a significant improvement in the data collection delay with almost 200% reduction. This reduction in data collection delay greatly improves the efficiency of the AMR system. However, improvement of the AMR throughput while maintaining acceptable data collection delay must be addressed in order to achieve a truly efficient AMR protocol. A hybrid contention-polling based protocol which enables polling of failed meter units is then proposed.

5.3 A Hybrid Contention-Polling Protocol

The hybrid contention-polling protocol involves two data collection phases. The first phase of the protocol on contention-based data collection with an innovative packet transmission system (as discussed in Section 5.2) is expected to improve the data collection delay by replacing the time consuming one-to-one polling with a contention period for data transmission. The throughput, however, can be further improved by

introducing a hybrid polling protocol which incorporates polling mechanism into the purely contention-based routing protocol. The second phase polling procedure (packet sent in polling (P) mode) is activated after the completion of the contention-based routing protocol in order to specifically poll and collect the metering data of failed meter units which were not collected in the contention period. Since the failed meter units are caused by the “hidden node” problem, the polling and data collection of failed meter units are performed by the DC through a “Good” neighbor meter unit whose metering data was successfully collected during the contention period. Similar to the NRP protocol, the neighbor meter unit refers to a meter unit that belongs to the same cluster and phase of the transformer as the “hidden node” to ensure minimal signal attenuation during data transmission.

The polling procedure involves a neighbor meter unit as an additional relay for data collection. The time taken for polling and receiving metering data from one failed meter unit in level 1 involves two processing time plus four transmission delays. Meanwhile, for failed meter units in level 2, data are sent to the DC through a relay meter unit from level 1, after the relay meter unit first sends a polling message. Thus, time taken includes three processing times and six transmission delays. Similarly, failed meter units in level 3 send back their metering data to the DC through a neighbor meter unit via two relay meter units in levels 1 and 2 consuming four processing times and eight transmission delays. In this research, it is assumed that the communication between neighbors within the same cluster is 100% successful.

A simulation model is developed to evaluate the performance of the proposed hybrid contention-polling protocol and to compare its performance with the NRP protocol. In the simulation, the data packet size is set to 24 bytes. It is assumed that the metering data in each meter unit is ready when the meter unit receives the “Request” packet. The performance analysis is performed on structured (network which exactly resembles the Housing Development Board (HDB) high-rise residential electrical power distribution network in Singapore) and unstructured (network built upon random combination of network topologies including radial and tree topologies) PLC access network models. The simulated AMR network consists of 21 sub-networks, each with a total of 24 meter units. The structured network equally groups 8 meter units in each level 1, 2 and 3 cluster. Meanwhile, the unstructured network randomly assigns a number of meter units

in each cluster of the sub-network extending to a tree topology to illustrate an unstructured network configuration. The results are obtained based on one year data collection period which is equal to 17,520 data collection cycles.

The data collection delay of the hybrid contention-polling and NRP protocols for both structured and unstructured networks are shown in Figure 5-5(a). It can be seen that the hybrid protocol performs significantly better than the NRP protocol with an average reduction of 57% and 55% in data collection delay for structured and unstructured networks respectively. This large improvement is due to the contention based approach employed in Phase 1 of the hybrid protocol as compared to time consuming polling based approach employed in the NRP protocol. In the NRP protocol, the DC individually polls and collects the metering data of each meter unit in the network. This also applies to “Bad” meter units where the DC has to wait a predefined time-out period before polling the next meter unit. In the proposed hybrid protocol, however, “Bad” meter units or “hidden nodes” do not participate in the contention period for data transmission, thus reducing the data collection delay. Furthermore, the “Request” packet broadcasting method and the dual purpose packet transmission, which enables a particular meter unit to send its metering data to the DC as well as re-broadcast metering data “Request” packet to lower level meter units, insure shorter data collection time. The data collection delay for hybrid protocol in unstructured network topology, as compared to structured network topology, is lower for $P_g < 0.6$ and higher for $P_g > 0.6$. The slight increase in data collection delay for $P_g > 0.6$ is mainly due to the existence of tree topological sub-networks which require longer data collection time due to the presence of more clusters which include separate contention periods. Furthermore, the hybrid protocol also involves Phase 2 for polling of failed meter units after the initial contention based data collection. In this phase, for a tree topological sub-network, a combination of two three-level clustering mechanisms is required to group all the meter units in the sub-network. This will increase the data collection delay corresponding to the number of failed meter units in each cluster. The lower delay for $P_g < 0.6$ is caused by the increase in cluster failure which is a function of the number of meter units in the cluster. Figure 5-6 shows the cluster failure as a function of P_g for structured and unstructured network topologies. Since, the tree network has more clusters that divide the number of meter units in the sub-network to smaller value, the probability of cluster failure increases with decreasing P_g . In the event of cluster

failure, the data collection of meter units located in the next level cannot be performed as there will be no “Good” relay meter unit to transmit the “Request” packet and hence the data collection time is lower.

Figure 5-5(b) shows the throughputs of the hybrid protocol and the NRP protocol. In comparison, the hybrid protocol performs similar to the NRP protocol achieving 100% throughput for $P_g > 0.5$. The throughput or data collection success rate of a purely contention protocol increases linearly with P_g . This is because for the contention protocol only metering data from “Good” meter units in the network which correspond to P_g are collected. The metering data of “Bad” meter units or hidden nodes are not collected. The hybrid and NRP protocols, however, perform polling of failed meter units after the initial data collection procedure. This increases the data collection success rate but also increases the data collection delay corresponding to the number of failed meter units. The hybrid protocol can achieve 100% throughput for $P_g > 0.5$ in the structured network topology because the hybrid protocol can successfully complete the polling of all failed meter units with the assistance of at least one “Good” neighbor meter unit in the same cluster as the failed meter unit. The lower throughput for $P_g < 0.5$ is due to cluster failures which limit the data collection of meter units in lower level clusters as well as polling of failed meter units in these clusters. This is verified in Figure 5-6 by the existence of cluster failure in the structured network for $P_g < 0.5$ as compared to zero cluster failure for $P_g > 0.5$. In comparison, the structured network performs better than the unstructured network due to the presence of tree topology in the unstructured network topology which increases the probability of cluster failure due to smaller number of meter units in each cluster. Even though the unstructured network has significantly higher cluster failures as compared to structured network, the number of meter units in lower level clusters that are affected by the cluster failure may not be significant as the clusters in a tree topology have smaller number of meter units compared to the structured network.

(a) Data collection delay

(b) Throughput

Figure 5-5: Performances for structured and unstructured topological networks.

Figure 5-6: Number of cluster failures for structured and unstructured networks.

This research found that the contention-based approach, “Request” packet broadcasting method and the dual purpose packet routing system significantly reduce the data collection delay by 57% and 55% for the structured and unstructured networks compared to the NRP protocol. The throughput of the proposed protocol is improved through the second phase on polling of failed meter units after the initial contention-based data collection with the help of a “Good” neighbor meter unit. The throughput achieved for the proposed protocol is similar to the NRP protocol. It can be said that the developed hybrid protocol performs better than the NRP protocol as it can achieve the same throughput but with a significantly lower data collection delay.

However, with the introduction of polling-based medium access method in the hybrid protocol, the key limitation of polling-based AMR systems such as high delay and inability for automatic association of new devices to the system are not addressed. Further studies to the hybrid protocol revealed that metering data of “hidden node” or failed meter units can be read using only contention-based approach. The improved

routing protocol using 4-hop broadcasting method for PLC-based AMR systems is discussed in the next section.

5.4 Proposed Routing Protocol

The proposed protocol utilizes a new packet routing system which combines a “Request” packet (request for meter units to transmit their metering data to the DC) and a “Data” packet (meter units transmit data as a reply to the “Request” packet) as shown in Figure 5-7.

Source Address	Destination Address	Request Flag	Data
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Figure 5-7: Combined “Request” and “Data” packet.

The new system allows meter units to send their metering data to the DC and at the same time re-broadcast the “Request” to other meter units. The packet consists of a request flag (as in Figure 5-7) which keeps track of the hop level origin of the “Request” packet in the network, thus giving the flexibility to stop broadcasting “Request” at the desired hop level. The request flag also ensures that meter units which have sent their data to the DC will not process the packet again.

Independent of the network topology, communication between meter units and the DC takes two transmission directions within the PLC network:

- Downlink – from DC to meter units
- Uplink – from meter units to DC

A transmission signal sent by the DC in the downlink direction is transmitted to all sub-networks. Therefore, all meter units in each sub-network receive the transmitted signal. In the uplink direction, a signal sent by a meter unit is transmitted not only to the DC but also received by all other meter units in the sub-network. Hence, the PLC access network holds a logical bus structure although the low-voltage power supply networks have physically a tree topology [14]. The PLC network structure is considered as a bus

system in this thesis.

The broadcasting method in the proposed protocol will establish a virtual 3-level cluster to create a multi-hop structure in the PLC access network, similar to the radial topology discussed in Chapter 3. The “Near”, “Medium” and “Far” clusters are referred as levels 1, 2 and 3 as shown in Figure 5-8.

Figure 5-8: Access network model.

Similarly, the cluster failure probabilities are defined as the probability that there is no one “Good” meter unit in a particular cluster during one data collection cycle. Levels 1, 2 and 3 are represented by subscripts 1, 2 and 3 respectively in the equations. The number of meter units in levels 1, 2 and 3 is denoted as n_1 , n_2 and n_3 respectively.

Let P_{L1Fail} be the probability of level 1 cluster failure, such that there is no one “Good” meter unit in the cluster.

$$P_{L1Fail} = (P_{b1})^{n_1} \quad (5.1)$$

The probability of level 2 cluster failure P_{L2Fail} is given by the probability that level 1 cluster has at least one “Good” meter unit and there is no “Good” meter unit in level 2 cluster.

$$P_{L2Fail} = (1 - P_{L1Fail})(P_{b2})^{n_2} \quad (5.2)$$

Similarly, the probability of level 3 cluster failure is given by the probability that level 1 and 2 clusters have at least one “Good” meter unit to serve as relays and there is no “Good” meter unit in level 3 cluster.

$$P_{L3Fail} = (1 - P_{L1Fail})(1 - P_{L2Fail})(P_{b3})^{n_3} \quad (5.3)$$

Similarly, the probability that all meter units in the sub-network can transmit their data is given by the probability that there are no cluster failures. Hence,

$$P_{AllGood} = 1 - P_{L1Fail} - P_{L2Fail} - P_{L3Fail} \quad (5.4)$$

This thesis adopts the assumption made in [28] that communication between neighboring meter units is 100% successful. Similar to the NRP protocol [28], the neighbor meter unit refers to a meter unit that belongs to the same cluster and phase of the transformer as the “hidden node” to ensure minimal signal attenuation during data transmission. The 3-level cluster system assumes that the DC can only communicate with “Good” meter units in level 1, but not with meter units in levels 2 and 3. The “Good” meter units in level 1 can communicate with the DC, “Bad” neighbor meter units in level 1 and “Good” meter units in level 2. “Good” meter units in level 2 can communicate with “Bad” neighbor meter units in level 2 and “Good” meter units in levels 1 and 3. “Good” meter units in level 3 can communicate with “Bad” neighbor meter units in level 3 and “Good” meter units in level 2, but not with meter units in level 1 or the DC. The protocol will not require a known network topology of the AMR system as the grouping of the meter units into hop levels is based on the ability to communicate only. This will enable the application of the proposed protocol to PLC systems with unstructured networks (or networks without known topologies).

Figure 5-9: Packet transmission flowchart.

The AMR system packet transmission over the PLC network is shown in Figure 5-9. At the start of each data collection cycle, all meter units in the network will initialize their hop number (h) to 4 such that the “Request” broadcast will stop after 4 hops. In a 3-level cluster network, hop 1 will involve “Request” packet transmission to “Good” meter units in level 1, hop 2 to “Bad” meter units in level 1 and “Good” meter units in level 2, hop 3 to “Bad” meter units in level 2 and “Good” meter units in level 3, and finally hop 4 involves “Request” packet transmission to “Bad” meter units in level 3. The DC will start the data collection cycle by broadcasting a “Request” packet (with request flag set to zero) to all meter units within its network. This broadcast packet, however, will be received by only a few meter units (“Good” meter units in level 1) close to the DC due to the signal attenuation mentioned earlier. These hop 1 (H1) meter units identify the packet as a “Request” packet based on the source address (which is the DC in this case). The meter units then process the “Request” packet and insert their metering data into the data field of the packet before re-broadcasting it. The destination address is set as the DC’s address. The request flag on the outgoing packet is increased to 1 and the meter unit’s hop number is set equal to the request flag. These H1 packets

will be received by the DC, “Bad” meter units in level 1 and “Good” meter units in level 2. Once the DC receives the H1 packets, the metering data of the H1 meter units are recorded in the database. Concurrently, hop 2 (H2) meter units that received the H1 packets recognize them as “Request” packets as the meter unit’s hop number ($h=4$ at this instant) is larger than the request flag (Request Flag=1 in the incoming packet). Each meter unit will then process the “Request” and re-broadcast the H1 packet with its metering data inserted while increasing the request flag (Request Flag=2) and setting its hop number equal to the request flag ($h=2$). The destination address is set as the DC’s address. These H2 packets will be received by H1 meter units, “Bad” meter units in level 2 and “Good” meter units in level 3. Since the hop number of H1 meters ($h=1$) will be smaller than the request flag of the incoming packets, they will re-transmit the packets according to the destination address in the packet. Hop 3 (H3) meter units that received the H2 packets recognize them as “Request” packets since the meter unit’s hop number ($h=4$) is larger than the request flag (Request Flag=2) in the incoming packet. Each will process the “Request” and re-broadcast the H2 packet with its metering data. The request flag will be increased to 3 and the meter unit’s hop number will be set to 3. These H3 packets will be received by H2 meter units and “Bad” meter units in level 3. H2 meter units will re-transmit the packets to H1 meter units and finally to the DC. Hop 4 (H4) meter units (“Bad” meter units in level 3) that received the H3 packets recognize them as “Request” packets since the meter unit’s hop number ($h=4$) is larger than the request flag (Request Flag=3) in the incoming packets. Each will process the “Request” and re-broadcast the H3 packet with its metering data. The request flag will be increased to 4 and the meter unit’s hop number will be set to 4. Since the hop number of H3, H2 and H1 meters units will be smaller than the request flag (Request Flag=4) of the incoming packets, they will each re-transmit the packet according to the destination address in the packet. Any meter unit that receives a H4 packet will not recognize it as a “Request” packet and will discard it because all the meter units’ hop numbers were initialized to 4 at the start of the data collection cycle.

The AMR packet creation and transmission using the 4-hop broadcasting method is shown in Figure 5-10. The packet is created at each level and broadcast to lower level meter units for metering data transmission to the DC, as well as to higher level meter units, as a metering data “Request” packet. This dual-purpose packet transmission will ensure higher efficiency in terms of data collection delay.

Figure 5-10: Packet creation and transmission using 4-hop broadcasting method.

In this protocol, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol is employed for data transmission. The existence of a carrier wave on the communication channel is used to determine whether other nodes are transmitting, because access nodes do not transmit any carrier wave except for their packet transmission. If the carrier wave is sensed on the channel, the communication channel is called “busy”; otherwise, it is “idle”. The CSMA/CA protocol decides whether packet transmission should start as a result of sensing a carrier. If the channel is sensed as “idle”, the node starts its packet transmission immediately. However, if the channel is sensed as “busy”, the node stops the carrier sense and invokes the back-off procedure for additional waiting before transmission. The additional back-off interval $T_{backoff}$ is randomly selected from the slots within a contention window based on the following:

$$T_{backoff} = W_{cw} \times \ell \times t_{tx} \quad (5.5)$$

where W_{cw} is a pseudo-random integer variable uniformly distributed over an interval $[0, D_{win}]$, D_{win} is the size of the contention window, and t_{tx} is the transmission delay for a packet. In this research, ℓ takes the values 1, 2, 3 and 4 for hops 1, 2, 3 and 4

respectively. Finding the exponential random back-off time with regard to re-transmission is a complex procedure and beyond the scope of this thesis. In this thesis, it is assumed that no meter units will have the same random back-off time due to a large contention window size (2 times the number of meter units transmitting in a particular hop). The one-way transmission delay for a packet is given by

$$t_{tx} = \text{Packet Size} / \text{Link Data Rate} \quad (5.6)$$

In the proposed protocol, the data collection will start when the DC broadcasts a “Request” packet. The “Request” will only be received by H1 meter units. It is assumed that all H1 meter units will process and start to re-broadcast H1 packets simultaneously, resulting in collision. All H1 meter units will then immediately cease transmission and acquire a random back-off interval before attempting to transmit again. It is assumed that H2 meter units will start transmission only after the last meter unit in H1 has completed its packet transmission. The data collection time is derived from the longest CSMA/CA random back-off period generated in each transmission hop. This will cater for the worst case scenario of the AMR system, as the longest random back-off period is the waiting time for the last meter unit in the hop level before broadcasting its data packet to the DC or the next hop level meter units. Therefore, the time taken to receive metering data from all meter units in H1 involves one processing time, as all the meter units start processing the “Request” packet simultaneously, plus one transmission delay, for data transmission from the last meter unit to the DC, plus the longest random back-off period, $R_{\max 1}$. Meanwhile, for H2 meter units, data will be sent to the DC through a relay meter unit in H1. Thus, the time taken to transmit metering data of all H2 meter units includes one processing time, for “Request” message processing at H2 meter units, plus two transmission delays, for data transmission from the meter unit to the relay meter unit in H1 and data transmission from the H1 relay meter unit to the DC, plus the longest random back-off period, $R_{\max 2}$. It is assumed that the relay meter units do not process the data packets received from the H2 meter units but simply re-broadcast the packets, which are then received by the DC. Similarly, meter units in H3 send back their metering data to the DC through two relay meter units in H1 and H2, consuming one processing time, three transmission delays and the longest random back-off period, $R_{\max 3}$. Finally, the time taken to transmit metering data of all H4

meter units includes one processing time, four transmission delays and the longest random back-off period, $R_{\max \ell}$. The longest random back-off period, $T_{backoff \ell}$ for each cluster is obtained from the selection of the maximum random back-off period generated for all meter units in that particular hop level, as given by (5.7), where σ denotes the selection process and subscript ‘max’ represents the propositional formula to select the maximum value. Equation (5.8) gives the routing protocol’s data collection delay for each hop level.

$$R_{\max \ell} = \sigma_{\max} [T_{backoff \ell}] \quad (5.7)$$

$$t_{C, \ell} = t_{proc} + (\ell \times t_{tx}) + R_{\max \ell} \quad (5.8)$$

5.5 Analytical Modeling of AMR Systems

The data collection delay and throughput are obtained based on the network traffic model. The data collection delay is defined as the average time taken to collect metering data from all the meter units in the network. Message processing delay t_{proc} is defined as the time taken to process a message at the meter unit.

In a PLC environment under impulsive noise interference, successful transmission of data can be achieved when no impulsive noise interference occurs during the data packet vulnerable time. The data packet vulnerable time is the duration time when the data packet is at risk of being destroyed by impulsive noise interference. The data packet vulnerable time for the proposed protocol is given by (5.9) for each hop level.

$$t'_{\ell} = (\ell \times t_{tx}) + t_w \quad (5.9)$$

The probability that no impulsive noise interference occurs during the data packet vulnerable time is given by

$$P_{k=0, \ell} = e^{-\lambda t'_{\ell}} \quad (5.10)$$

In the proposed protocol, there are only two possible outcomes for each data collection procedure. First is the successful data collection which occurs when there is no impulsive noise interference occurrence during the data packet vulnerable time. The data collection delay to successfully collect metering data from all meter units in hop level ℓ is given by

$$t_{S\ell} = P_{k=0,\ell} \times t_{C,\ell} \quad (5.11)$$

Second is the unsuccessful data collection due to impulsive noise interference. This occurs when there is impulsive noise interference occurrence during the data packet vulnerable time. The data collection delay for unsuccessful metering data collection for hop level ℓ is given by

$$t_{F\ell} = (1 - P_{k=0,\ell}) \times (t_{C,\ell} + t_w) \quad (5.12)$$

The total data collection delay for the proposed protocol is associated with cluster failure probabilities. In the event of level 1 cluster failure, no data collection can be performed as all meter units in the cluster are “Bad”. Furthermore, data collection of meter units in levels 2 and 3 cannot be performed as there will be no “Good” meter units in level 1 to serve as a relay meter unit to broadcast the data packet to the DC and hence data collection stops. Therefore, the data collection delay only involves the time for a “Request” packet broadcast by DC to meter units in level 1. In the event of level 2 cluster failures, data collection of meter units in levels 2 and 3 cannot be performed. Thus the data collection delay includes the time for “Request” packet broadcast and data collection of “Good” meter units in level 1 during hop 1 transmission and “Bad” meter units in level 1 during hop 2 transmissions. Data collection delay in the event of level 3 cluster failures involves time for “Request” packet broadcast and data collection delays of i) “Good” meter units in level 1 during hop 1 transmission, ii) “Bad” meter units in level 1 and “Good” meter units in level 2 during hop 2 transmission, and iii) “Bad” meter units in level 2 during hop 3 transmission. Meanwhile, metering data of all meter units in the network can be collected when no cluster failures occur. The data collection delay includes time for “Request” packet broadcast and data collection delays of i) “Good” meter units in level 1 during hop 1 transmission, ii) “Bad” meter

units in level 1 and “Good” meter units in level 2 during hop 2 transmission, iii) “Bad” meter units in level 2 and “Good” meter units in level 3 during hop 3 transmission, and iv) “Bad” meter units in level 3 during hop 4 transmission. The total data collection delay for one network is given by

$$\begin{aligned}
 T = & P_{L1Fail} \times t_{tx} + P_{L2Fail} (t_{tx} + \sum_{\ell=1}^2 t_{S\ell} + t_{F\ell}) \\
 & + P_{L3Fail} (t_{tx} + \sum_{\ell=1}^3 t_{S\ell} + t_{F\ell}) + P_{AllGood} (t_{tx} + \sum_{\ell=1}^4 t_{S\ell} + t_{F\ell})
 \end{aligned} \quad (5.13)$$

The throughput only includes successful data collection of meter units in each hop level where there is no impulsive noise interference during the data packet vulnerable time. The number of successful data collections for ℓ hop level is given by (5.14). Since there are only 3 clusters in the network, n_0 and n_4 in the equation are equal to zero.

$$N_{S\ell} = n_{(\ell-1)} \times P_{b(\ell-1)} \times P_{k=0,(\ell-1)} + n_{\ell} \times P_{g\ell} \times P_{k=0,\ell} \quad (5.14)$$

Similarly to the derivation of the data collection delay, the throughput is determined from cluster failure probabilities. In the event of level 1 cluster failure, no data collection can be performed as all meter units in the cluster are “Bad”. In the event of level 2 cluster failures, the successful data collection includes “Good” meter units in level 1 that transmit their data during hop 1 transmission, N_{S1} , and “Bad” meter units in level 1 that transmit their data during hop 2 transmission. Similarly, in the event of level 3 cluster failures, the successful data collection includes “Good” meter units in level 1 that transmit their data during hop 1 transmission, N_{S1} , “Bad” meter units in level 1 and “Good” meter units in level 2 that transmit their data during hop 2 transmission, N_{S2} , and “Bad” meter units in level 2 that transmit their data during hop 3 transmission, N_{S3} . Metering data of all meter units in the sub-network can be collected when no cluster failures occur. The successful data collection includes “Good” meter units in level 1 during hop 1 transmission, N_{S1} , “Bad” meter units in level 1 and “Good” meter units in level 2 during hop 2 transmission, N_{S2} , “Bad” meter units in level 2 and “Good” meter units in level 3 during hop 3 transmission, N_{S3} , and “Bad” meter units in level 3 during hop 4 transmission, N_{S4} . Then, the throughput for one sub-network is given by (5.15).

$$\begin{aligned}
 S = & P_{L2Fail}(N_{S1} + P_{k=0,2} \times n_1 \times P_{b1}) \\
 & + P_{L3Fail}[N_{S1} + N_{S2} + P_{k=0,3} \times (n_2 \times P_{b2})] \\
 & + P_{AllGood}[N_{S1} + N_{S2} + N_{S3} + N_{S4}]
 \end{aligned} \tag{5.15}$$

5.6 Performance Analysis of AMR Systems

In order to verify the developed models, the analytical models are compared with simulation models. The performances of the proposed protocol are analyzed and compared with the NRP protocol. In the simulation model, the message processing time is taken to be 1 second for all meter units in the network. The message processing delay at the DC can be ignored because the DC can process the metering data collected from a meter unit during the data transmission of another meter unit. The data rate for the narrowband PLC access network is taken as 2.4kbps. In this thesis, the packet size is set to 24 bytes. It is assumed that the metering data in each meter unit is ready when the meter unit receives the “Request” packet. The AMR network consists of 21 sub-networks, each with a total of 24 meter units. One sub-network is represented by eight meter units each in levels 1, 2 and 3. The results are obtained based on one year data collection period which is equal to 17,520 data collection cycles.

Referring to the two-state Markov model, it can be concluded that, of the six parameters P_g , P_b , P_{gg} , P_{gb} , P_{bb} and P_{bg} , only P_g and P_{gb} are independent parameters. Hence, by varying P_g and P_{gb} , the throughput and data collection delay of the proposed protocol and NRP protocol can be observed. However, in [28] it was observed that the throughput and data collection delay are not significantly affected by P_{gb} . Hence, in this thesis the P_{gb} value is set to 0.1 while the P_g is varied between 0.1 and 0.9.

The performance of the proposed protocol is analyzed under three disturbance models: lightly disturbed, moderately disturbed and heavily disturbed, as given in [32] and [34]. Table 5-1 describes for each disturbance model the mean inter-arrival time t_{IAT} between two impulsive noise interferences and the mean duration of the impulsive noise interference t_w . The data collection delays of the proposed routing and NRP protocols are shown in Figure 5-11.

Table 5-1: Parameters of Impulsive Noise Interference

Disturbance model	t_{IAT}	t_w
I: Lightly disturbed	1.903s	1.82ms
II: Moderately disturbed	0.476s	0.87ms
III: Heavily disturbed	0.015s	2.08ms

Figure 5-11: Data collection delay under impulsive noise interference.

It can be seen that the analytical results correspond well with those from the simulations, which verifies that the analytical model has been accurately developed. It can also be seen that the proposed protocol performs significantly better than the NRP protocol, with an average reduction of 540%. This large improvement is due to the contention-based approach employed in the proposed routing protocol as compared to the time-consuming polling-based approach employed in the NRP protocol. In the first phase of the NRP protocol, the DC individually polls and collects the metering data of each meter unit in the network. This also applies to unsuccessful polling of "Bad" meter units where the DC has to wait a predefined time-out period before polling the next meter unit. A second phase of polling of "Bad" meter units using a "Good"

neighbor meter unit is then performed which further increases the data collection delay. In the proposed routing protocol, however, “Bad” meter units or “hidden nodes” in a particular cluster participate in the contention period for data transmission in the subsequent hop level after receiving the “Request” packet broadcast from a “Good” neighbor meter unit during the previous transmission hop. Furthermore, the “Request” packet broadcasting method and the dual-purpose packet transmission, which enables a particular meter unit to send its metering data to the DC as well as to re-broadcast the metering data “Request” packet to higher level meter units, ensure shorter data collection time. It can also be seen that the data collection delay for the NRP protocol exceeds the ideal data collection cycle limit of 1,800 seconds for $P_g > 0.2$. The proposed protocol, however, does not go beyond 400 seconds. The additional time is critical as it will enable market operators to provide other value-added services. The data collection delays for the three disturbance models are not shown for clarity purposes as they are all similar to the data collection delay without impulsive noise interference. This is because impulsive noise interference occurrence on the power line environment does not affect the data collection time since the additional time due to the small duration impulsive noise interference t_w in the scale of milliseconds is not significant compared with the data transmission time.

Figure 5-12 shows the throughputs of the proposed routing and NRP protocols. It can be observed that the analytical results correspond well with those from the simulations, which verifies that the analytical model has been accurately developed. In comparison, the proposed protocol performs similarly to the NRP protocol. The proposed protocol can achieve 100% throughput for $P_g > 0.5$ as the protocol ensures that all “Bad” meter units or “hidden nodes” can transmit their data to the DC with the assistance of at least one “Good” neighbor meter unit in the same cluster. The lower throughput for $P_g < 0.5$ is due to cluster failures which limit the data collection of meter units in lower level clusters, as well as polling of failed meter units in these clusters. This is verified in Figure 5-13 by the existence of cluster failure in the network for $P_g < 0.5$ compared to zero cluster failure for $P_g > 0.5$. The throughput is affected by the impulsive noise interference as the number of failed meters is increased. This is because, even though a particular meter unit can establish communication with the DC or relay meter unit, it may not be able to send its metering data correctly, as bit or burst error could occur

during data transmission due to impulsive noise interference. This results in significant drops in the throughput of the proposed protocol, typically an average of 9.7%, 32.7% and 99.9% for lightly, moderately and heavily disturbed models respectively as compared with those without impulsive noise interference. It can also be concluded that the proposed protocol does not perform well in moderately and heavily disturbed impulsive noise interference environments, with about 33% and 100% drop in throughput.

Figure 5-12: Throughput under impulsive noise interference.

Figure 5-13: Number of cluster and meter unit failures.

The performance analysis presents two issues that need to be addressed in order to improve the performance of the proposed protocol: 1) the effect of cluster failure on throughput; and 2) the impact of impulsive noise interference on throughput. The cluster failure probability is a function of P_b and the cluster size. Therefore, by increasing the cluster size, the probability of cluster failure will decrease, as shown in Figure 5-14. This will correspondingly increase the throughput of the proposed protocol. It can be seen that for P_g of 0.1 (worst case), 100% throughput can be achieved with a cluster size of 60.

Figure 5-14: Throughput and cluster failure probability for varying cluster size.

The performance of the proposed protocol under impulsive noise interference can be improved by using a broadband PLC system. This is because with the use of the higher data rate PLC system, the one-way transmission delay for a packet, t_{tx} can be reduced and eventually the data packet vulnerable time to impulsive noise interference is minimized. The throughput of the proposed protocol under impulsive noise interference using a 2 Mbps broadband PLC system is shown in Figure 5-15. It can be seen that the throughput of the proposed protocol is significantly improved, especially for moderate and heavy impulsive noise interference models. It is observed that, by utilizing broadband PLC, the proposed protocol can achieve similar throughput as without impulsive noise interference (100% throughput for $P_g > 0.5$) under light and moderate impulsive noise interferences. The throughput for a heavily disturbed environment is significantly improved to an average of 75% (85% throughput for $P_g > 0.5$) compared to less than 0.01% using narrowband PLC.

Figure 5-15: Throughput using broadband PLC.

5.7 Concluding Remarks

In this chapter, a new and effective communication protocol, contention-based routing protocol, was proposed and studied for implementation of an AMR system using power line communications. Analytical models were developed to study and compare the performances in terms of data collection delay and throughput with the NRP protocol. The models developed were verified by comparing the analytical results with those obtained from simulations. The contention-based approach of the proposed protocol significantly reduces the data collection delay compared to the NRP protocol. This improvement is necessary as the future technology trends of AMR will not be purely data acquisition but more advanced meter-to-bill processes streamlining new objectives and functionalities which may include the ability to respond to market demand, perform service quality monitoring and provide reliable grid and market operations. The throughput achieved for the proposed protocol is similar to the NRP protocol. It was also found that, with a cluster size larger than 60, 100% throughput can be achieved for the worst case scenario, P_g of 0.1. The performances of the proposed protocol were also analyzed under impulsive noise interference. It was found that there are significant

drops in the throughput of the proposed protocol, typically an average of 9.7%, 32.7% and 99.9% for lightly, moderately and heavily disturbed models respectively. It was observed, however, that maximum throughput (similar to an environment without impulsive noise interference) can be achieved for light and moderate impulsive noise interference environments by using a broadband PLC system. The throughput of a heavily disturbed environment is also significantly improved to an average of 75% compared to using narrowband PLC. Therefore, the use of a higher data rate PLC system will significantly mitigate the effect of impulsive noise interference on the AMR system performance. In conclusion, the proposed protocol, in addition to significantly lower data collection delay, will be able to achieve 100% throughput for light and moderate impulsive noise interference environments and 75% throughput for heavy impulsive noise interference environment using broadband PLC with a cluster size larger than 60.

CHAPTER 6 A PLC-WIMAX BASED ADVANCED METERING INFRASTRUCTURE (AMI) FOR SMART GRID

6.1 Introduction

Around the world, utilities and governments are looking at utilizing advanced monitoring, control and communication technologies to enhance the capabilities of the power grid to achieve greater efficiency and reliability. In Singapore, the Energy Market Authority (EMA) launched a \$30 million pilot project for an “Intelligent Energy System” (IES) [13]. The project will test a range of smart grid technologies to enhance the capabilities of Singapore’s power grid infrastructure. The IES project will involve around 4,500 consumers in various residential, commercial and industrial locations, including the Nanyang Technological University (NTU) campus, the CleanTech Park at Jalan Bahar and the Punggol Eco-Precinct. The IES pilot will be conducted in two phases. Phase 1 (2010-2012) will focus on the implementation of the enabling infrastructure for the IES while Phase 2 (2012-2013) will focus on the smart grid applications [13].

As discussed in Chapters 1 and 2, advanced metering infrastructure (AMI) is the fundamental building block of a smart grid system. The key aspect in realizing the vision of AMI is to establish a two-way seamless communication infrastructure to provide an essential link between the entities of a smart grid. Therefore, the key emphasis in the first phase of the IES pilot is to establish the smart metering communication protocols and standards.

In this chapter, a viable communication infrastructure for implementation of an AMI in the Intelligent Energy System pilot project at Nanyang Technological University, Singapore is proposed. The proposed AMI communication infrastructure utilizes a hybrid power line communication - Worldwide Interoperability for Microwave Access (WiMAX) technology for the last mile and backhaul communications respectively. The PLC-based communication employs the routing protocol proposed in Chapter 5. The WiMAX-based communication operates on the 3.5GHz licensed band satisfying the Stanford University Interim (SUI) model for path loss prediction. Analytical models to

study the performance of the proposed AMI in terms of data collection delay and throughput under impulsive noise interference are presented.

6.2 Proposed AMI Communication Model

The AMI communication infrastructure supports continuous interaction between the utility and the consumer. In future, it has to serve as the foundation for a multitude of modern grid functions beyond AMI. There are many architectures that can be employed for the AMI communication system, with one of the most common being local data concentrators that collect data from groups of smart meters and transmit that data to a central server via a backhaul channel. Various communication media have been considered to provide part or entire architecture, with PLC being atop the list because cabling infrastructure is already available [90]. However, due to its limited bandwidth and other shortcomings, PLC alone can hardly scale to support a large network. Other communication paradigms are needed to implement a full-scale AMI. In this thesis, a viable communication infrastructure for the AMI at NTU campus utilizing PLC for last mile communication and Worldwide Interoperability for Microwave Access (WiMAX) for backhaul communication is proposed.

The inherent communication infrastructure presented by PLC, which significantly reduces the cost of building a new communication network, makes PLC a favorable solution for “last mile” communication. Furthermore, its strong anti-jamming capability and good data transmission security ensure reliable two-way real-time IP communications. In the past, power lines were considered unacceptable for signal transmission, since the channel contained a lot of noise, multi-path effect causing significant attenuation, interference, and fading. However, the advancement of signal modulation technologies, digital signal processing, and error control techniques has reduced the impact of channel imperfections, making high speed signal transmission through power lines feasible [91].

Wireless communication technologies such as ZigBee, Wi-Fi and WiMAX have a wide range of advantages such as high throughput and fast data rate. However, wireless devices such as ZigBee transceivers have limited battery energy supply, internal memory and processing capacity due to limited physical size. Wireless transmission is

also highly vulnerable to interference, and the communication quality and distance can be greatly affected by walls and steel doors as it cannot penetrate through obstacles especially with higher frequencies. In Singapore, 86% of its population lives in Housing Development Board (HDB) high-rise residential buildings [25]. The electricity meters are usually installed in a concrete room, either in the individual housing units or in an aggregated meter room at the ground floor of each HDB building. Similarly, staff and graduate student apartments, and the hall of residences at NTU campus have its meter units installed in an enclosed meter room. The challenge for wireless communication is to provide an efficient data transmission through this signal blocking mechanism. Furthermore, AMI security is a serious concern on the provision of data integrity as opposed to data privacy. Therefore, PLC can provide a cost-effective, efficient and reliable last mile communication network for AMI at NTU campus.

However, on the backhaul communication network, for data transmission from local data concentrators to the central server, the use of PLC is limited. This is because, 1) longer transmission distance increases the attenuation suffered in PLC networks; and 2) there is no direct communication path from the local data concentrators to the central server and it requires bypassing the transformer. Wireless communication technology, typically WiMAX offer a suitable solution for the high load backhaul transmission as it provides large coverage area and sufficiently high data rate. It provides data rate up to 70Mbps and distance up to 48km. Lower frequency licensed spectrums such as 2G, 2.5G, 3G and 3.5G are most practical for AMI applications especially in urban area as it allows higher power, longer transmission distance and performs better in the presence of signal blocking mechanism. The proposed communication infrastructure for AMI at NTU campus will utilize PLC technology for the last-mile network (from individual meter units to the PLC-WiMAX DCs) and WiMAX technology for the backhaul network (from PLC-WiMAX DCs to the central server located at the Admin building) as shown in Figure 6-1.

Figure 6-1: Proposed communication infrastructure for AMI at NTU campus.

This thesis will consider the metering data collection of 1,250 meter units located around the NTU campus. This includes 664 individual meter units in the staff and graduate student apartments, 16 bulk meter units for the Hall of Residences, 79 individual meter units for each block of the Hall of Residences, 80 meter units for the Hall Fellows, 120 and 160 meter units for schools and departments in the North Spine and South Spine respectively, 31 meter units for lecture theatres and 4 bulk meter units for independent buildings. The metering data from all these meter units will be read through PLC by 19 PLC-WiMAX enabled DCs located between step-down transformers and the respective meter unit clusters as shown in Figure 6-1. The location of DCs at the NTU campus is shown in Figure 6-2. The number of meter units connected to each DC and its serving cluster are shown in Table 6-1. The DCs will then send the collected metering data to the central server located at the Admin building via a 3.5G WiMAX network.

Table 6-1: Data Concentrator Loading Profile and Serving Cluster

DC Number	Number of Meter Units Connected	Serving Cluster
1	350	Staff Apartment
2	250	Staff Apartment
3	65	Staff Housing
4	30	Halls 4 and 5
5	16	Halls 3 and 7
6	18	Hall 6, Sports and Recreational Centre and Nanyang House
7	20	Halls 8 and 9
8	40	Halls 10 and 11, and Graduate Apartment
9	20	Halls 14 and 15
10	35	Halls 12, 13 and 16
11	40	Block S1, South Spine
12	45	Block S2, South Spine
13	55	Block S3, South Spine
14	55	Block S4, South Spine
15	45	Block N4, North Spine
16	50	Block N3, North Spine
17	60	Block N2, North Spine
18	46	Block N1, North Spine
19	10	National Institute of Education and Independent Buildings
Total: 1,250		

6.2.1 Last Mile PLC Network

The last mile PLC network utilizes the routing protocol proposed in Chapter 5. In Chapter 5 it was found that broadband PLC can help to mitigate the effect of impulsive noise interference on the AMR system performance. Therefore, broadband PLC technology will be used to determine the performance of the AMI system under

impulsive noise interference environment. Similar to the Chapter 5, CSMA/CA MAC protocol is employed for data transmission for the routing protocol. The additional back-off interval $T_{backoff}$ that is invoked when the channel is sensed as “busy” is randomly selected from the slots within a contention window based on the following:

$$T_{backoff} = W_{CW} \times \ell \times t_{tx(PLC)} \quad (6.1)$$

where W_{CW} is a pseudo-random integer variable uniformly distributed over an interval $[0, D_{Win}]$, D_{Win} is the size of the contention window, and $t_{tx(PLC)}$ is the transmission delay for a packet. In this thesis, ℓ takes the values 1, 2, 3 and 4 for hops 1, 2, 3 and 4 respectively. Similarly, it is assumed that no meter units will have the same random back-off time due to a large contention window size (2 times the number of meter units transmitting in a particular hop). The one-way PLC transmission delay for a packet is given by

$$t_{tx(PLC)} = \frac{\text{Meter Unit Data Packet Size}}{\text{PLC Link Data Rate}} \quad (6.2)$$

where each meter unit data packet consist 48 half hourly consumption data. It is assumed that, each half hour consumption data contains 10 bytes of information. The broadband PLC link data rate is set to 1Mbps.

The longest random back-off period for each cluster is obtained from the selection of the maximum random back-off period generated for all meter units in that particular hop level, as given by (6.3). Equation (6.4) gives the routing protocol’s data collection delay for each hop level.

$$R_{\max\ell} = \sigma_{\max} [T_{backoff}] \quad (6.3)$$

$$t_{C,\ell} = t_{proc} + (\ell \times t_{tx(PLC)}) + R_{\max\ell} \quad (6.4)$$

6.2.2 Backhaul WiMAX Network

The WiMAX data transmission will employ contention resolution mechanism as its MAC protocol [92]. The contention resolution protocol requires a transmitting node to acquire a random back-off number within an internal back-off window as it enters the contention resolution process. The transmitting node must then wait for this number of transmission time before sending a request again. If no data grant has been given within the waiting interval, the transmitting node will consider the request as lost. It will then increase its internal back-off window by a factor of two and chooses a new random number. This process will continue repetitively until the internal back-off window of the transmitting node reaches the back-off end value or it successfully obtains a data grant. In this thesis, it is assumed that no DCs will have the same random back-off number due to a large contention window size (2 times the number of DCs transmitting). This ensures that each DC will transmit its data to the central server after the first waiting interval. The waiting interval T_{wait} is given by:

$$T_{wait} = W_{CR} \times t_{tx(WiMAX)} \quad (6.5)$$

where W_{CR} is a pseudo-random integer variable uniformly distributed over an interval $[0, D_{backoff}]$, $D_{backoff}$ is the size of the internal back-off window, and $t_{tx(WiMAX)}$ is the transmission delay for a DC WiMAX packet. The one-way transmission delay for a DC WiMAX packet is given by

$$t_{tx(WiMAX)} = \frac{DC \text{ Packet Size}}{WiMAX \text{ Link Data Rate}} \quad (6.6)$$

where the WiMAX DC packet consists of 4 meter units' data packets, 6 bytes MAC header, 4 bytes cyclic redundancy check (CRC) and 8 bytes of data for meter units address information (2 bytes for each meter unit). The WiMAX link data rate is set to 5Mbps in this thesis.

The DC to central server data transmission starts when all DCs have completed their respective network's meter unit data collections. Then, all DCs will process their

WiMAX packets (by bundling 4 meter unit data packets into one WiMAX packet) and enter the contention resolution process by acquiring a random back-off number before attempting to request for data grant. Once a DC receives the data grant, it will transmit only one WiMAX packet to the central server. If there are more WiMAX packets to be sent, then it will re-enter the contention resolution process in the next round by acquiring a new random number. It is assumed that, the next round of WiMAX packets will be sent only after all the DCs have sent their first WiMAX packet. This process will continue until all the WiMAX packets at each DC are sent to the central server. The data collection time is derived from the longest waiting interval generated in each transmission round. This will cater for the worst case scenario of the transmission system, as the longest waiting interval is the waiting time for the last DC (who acquired the largest random number) before transmitting its WiMAX packet. Therefore, the time taken to receive metering data from all DCs in one transmission round, ω , involves one processing time, as all the DCs start processing the WiMAX packet simultaneously, plus one transmission delay for data transmission from the last DC to the central server and plus the longest waiting interval, $K_{\max} \omega$. The longest waiting interval for each transmission round is obtained from the selection of the maximum waiting interval, T_{wait} generated for all DCs in one particular transmission round, as given by (6.7). Equation (6.8) gives the protocol's data collection delay for each transmission round.

$$K_{\max} \omega = \sigma_{\max} [T_{wait}] \quad (6.7)$$

$$t_{K,\omega} = t_{proc} + t_{tx(WiMAX)} + K_{\max} \omega \quad (6.8)$$

WiMAX systems operate in the frequency range of 2-11GHz, which make them suitable for non-line-of-sight (NLOS) applications. Depending on licensing and band regulation, practical deployments often occur in the 2.5GHz and 3.5GHz frequency band. In this thesis, a 3.5GHz WiMAX system is proposed for implementation in the AMI backhaul communication network. The successful deployment of the WiMAX system will rely on the acceptable received signal power. Usually, for network planning and performance analysis, empirical models are often utilized to study propagation loss and predict mean received signal power. In this thesis, Stanford University Interim (SUI) model will be used for propagation loss prediction in order to establish the

minimum transmitter height to ensure reliable communication throughout the smart grid. In [93] and [94], it was found that the SUI model provides the most accurate path loss prediction for NLOS 3.5GHz WiMAX system.

The SUI is developed and recommended by the Institute of Electrical and Electronic Engineers (IEEE) 802.16 Broadband Wireless Access Working Group. The model is an extension of Hata model with correction parameters for frequencies above 1900 MHz [95]. The path loss is given by

$$PL_{SUI} = A + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_f + X_h + s \quad (6.9)$$

where d is the distance between transmitter and receiver, d_0 is 100 m. The term, s is the correction factor for shadowing caused by trees and other clutters on a propagation path. A is then given by

$$A = 20 \log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \quad (6.10)$$

where λ is the wavelength. The parameter γ is path loss exponent and is given by

$$\gamma = a - bh_b + \left(\frac{c}{h_b}\right) \quad (6.11)$$

where h_b is the base station antenna height in meters. The constants a , b and c depend on the terrain and are given in the Table 6-2. Three different terrain profiles are defined to represent the communication area. Terrains with hilly areas and moderate or very dense vegetation are represented as terrain A. Flat terrains with moderate or very dense vegetation or hilly terrains with rare vegetation are represented as terrain B while flat terrains with rare vegetation are represented as terrain C.

Table 6-2: SUI Parameters for Different Terrains

Parameter	Terrain A	Terrain B	Terrain C
a	4.6	4.0	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20

The operating frequency correction factor X_f and the height correction factors X_h are given by

$$X_f = 6.0 \log_{10} \left(\frac{f}{2000} \right) \quad (6.12)$$

$$X_h = \begin{cases} -10.8 \log_{10} \left(\frac{h_r}{2000} \right), & \text{for terrains A and B} \\ -20.0 \log_{10} \left(\frac{h_r}{2000} \right), & \text{for terrain C} \end{cases} \quad (6.13)$$

where h_r is the receiver antenna height.

Figure 6-3 shows the required WiMAX DC transceiver's height for varying distance from the central server in order to achieve a minimum -82dBm received signal strength. Parameters a, b and c for terrain A are used to approximately represent NTU's garden campus. Transmitter power of 20dBm, channel bandwidth of 10MHz, frequency of 3500MHz, base station antenna height of 22m (Admin building height), transmitter antenna gain of 23dB, receiver antenna gain of 14dB and shadowing correction factor of 10.6 dB are used to predict the propagation path loss using the SUI model. In this thesis, the performance analysis of the AMI will be performed on the assumption that the PLC-WiMAX DC transceivers have the minimum receiver height according to their distance to the central server as shown in Figure 6-3.

Figure 6-3: Receiver antenna height versus transmission distance.

6.3 Analytical Modeling of AMI Systems

The data collection delay and throughput are obtained based on the network traffic model. The data collection delay is defined as the average time taken to collect metering data from all the meter units in the network. Message processing delay t_{proc} is defined as the time taken to process a message at the meter unit and the DC.

In a PLC environment under impulsive noise interference, successful transmission of data can be achieved when no impulsive noise interference occurs during the data packet vulnerable time. The data packet vulnerable time is the duration time when the data packet is at risk of being destroyed by impulsive noise interference. The data packet vulnerable time for the proposed protocol is given by (6.14) for each hop level.

$$t'_\ell = (\ell \times t_{tx(PLC)}) + t_w \quad (6.14)$$

The probability that no impulsive noise interference occurs during the data packet vulnerable time is given by

$$P_{k=0,\ell} = e^{-\lambda' t'_\ell} \quad (6.15)$$

The throughput of the last mile PLC network presents the overall AMI throughput as the WiMAX communication is assumed to achieve reliable communication through the accurate representation of the DC transceiver height to achieve a minimum -82dBm received signal strength at the central server. Then, the throughput of the AMI only includes successful data collection of meter units in each hop level where there is no impulsive noise interference during the data packet vulnerable time. The number of successful data collections for ℓ hop level is given by (6.16). Since there are only 3 clusters in the network, n_0 and n_4 in the equation are equal to zero. The throughput is associated with cluster failure probabilities. In the event of level 1 cluster failure, no data collection can be performed as all meter units in the cluster are “Bad”. In the event of level 2 cluster failures, the successful data collection includes “Good” meter units in level 1 that transmit their data during hop 1 transmission, N_{S1} and “Bad” meter units in level 1 that transmit their data during hop 2 transmission. Similarly, in the event of level 3 cluster failures, the successful data collection includes “Good” meter units in level 1 that transmit their data during hop 1 transmission, N_{S1} , “Bad” meter units in level 1 and “Good” meter units in level 2 that transmit their data during hop 2 transmission, N_{S2} , and “Bad” meter units in level 2 that transmit their data during hop 3 transmission, N_{S3} . Metering data of all meter units in the sub-network can be collected when no cluster failures occur. The successful data collection includes “Good” meter units in level 1 during hop 1 transmission, N_{S1} , “Bad” meter units in level 1 and “Good” meter units in level 2 during hop 2 transmission, N_{S2} , “Bad” meter units in level 2 and “Good” meter units in level 3 during hop 3 transmission, N_{S3} , and “Bad” meter units in level 3 during hop 4 transmission, N_{S4} . Then, the throughput for one network is given by (6.17).

$$N_{S\ell} = n_{(\ell-1)} \times P_{b(\ell-1)} \times P_{k=0,(\ell-1)} + n_\ell \times P_{g\ell} \times P_{k=0,\ell} \quad (6.16)$$

$$\begin{aligned}
 S = & P_{L2Fail}(N_{S1} + P_{k=0,2} \times n_1 \times P_{b1}) \\
 & + P_{L3Fail}[N_{S1} + N_{S2} + P_{k=0,3} \times (n_2 \times P_{b2})] \\
 & + P_{AllGood}[N_{S1} + N_{S2} + N_{S3} + N_{S4}]
 \end{aligned} \tag{6.17}$$

In the last mile PLC network, there are only two possible outcomes for each data collection procedure. First is the successful data collection which occurs when there is no impulsive noise interference occurrence during the data packet vulnerable time. The data collection delay to successfully collect metering data from all meter units in hop level ℓ is given by

$$t_{S\ell} = P_{k=0,\ell} \times t_{C,\ell} \tag{6.18}$$

Second is the unsuccessful data collection due to impulsive noise interference. This occurs when there is impulsive noise interference occurrence during the data packet vulnerable time. The data collection delay for unsuccessful metering data collection for hop level ℓ is given by

$$t_{F\ell} = (1 - P_{k=0,\ell}) \times (t_{C,\ell} + t_w) \tag{6.19}$$

Similarly to the derivation of the throughput, the data collection delay is determined from cluster failure probabilities. In the event of level 1 cluster failure, no data collection can be performed as all meter units in the cluster are “Bad”. Furthermore, data collection of meter units in levels 2 and 3 cannot be performed as there will be no “Good” meter units in level 1 to serve as a relay meter unit to broadcast the data packet to the DC and hence data collection stops. Therefore, the data collection delay only involves the time for a “Request” packet broadcast by DC to meter units in level 1. In the event of level 2 cluster failures, data collection of meter units in levels 2 and 3 cannot be performed. Thus, the data collection delay includes the time for “Request” packet broadcast and data collection of “Good” meter units in level 1 during hop 1 transmission and “Bad” meter units in level 1 during hop 2 transmission. Data collection delay in the event of level 3 cluster failures involves time for “Request” packet broadcast and data collection delays of i) “Good” meter units in level 1 during hop 1 transmission, ii) “Bad” meter units in level 1 and “Good” meter units in level 2 during hop 2 transmission, and iii) “Bad” meter units in level 2 during hop 3

transmission. Meanwhile, metering data of all meter units in the network can be collected when no cluster failures occur. The data collection delay includes time for “Request” packet broadcast and data collection delays of i) “Good” meter units in level 1 during hop 1 transmission, ii) “Bad” meter units in level 1 and “Good” meter units in level 2 during hop 2 transmission, iii) “Bad” meter units in level 2 and “Good” meter units in level 3 during hop 3 transmission, and iv) “Bad” meter units in level 3 during hop 4 transmission. The data collection delay for one last mile PLC network is given by

$$T_{PLC} = P_{L1Fail} \times t_{tx} + P_{L2Fail} (t_{tx} + \sum_{\ell=1}^2 t_{S\ell} + t_{F\ell}) + P_{L3Fail} (t_{tx} + \sum_{\ell=1}^3 t_{S\ell} + t_{F\ell}) + P_{AllGood} (t_{tx} + \sum_{\ell=1}^4 t_{S\ell} + t_{F\ell}) \quad (6.20)$$

In the backhaul WiMAX network, the data collection time corresponds to the number of transmission round required to send all WiMAX packets to the central server. The number of WiMAX packets for each DC is given by (6.21). This is obtained from the number of successful collections of meter unit’s data at each DC. This value is then divided by 4 as each WiMAX packet combines 4 meter unit’s data into one packet. The number of transmission rounds required, Γ , to transmit all WiMAX DC packets can be obtained from the selection of maximum P of all the DCs as given by (6.22).

$$P = \left\lceil \sum_{\ell=1}^3 N_{S\ell} / 4 \right\rceil + 1 \quad (6.21)$$

$$\Gamma = \sigma_{\max}[P] \quad (6.22)$$

The data collection time for backhaul WiMAX network is given by

$$T_{WiMAX} = \sum_{\omega=1}^{\Gamma} t_{K,\omega} \quad (6.23)$$

6.4 Performance Analysis of AMI Systems

In order to verify the developed models, the analytical models are compared with simulation models. The performances of the AMI network are analyzed in terms of data collection delay and throughput. In the simulation model, the message processing time is taken to be 1 s for all meter units and DCs in the network. In this thesis, it is assumed that the metering data in each meter unit is ready when the meter unit receives the “Request” packet. The AMI network consists of 19 DCs, each with different number of meter units as discussed earlier. One DC network is represented by equal number of meter units each in levels 1, 2 and 3. Each meter unit is read by the DC 48 times in a day (half-hourly). The results are obtained based on a 1-year data collection period which is equal to 17520 data collection cycles

Similar to the performance analysis in Section 5.6, the P_{gb} value is set to 0.1 while P_g is varied between 0.1 and 0.9. The performances of the proposed protocols under three disturbance models are analyzed. Table 6-3 describes for each disturbance model the mean inter-arrival time t_{IAT} between two impulsive noise interferences and the mean duration of the impulsive noise t_w .

Table 6-3: Parameters of Impulsive Noise Interference

Interference model	t_{IAT}	t_w
I: Lightly disturbed	1.903s	1.82ms
II: Moderately disturbed	0.476s	0.87ms
III: Heavily disturbed	0.015s	2.08ms

The data collection delays of the AMI are shown in Figure 6-4. Only data collection delays under no impulsive noise interference and lightly disturbed environments are shown for clarity. This is because the data collection delays for all noise models are similar to the environment without impulsive noise interference as the additional time due to the small duration impulsive noise interference t_w in the scale of milliseconds is not significant compared with the data transmission time. It can be seen that the

analytical results correspond well with those from the simulations, which verifies that the analytical model has been accurately developed. The proposed AMI is able to complete the data collection of 1,250 meter units located around the NTU campus through 19 DCs in less than 205 seconds. The low delay is due to the contention-based approach employed in the PLC routing protocol as compared to the time-consuming polling-based approach employed in many PLC communications such as in [35]. In polling-based PLC protocols, the DC individually polls and collects the metering data of each meter unit in the network. This also applies to unsuccessful polling of “Bad” meter units where the DC has to wait a predefined time-out period before polling the next meter unit. In the PLC routing protocol, however, “Bad” meter units or “hidden nodes” in a particular cluster participate in the contention period for data transmission in the subsequent hop level after receiving the “Request” packet broadcast from a “Good” neighbor meter unit during the previous transmission hop. Furthermore, the “Request” packet broadcasting method and the dual-purpose packet transmission, which enables a particular meter unit to send its metering data to the DC as well as to re-broadcast the metering data “Request” packet to higher level meter units, ensure shorter data collection time. The backhaul WiMAX network also contributes significantly to the short duration data collection delay due to its high speed deployment over a large coverage area and a high load network. This could not be achieved with the use of other short range wireless technologies or entirely on PLC system because many repeaters have to be used in order to achieve reliable communication for the large coverage area. The contention resolution mechanism used in the WiMAX system also ensures lower data collection delay as data is sent whenever resources are available and not required by any other scheduling-service classes. It can also be seen that the data collection delay is well below the ideal data collection cycle limit of 1800 seconds. The additional time is critical as it will enable market operators to provide other value-added services.

Figure 6-4: Data collection delay under impulsive noise interference.

Figure 6-5 shows the throughputs of the proposed AMI. It can be observed that the analytical results correspond well with those from the simulations, which verifies that the analytical model has been accurately developed. The proposed system can achieve 100% throughput for $P_g > 0.5$ in environment without impulsive noise interference as the protocol ensures that all “Bad” meter units or “hidden nodes” can transmit their data to the DC with the assistance of at least one “Good” neighbor meter unit in the same cluster. The slightly lower throughput for $P_g < 0.5$ is due to cluster failures which limit the data collection of meter units in lower level clusters, as well as data collection of “Bad” meter units in these clusters. Average throughputs of 96%, 95% and 46% are recorded for lightly, moderately and heavily disturbed impulsive noise interference environments respectively. The throughput is affected by the impulsive noise interference as the number of failed meters is increased. This is because, even though a particular meter unit can establish communication with the DC or relay meter unit, it may not be able to send its metering data correctly, as bit or burst error could occur during data transmission due to impulsive noise interference. The WiMAX communication does not affect the throughput of the AMI system as we have assumed that the PLC-WiMAX transceivers will meet the required height profile to achieve a

minimum -82dBm received signal strength at the central server. It can also be concluded that the proposed AMI can perform well in lightly and moderately disturbed impulsive noise interference environments, with only 4% and 5% drop in throughput respectively.

Figure 6-5: Throughput under impulsive noise interference.

6.5 Concluding Remarks

In this chapter, a new PLC-WiMAX communication infrastructure was proposed for implementation of an AMI system in the Intelligent Energy System pilot project at Nanyang Technological University, Singapore. Analytical models were developed to study the performances in terms of data collection delay and throughput. The models developed were verified by comparing the analytical results with those obtained from simulations. The proposed AMI is able to complete the data collection of 1,250 meter units located around the NTU campus through 19 DCs in less than 205 seconds. The contention-based approach employed in the last mile PLC communication and backhaul WiMAX communication ensure significantly low data collection delay compared to polling-based approach. This reduction is necessary as the future technology trends of AMI will not be purely data acquisition but more advanced meter-to-bill processes

streamlining new objectives and functionalities which may include the ability to respond to market demand, perform service quality monitoring and provide reliable grid and market operations. The proposed AMI system can achieve an average 97% throughput for an environment without impulsive noise interference. Average throughputs of 96%, 95% and 46% are achieved for lightly, moderately and heavily disturbed impulsive noise interference environments respectively. The use of broadband PLC significantly mitigates the effect of impulsive noise interference on the PLC system performance as the data packet vulnerable time to impulsive noise interference is greatly reduced. In conclusion, the proposed protocol, in addition to significantly lower data collection delay, will be able to achieve less than 5% drop in throughput for light and moderate impulsive noise interference environments.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions

In the near future, more and more utilities and governments around the world will be actively involved in incorporating intelligence to their traditional electricity generation, transmission and distribution systems. This will pave a way for a smart grid system that offers a completely automated electricity monitoring and control system which intelligently integrates the actions of utilities and consumers to efficiently generate, deliver, and use electricity. The fundamental building block of a smart grid is the Advanced Metering Infrastructure (AMI). AMI provides the necessary communication and control functions needed to implement critical energy management services such as demand side management, automatic meter reading, demand response management and power quality management. AMR system which is part of the larger AMI allows for the automatic collection and transfer of data from consumer energy-metering devices to a central database at the utility premises for analysis and billing purposes. AMR offers utilities significant reduction in operational costs, improved meter reading accuracy, and improved efficiency through various other energy management services that ride on the data collected via AMR.

Communication is an important enabler for the transition from the traditional power grid to the smart grid. Different communication networks are available in the market to serve smart grids in rural, sub-urban or urban landscapes, and under different weather conditions. The inherent communication infrastructure presented by power line communications (PLC), which significantly reduces the cost of building a new communication network, makes PLC a favorable solution for AMR communication networks. PLC enables a new and highly convenient communication technology that requires no additional cables for data communication, Internet access, VoIP, home networking and home/building energy management. However, power supply networks were not originally designed for communications. Therefore, they do not present a favorable transmission medium. PLC-based AMR systems face some challenges that need to be addressed in order to provide viable, reliable and efficient AMR systems.

The “hidden node” problem, caused by significant signal attenuation along cables and varying in-home impedance and impulsive noise interference are major concerns in the implementation of PLC based AMR systems.

In this thesis, analytical models were developed to study the performances of two AMR protocols, clustered simple polling (CSP) and neighbor relay polling (NRP), that have been shown to effectively overcome the “hidden node” problem in PLC based AMR systems. In order to verify the developed models, the analytical models were compared with simulation models. In the simulation model, the message processing time was taken to be 1 second for all meter units in the network. The data rate for the narrowband PLC access network was taken as 2.4kbps. The packet size was set to 24 bytes. The AMR network consists of 21 sub-networks, each with a total of 24 meter units. The analytical models were accurately developed and the performances of the two protocols were analyzed under impulsive noise interference based on radial and tree topological network structures. It was found that the NRP protocol performed better than the CSP protocol in terms of throughput but required longer data collection delay to cater for re-polling of failed meter units. The CSP and NRP protocols did not perform well under heavy impulsive noise interference, resulting in a drop of up to 99.8% in successful metering data collection. It was observed, however, that high throughput can be achieved for moderate and heavy impulsive noise interference environments by reducing the packet size of the AMR system.

From the performance analysis of the two AMR protocols, it was observed that, even though the NRP protocol provides the best performance typically achieving 100% throughput for $P_g > 0.5$ (without impulsive noise interference), the data collection delay far exceeds the ideal data collection cycle of 1,800 seconds. This is characteristically due to two levels of polling-based medium access method employed in the NRP protocol. In general, delay associated with the polling-based protocol is higher and increases with the number of nodes connected to the master polling station. A new and effective communication protocol which utilizes contention-based medium access method was then proposed and studied for implementation in PLC based AMR systems. Similar conditions for the simulation and numerical models were used. Generic analytical models which can be applied to both narrowband and broadband PLC systems were accurately developed. The performance of the proposed protocol

was compared with the NRP protocol. It was found that, the contention-based approach of the proposed protocol significantly reduces the data collection delay compared to the NRP protocol while achieving similar throughput. The analysis of impulsive noise interference revealed an average drop in throughput of 9.7%, 32.7% and 99.9% for lightly, moderately and heavily disturbed models respectively. Optimization of the proposed protocol found that, in addition to significantly lower data collection delay, the proposed protocol is able to achieve 100% throughput for light and moderate impulsive noise interference environments and 75% throughput for heavy impulsive noise interference environment using broadband PLC with a cluster size larger than 60.

The developed protocol was then employed in the design of a communication infrastructure for implementation of AMI in the Intelligent Energy System pilot project at Nanyang Technological University, Singapore. The proposed AMI communication infrastructure utilizes a hybrid broadband PLC and Worldwide Interoperability for Microwave Access (WiMAX) technology for the last mile and backhaul communications respectively. The half hourly metering data packet size and broadband PLC link data rate were taken as 10 bytes and 5 Mbps respectively. The analytical models were accurately developed and the performance of the AMI in terms of data collection delay and throughput was studied. The proposed AMI is able to complete the data collection of 1,250 meter units located around the NTU campus through 19 DCs in less than 205 seconds. This reduction is necessary as the future technology trends of AMI will not be purely data acquisition but more advanced meter-to-bill processes streamlining new objectives and functionalities which may include the ability to respond to market demand, perform service quality monitoring and provide reliable grid and market operations. The proposed AMI system can achieve an average 97% throughput for an environment without impulsive noise interference. Average throughputs of 96%, 95% and 46% are achieved for lightly, moderately and heavily disturbed impulsive noise interference environments respectively. The use of broadband PLC significantly mitigates the effect of impulsive noise interference on the PLC system performance with less than 5% drop in throughput for light and moderate impulsive noise interference environments.

7.2 Recommendations for Future Research

The followings are some recommendations and issues opened for future research and development for PLC-based AMR systems:

1. The proposed contention-based routing protocol utilizes a broadcasting-based routing of request and data packets. It improves the efficiency of the system by reducing redundant broadcasting by meter units that have sent their metering data. The efficiency of the routing protocol can be further verified by comparing the performance of the routing protocol with the NRP protocol for different cluster sizes. Furthermore, the use of mesh routing protocol that selects the best path between meter units and DC could significantly improve the efficiency and reduce data collection delay. It could also improve the reliability of the protocol as the routing protocol should be able to re-route fast around failed nodes and broken links.
2. Besides the effects of WiMAX path loss on the performance of the AMI system, further studies could include the effects of packet loss (due to bit errors or insufficient buffers caused by network congestion), jitter (variation in the delay introduced by the components along the communication path) and multipath fading (signal replication due to scattering by different objects and various multipath signals undergoing different attenuation, distortions, delays and phase shifts).
3. The knowledge and experience gained from this thesis could also be applied to develop viable PLC-based communication infrastructure for the sensing and control network employed in microgrid energy management systems. This is because, very similar to the DC in AMR systems, the centralized server in the microgrid energy management system sends commands and collects timely energy related information from distributed energy resources (DER), smart energy meters and energy storage devices in the microgrid in order to perform various functions including interval energy consumption monitoring, power quality measurement, energy distribution, and active and reactive power flow

management. PLC could be a very cost-effective and reliable solution for the microgrid energy management system.

4. The IES pilot project will soon commence the evaluation of suitable communication infrastructure that links 1,250 smart meters to the NTU Central Host. The proposed protocol on a hybrid PLC-WiMAX AMI system could be applied in the IES project to evaluate and validate the theoretical results with practical measurements.
5. The performances of the developed protocols for overcoming the ‘hidden node’ problem in PLC-based AMR systems could be compared with those of the existing MAC protocols such as Inhibit Sense Multiple Access (ISMA) in order to better evaluate the performances of the developed protocols.

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