PERFORMANCE EVALUATION OF OPTIMAL GEOMETRY OF INTERCONNECTING DEVICES FOR AMI SMART GRID NETWORKS

by

Nisha Rajendran

Bachelor of Engineering in Electronics & Instrumentation, Chennai, India, 2012

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

Masters of Science in Electrical Engineering

in the Graduate Academic Unit of Electrical and Computer Engineering

Supervisors: Julian Meng, PhD, Electrical and Computer Engineering
Eduardo Castillo Guerra, PhD, Electrical and Computer Engineering

Examining Board: Wei Song, PhD, Computer Science
Julian Cardenas Barrera, PhD, Electrical and Computer Engineering
Bo Cao, PhD, Electrical and Computer Engineering

This thesis is accepted by the
Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

October, 2019

ABSTRACT

Advanced Metering Infrastructure (AMI) is an automated two-way communication network between smart meters and a utility company. AMI generally utilizes Radio Frequency (RF) Mesh technology to form a network of endpoints (or smart meters) and interconnecting devices (routers or collectors). The main purpose of this research work is to evaluate the performance of AMI networks by analyzing the optimal geometry of the interconnecting devices and the impact of this repositioning on the performance metrics. The performance of such a network is evaluated in terms of statistical measures such as end-to-end delay, packet hop counts and packet success rates.

The analysis will assess the impact on the network performance by changing the geographical positions or the number of interconnecting devices using a common AMI test network. The focus is on interconnecting devices, mainly routers, as endpoints are assumed to be fixed by residential locations. Clustering algorithms such as MDAV and Lloyd's help facilitate the positioning of interconnecting devices. The research work will also focus on a comparison study of a selection of AMI specific routing protocols for bi-directional packet delivery between endpoints and collectors situated in the network.

The test network used in this research is based on the AMI network currently deployed by Barbados Power and Light Company (BLPC). Closer to the real-world scenario is obtained by using the actual latitude and longitude information from BLPC to place all AMI devices in the correct geographical locations. This will be used as the baseline case study. All the analyses and observations are done using OMNeT++ which has several modules and libraries that make it a good choice for simulation of large communication networks.

DEDICATION

I dedicate this work to my husband, Arvind Raguraman, for his constant support and belief in me without which nothing would have been possible.

ACKNOWLEDGMENTS

I would like to sincerely thank my supervisors, Dr. Julian Meng and Dr. Eduardo Castillo Guerra for their constant support and guidance throughout my course of study. Their timely help and suggestions were invaluable. Also, I would like to extend my sincere gratitude to Dr. Julian Cárdenas-Barrera, Dr. Ahmad Mohamad Mezher, and Dr. Miguel Mendoza for their technical guidance and for keeping me on top of my work regularly. My thanks to my co-researchers and my professors for their inputs and help whenever I needed it. I deeply appreciate the support and funding from the UNB Smart Grid Research Laboratory and Dr. Liuchen Chang.

I extend my gratitude to my family, my husband and my son, my parents and mother in law for their encouragement and help which is the backbone of my success. I wouldn't be what I am without them. I sincerely owe it to them for their timely help and support whenever I am swamped with coursework. This list wouldn't be complete without mentioning the encouragement I got from my brother, sister in law and my best friend, for they are my pillars of support. I am grateful for my family and extended family and sincerely wish to make you all proud of me one day.

Table of Contents

List of Tables

List of Figures

List of Symbols, Nomenclature or Abbreviations

AMI- Advanced Metering Infrastructure

BLPC- Barbados Light and Power Company

RF- Radio Frequency

BPL- Broadband over Power Lines

PLC- Power Line Communications

DR- Demand Response

MDAV- Maximum Distance to Average Vector

ISM- Industrial Scientific and Medical

FSK- Frequency Shift Keying

FHSS- Frequency Hop Spread Spectrum

WAN- Wide Area Network

NAN- Neighborhood Area Network

HES- Head-End Systems

MAC- Medium Access Control

NED- Network Description Language

EIRP- Equivalent Isotopically Radiated Power

τ_H – Total number of meters that can reach a router in *h* hops

δ_h – Total number of routers that can reach a collector in *h* hops

τ_D – Relative average end-to-end delay

τ_L – Relative percentage of packet losses

Chapter I

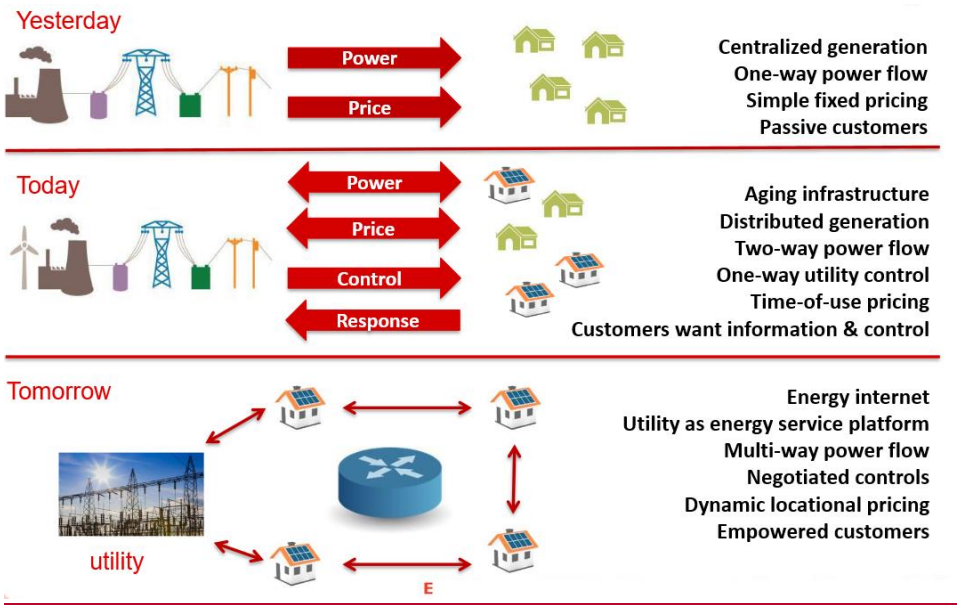
Introduction

1. 1. Overview

Barbados Light and Power Company (BLPC) is seeking to upgrade its existing power system to meet "*100% Renewable by 2030*". The transition to fully renewable energy is challenging because it needs an accurate assessment of available resources, generation forecasting, system optimization, effective load management and energy storage strategy. University of New Brunswick, in partnership with BLPC, is working on the above-mentioned research components assisting the company to achieve its long-term goal. All these components rely strongly on a fast and reliable real-time communication network.

The communication network in Barbados should offer real-time control, distribution automation information and integration of smart devices. The underlying communication link of smart devices consists of wireless mesh networks with multiple end nodes and fiber backbone in generation and distribution sites. Figure 1 represents the long term energy optimization goal of BLPC and the role of Advanced Metering Infrastructure (AMI) in achieving such goal. Tens of thousands of communication nodes are connected in a wireless mesh network for bi-directional data exchange with the utility. There are many

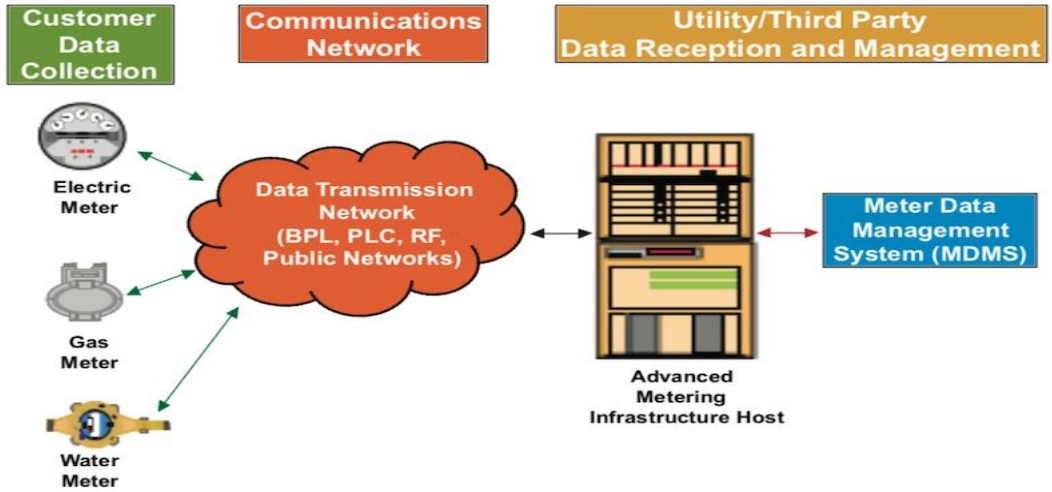
types of communication nodes, such as end nodes, routers, and collectors. Commonly used end nodes are smart meters installed at customer locations.



Source: Barbados Light and Power Company

Figure 1: BLPC Long Term Goals

The wireless mesh network between smart meters and utility, Head-End Systems (HES), forms the Advanced Metering Infrastructure (AMI). AMI is an integration of smart meters, communication networks, and data management systems which enables automated two-way communication between the customers and the utility companies. HES is a combination of hardware and software components that receives and processes the data collected by the smart devices in an AMI network. Studies on AMI are gaining popularity in both academic and industrial communities for its range of applications in the areas of utility systems and management. Figure 2 represents an overview of AMI systems.



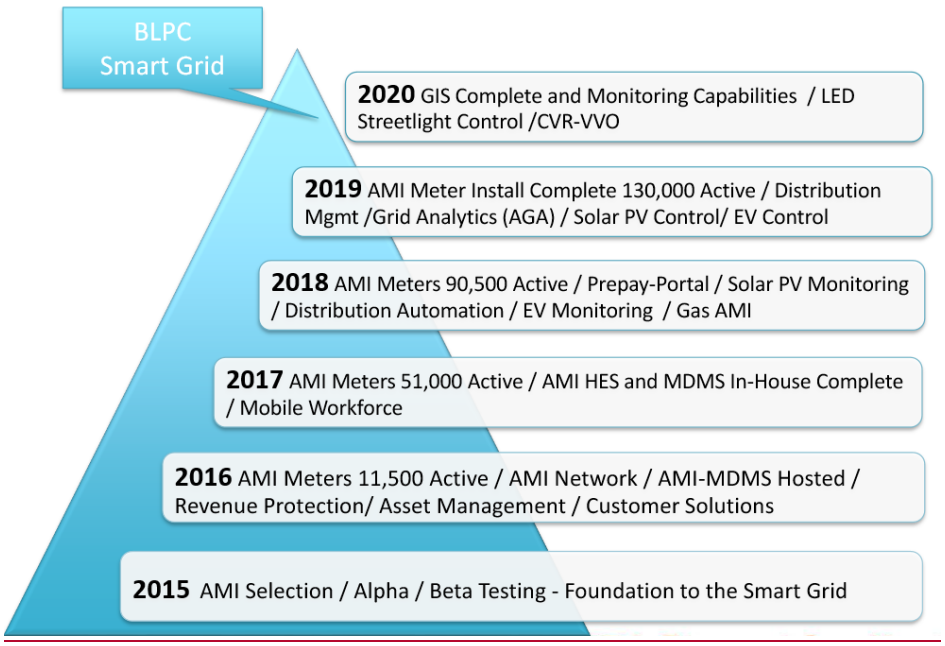
Source: Electric Power Research Institute, California

Figure 2: General Structure of AMI Network

Utility companies around the world are upgrading to AMI networks to perform automatic meter readings to capture customer interval data as well as to offer Demand Response (DR) programs [1]. AMI can be fully integrated into the utilities' information system to acquire power consumption profiles of residential customers at minute-level intervals. Potential benefits include better peak-hour energy management, improved customer intelligence on their energy consumption, variable pricing structures for time-of-day energy use, and the elimination of estimated customer billing. The improved data quality of energy consumption information will improve efficiencies in energy utilization. Utilities believe that such benefits will facilitate growth in customer enrollment in AMI and future smart grid initiatives.

BLPC in partnership with Landis & Gyr is incorporating smart meters into its utility systems to manage customer information. Figure 3 shows the timeline for the BLPC AMI implementation. The existing AMI framework of BLPC consists of smart meters, routers, and collectors in a RF mesh network. RF mesh based communication systems are widely

used in North America [2] for smart metering applications. Such systems have a long track record of success and have been proven to be highly reliable in distributed control applications.



Source: Barbados Light and Power Company

Figure 3 : BLPC Road Map for AMI implementation

1. 2. Problem definition

BLPC's current AMI design consists of a network composed of a large number of smart meters with a hierarchal structure of routers and then collectors to manage information flow in a mesh architecture. Smart meters and collectors are placed in fixed locations with routers being geographically positioned to ensure maximum coverage and reliability. Smart meters are deployed at customers' residences and industrial venues while collectors are placed in existing utility substations. One of the key design challenges in an AMI deployment is determining the optimal position of routers that ensure maximum coverage of all the smart meters. Routers are interconnecting devices that enable the

connectivity needed to transport information from any smart meter to a data-aggregator or collector. The selected geographical position of the routers relative to meter locations can improve or deteriorate the performance of the communication network. In other words, the analysis of the placement of routers plays a major role in the network architecture. This research includes a comprehensive simulation analysis of the existing BLPC design that leads to recommendations on optimal router numbers and positions. The main goal of this research is to provide recommendations to BLPC on how to achieve 100% coverage of the smart grid meters with a minimal number of routers while achieving acceptable network performance.

The impact of flexible geographical router positions and/or the number of interconnecting devices on the performance of the AMI network has not been vastly explored in research communities. The number and position of the routers will be changed in our study and the impact of these actions on the performance of the AMI network will be evaluated in terms of packet delivery rates, packet delays and hop counts between the smart meters and the head end systems where the DR program can be implemented [1]. The performance of the AMI networks not only depends on the optimal number and placement of devices but also choosing a suitable routing protocol. A routing protocol is defined as the algorithm with which data is transmitted in the network so that the data packets reach their destination efficiently. The selection of suitable AMI specific routing protocols is challenging and requires extensive studies and simulations. This thesis will also identify different routing protocols in terms of scalability, ease of implementation and packet delays.

1. 3. Objectives

The following are the objectives of this thesis work.

- Analyze the existing BLPC AMI framework through extensive simulations to identify areas of improvement in existing design.
- Evaluate the impact of repositioning and/or changing the number of routers on the AMI network performance.
- Identify the routing protocols for AMI networks to ensure maximum throughput and minimum latency.

The optimal positions of routers in the simulated network are calculated using clustering algorithms. Given that the meters and collectors are in fixed positions, the methodology followed in this research is to generate alternative router positions using Maximum Distance to Average Vector (MDAV) and Lloyd's Algorithms and evaluate the impact of new positions on the performance of the network. A case study is first performed to evaluate the algorithms and to position the communication nodes with a publicly available dataset from the City of Montreal before the recommendations to the BLPC AMI is done.

1. 4. Organization of the thesis

The thesis is organized as follows. Chapter II gives background information on AMI technologies and details on RF mesh networks, its challenges, routing protocols used and its applications. Chapter III provides information on the design of the network, simulation preliminaries, and research methodology. Chapter IV gives a basic idea of

clustering algorithms used. Chapter V details the optimization of key devices in the case study of the Montreal dataset and its corresponding results. Chapter VI provides information on optimized router positions in large scale RF mesh networks in Barbados, and the experimental results. Finally, Chapter VII lists the observations and future works in the field of study.

Chapter II

Background and state of the art on RF Mesh networks

2. 1. Literature review

The main purpose of the AMI is to connect a large number of smart meters to the Metering Data Management Systems (MDMS) [24]. Many existing Wireless Mesh Network (WMN) technologies are currently used in the implementation of AMI's, such as Wi-Fi, Low Power Wide Area Network (LPWAN), and Radio Frequency (RF) Mesh. Among the three abovementioned technologies, the RF Mesh system is currently one of the most used in North America where reputable manufacturers such as ACLARA, Intron, and Landys & Gyr are utilizing RF Mesh radio technology [1, 25]. The RF Mesh system allows communication in a mesh architecture where meter data is transmitted via meter-to meter, meter-to-router, router-to-router, and router-to-collector connectivity. The smart meter is the core element of AMI, and it acts as a data traffic generator for smart metering messages. Furthermore, the smart meter should also be able to receive messages within the mesh network such as the remote meter control messages. Routers are used to extend the wireless coverage and act as intermediate nodes between meters and collectors and form a high-speed communication path for the meter traffic. Finally, collectors receive the

messages coming from the meters and can also initiate a communication with the meters. Collectors are the backhaul point of connection to the rest of the IT network.

The performance of a RF mesh network in similar smart grid systems is studied in [1] and [3]. L&G reported a network design based on geographical routing in [1] that is the paradigm in our AMI network. Different communication technologies such as GPRS, 3G and Power Line Communications (PLC) are alternatively used in smart metering applications [26]. European smart grid topologies, in particular, lend themselves to the latter type of solution because a single sub-station transformer typically supplies several hundreds of homes. Narrow-band PLC communication technology is required by regulation in Europe to comply with the Cenelec A band and communication is possible over distances of up to 2-3km between hops at a typical data rate of 2.4kbps. However, power line technology is less suited to the North American market because the transformers are usually located in close proximity to a small cluster of homes, thus making concentration economically non-viable. RF mesh based communication solutions are less dependent on the power grid topology [1]. It is also possible to directly connect each meter to the utility HES via a dedicated GPRS or 3G connection. This solution depends on having adequate network coverage and also incurs higher operational costs due to the large number of GPRS or 3G subscriptions required. Often a combination of both PLC and GPRS/3G can be used if the particular technology is available. ([1] and [26])

The researchers in [3] analyzed the performance of WMN's in terms of delay and packet hop counts and compared these metrics based on two commonly used routing protocols: RPL and geographical Routing. The pros and cons of these two routing protocols

are briefly discussed in this paper. A simulation environment is designed using OMNEST and a wireless sensor network framework called Castalia is formulated. This paper evaluates the performance of the network in terms of average end-to-end delay and packet losses. We use these two quantities, along with hop count, as the performance metrics for AMI evaluation.

Studies on comparing common routing protocols and standard practices in smart utility systems, such as [5] and [6], provide information on the design of AMI networks. Detailed studies on various routing protocols, their advantages, disadvantages and applications are discussed in [10-16].

The latest improvements in this field involve studies on network sustainability through performance analysis and different deployment possibilities. AMI-specific and more energy-efficient routing algorithms are explored to offer further stability to smart grid systems ([7] and [8]). The communication simulation software OMNeT++, described in [38 and 40], is used extensively throughout this research for modeling the AMI networks as it has numerous libraries to configure end devices (e.g. smart meters) and interconnecting devices (e.g. routers and collectors) in a RF mesh network. Our router positioning study uses two clustering algorithms, Maximum Distance to Average Vector (MDAV) and Lloyd's algorithm, described in [17-21]. According to our knowledge, there is limited literature studying the impact on the performance of the AMI network relating to the repositioning or changing the number of interconnecting devices and/or varying the routing protocols. This research analyses such scenarios for the optimization of the Barbados AMI network by carrying out extensive simulations using OMNeT++.

2. 2. Introduction to RF mesh Networks

RF mesh technology is uniquely suited for use in smart metering applications due to its ability to dynamically form ad-hoc communication links between neighboring network nodes [1]. The communication range of the devices in the network can be increased by performing multiple hops from one node to the next until the final destination is reached. Different propagation limitations such as obstruction from high rise buildings, attenuation from noise are typically present in neighborhood area networks. RF mesh systems are able to overcome these propagation conditions by finding alternative paths through the mesh in the event that one path is blocked by an obstruction. Other RF solutions such as point-to-point or point-to-multi-point systems are constrained by the need to have consistent reliable links between each pair of communicating nodes. This wireless mesh architecture offers several advantages over others including flexibility, minimal infrastructure, extensive network coverage, and low deployment cost.

Smart-metering systems based on a RF mesh network operate in the ISM bands 902- 928MHz. Use of this band offers the advantage of extended range and improved penetration through walls and objects compared to higher frequency ISM bands such as 2.4GHz. Currently, RF mesh smart metering systems are typically based on proprietary frequency shift keying (FSK) modulation schemes and use Frequency Hop Spread Spectrum (FHSS) for collision avoidance. The use of FHSS also offers improved link budget and increased receiver sensitivity compared to direct sequence spread spectrum (DSSS) because of their smaller channel bandwidth [1]. Increased link budget, in turn, leads to improved range. FHSS also provides mitigation to the risk of interference which is typical in shared ISM bands. FCC Part 15 allows frequency hopping based systems to

transmit at 30dbm power level in combination with antenna gains of 6dbi to achieve a total EIRP of 36dbm. Non-hopping systems are subject to more stringent regulations. Standardization efforts for RF mesh based smart systems are currently under development (e.g. through the IEEE's 802.15.4g SUN workgroup) and will take some time to complete.

RF mesh systems in AMI typically employ a layered system architecture in which end nodes (i.e., smart meters) mesh together at the lowest layer. Usually, distance-limited end nodes connect with other end nodes to "hop" data to reach an intermediate layer of interconnecting nodes or routers. Routers interconnect the smart meter mesh to form a pathway to a collector gateway connected to the upper Wide Area Network (WAN) layer. The traffic from the WAN layer is then backhauled to the Utility's HES. The backhaul is typically a fiber network. The smart meter mesh, router nodes, and collectors are sometimes collectively referred to as Neighborhood Area Network (NAN).

2. 3. Challenges in RF mesh networks

The capacity of mesh networks is affected by many factors such as network topologies, traffic patterns, network node density, optimal placement of communication nodes, number of channels used for each node, transmission power levels, and node mobility. A clear understanding of the relationship between network capacity and the above factors provides a guideline for the design, deployment, and operation of the network [2].

It has been shown in [9] that the optimum transmission power level of an end node is reached in a stationary multi-hop network when the node has six neighbors. An optimum tradeoff is achieved with this value between the number of hops from source to destination and the channel spatial-reuse efficiency. The derivation of new results by considering

critical factors such as transmission power levels, traffic patterns, optimal routing path, channel optimization, etc., is still a challenging research topic and to our knowledge, development capacity models for ad-hoc RF mesh networks have had limited success [2 & 9].

2. 4. Routing in RF mesh networks

A routing protocol determines how to effectively transmit data without unnecessary delays and collisions. Selecting a routing protocol is an important step in network design to ensure maximum throughput and minimum latency. This selection of suitable AMI specific routing protocols is challenging and requires details studies and simulations. Below is the list of commonly used routing protocols in smart grid applications.

- **DADR (Distributed Autonomous Depth First Routing)** [10]

  DADR is a distributed wireless mesh routing protocol designed to improve how independent control and data planes handle unreliable links. It addresses the inefficiencies of one-phase routing schemes. This routing protocol is found to be very reliable and easy to scale in larger networks and adapts quickly to changing link conditions while minimizing network control overhead.

- **HYDRO (Hybrid Routing Protocol) [11]**

  HYDRO is a combination of centralized and distributed mechanisms. Low-power nodes form and maintain a distributed Directed Acyclic graph (DAG) that provides them with a set of default routes for communicating with border routers. The border routers maintain a global view of the network using topology reports received from each of the nodes and subsequently install optimized point-to-point routes within

the network. HYDRO combines local agility and centralized control and is very robust to node failures.

- **IEEE 802.11s Routing (HWMP) [12]**

  Hybrid routing protocols combine both reactive and proactive routing to increase the overall scalability of routing in networks. Proactive routing establishes a routing path between two nodes before any flow of data traffic. Reactive routing establishes a routing path only when the source needs to communicate with a destination. HWMP protocol uses airtime routing metric default as specified in the IEEE802.11s draft standard. It reflects the amount of channel resource consumed for transmitting a frame over a particular link. HWMP is found to be very reliable in ad-hoc networks and is easy to implement and evaluate.

- **LA-HWMP (Load-Aware Hybrid wireless mesh protocol)** [13]

  HWMP with load balancing sacrifices some amount of airtime link metric and chooses the links with a higher airtime link metric. This avoids the bottleneck in the network at heavy traffic times since the packet will not wait for the particular link with minimal airtime link metric and will pass through any available link even though the airtime link metric is higher. LA-HWMP improves on the performance of HWMP but does not scale well in large networks since the protocol tries to find the best route based on load in the network. This leads to constant hops from one path to another until a desirable route is selected.

- **RPL (Routing Protocol for LLNs (Low power and Lossy Networks))** [3]

  RPL is a form of gradient routing designed by the IETF ROLL (Routing Over LLNs) group. It is an IPv6 routing protocol developed for a variety of applications

and is on its way to become a routing standard for smart utility networks. RPL is scalable, flexible and easily configurable but it can cause unreliability and inconsistencies in the network. That said, RPL offers comparatively better performance in terms of delay than the commonly used geographical routing.

- **Geographical Routing** [1 and 3]

  Geographical Routing is a distance vector routing protocol that adopts a combination of weighted link metrics and geographical proximity to route data packets. Geographical routing has a multitude of implementation flavors and mechanisms to build routes in the network. It uses peer-peer communication that incorporates geographical co-ordinates of the neighboring nodes. This algorithm ensures that the communication path has the minimum number of hops and the lowest latency and is easily scalable for larger networks.

- **Timer-based Multipath Diversity** [14]

  It is a tree-based multipath diversity routing scheme. The proposed route diversity takes advantage of the multi gateway tree-based routing scheme with the objective of managing the transmission of packets through a different path to possibly another gateway, which may suffer less from interference. This protocol is reliable, self-healing and has better throughput in performance. The back-press scheme used in this protocol helps reduce the congestion in the network and limits the delay below a certain value even when the traffic increases.

- **HWMP-Reliability Enhancement** [15]

  The HWMP-RE architecture attempts to improve the reliability of 802.11s WLAN mesh networks. The aim is to improve route stability and to mitigate the loss of

important data packets. Various smart grid applications can be successfully transmitted in 802.11s by achieving these objectives. A new method of calculating the airtime cost metric for the HWMP standard and a route instability prevention scheme is used to improve the reliability of route selection. A reserved route algorithm is used to prevent packet loss during link breakage, and a latency-tolerant traffic management scheme is designed to differentiate smart grid data efficiently. It incorporates changes in the self-healing mechanism to reduce overhead and to provide delay-tolerant functions in the network.

- **HLR-AODV (Health, Link Quality and reputation Aware- AODV)** [16]

  It is a modified version of the AODV routing protocol. A node's energy consumption and congestion are minimized by considering its remaining energy and queue status during route selection. Smart meters close to sink will be involved in most multi-hop transmissions leading to congestion and fast energy depletion. Using routes with good RF strength leads to fewer retransmissions and end-to-end delay. It has energy-efficient and reliable communication with self-healing characteristics and offers better network performance in terms of delay and packet success rates.

The AMI test network in this research incorporates geographical routing since to our knowledge it represents a reasonable facsimile to that used by Landis & Gyr AMI networks. It is a distance-vector routing protocol that utilizes the geographical proximity of communication nodes to route data packets. All the smart meters or endpoints in the network are provided with the geographical coordinates of the interconnecting devices

during commissioning. The transmitting node discovers the neighbor that is geographically closest to the final destination node [1]. Thus the communication path has the minimum number of hops to achieve the lowest latency. Routers are always given preference in the list of neighbors over other endpoint nodes due to its ability to transmit data at higher speeds directly to the collector and their higher transmission range. The maximum number of hops a packet is allowed to take when reaching a collector is configurable. A "time to live" mechanism can be incorporated in the routing protocol, so packets are not repeatedly retransmitted.

2. 5. Applications of RF mesh networks

RF mesh networks are becoming popular in various fields including,

- ***Broadband home networking***

  Currently broadband home networking is realized through IEEE 802.11 WLANs. An obvious problem is the location of the access points. A home usually has many dead zones without service coverage and mesh networking can solve these issues in home networking such as the installation of multiple access points, etc.

- ***Community and neighborhood networking***

  Mesh networks mitigate the disadvantages of traditional cable networks through flexible mesh connections between homes. It can also enable many applications such as distributed file storage, distributed file access, and video streaming.

- ***Enterprise networking***

  This can be a small network within an office or a medium-size network for all offices in an entire building, or a large scale network among offices in multiple buildings. RF

mesh networks can grow easily as the size of the enterprise expands. The service model of enterprise networking can be applied to many other public and commercial service networking scenarios such as airports, hotels, shopping malls, convention centers, sports centers, etc.

- ***Metropolitan area networks***

  Mesh networks in the metropolitan areas have several advantages. The physical-layer transmission rate of a node in mesh networks can be much higher than that in any cellular network. Wireless mesh MAN is an economical alternative to broadband networking, especially in underdeveloped regions. A wireless mesh MAN covers a potentially much larger area than home, enterprise, building, or community networks.

- ***Smart Energy Management***

  Utility companies are investing in smart energy management systems consisting of smart meters and wireless mesh devices to facilitate automated meter readings and demand response controls. RF mesh networks can also be used to transport data from intelligent electronic devices deployed to monitor power grid assets such as substations, distribution and transmission lines, generation resources, etc.

The background, characteristics, applications, and challenges in a RF mesh network were presented in this chapter. This offers an overview of the RF mesh network that will be incorporated in BLPC AMI configuration and will form a foundation of performance studies described in the following chapters.

Chapter III

Network Architecture

One of the main goals of this research is to study a communication network created based on the current BLPC AMI network, and future variations, so as to assess current network performance and to provide recommendations for improved performance based on selected metrics. This chapter covers the characteristics of the BLPC network, communication requirements and the establishment of the framework required to conduct performance and quality studies.

3. 1. Introduction

Smart meters, routers, and collectors are positioned in a test AMI network based on the information provided by BLPC to simulate real-time data exchange between smart meters, routers and collectors deployed throughout Barbados. The smart meters are positioned on customer's addresses and the collectors are placed in the substations. The routers are pole-mounted in various locations to offer maximum network coverage.

3. 2. BLPC Network

The smart-meters used by BLPC are Landys&Gyr (L&G) Focus residential meters. These meters use three communication protocols (optical, telephone modem and data IP

based on C12.22) according to ANSI C12.19. The standard defines push and pull communications. Landis & Gyr uses a RF mesh network for their AMI implementation.

Below are the geographical details of the Barbados Island.

- Total communication network area: 432 km^2
- North to south: 34 km maximum distance
- East to west: 23 km maximum distance
- Estimated total number of smart meters to be installed: ~120,000
- Number of smart meters currently implemented in this study: 63122

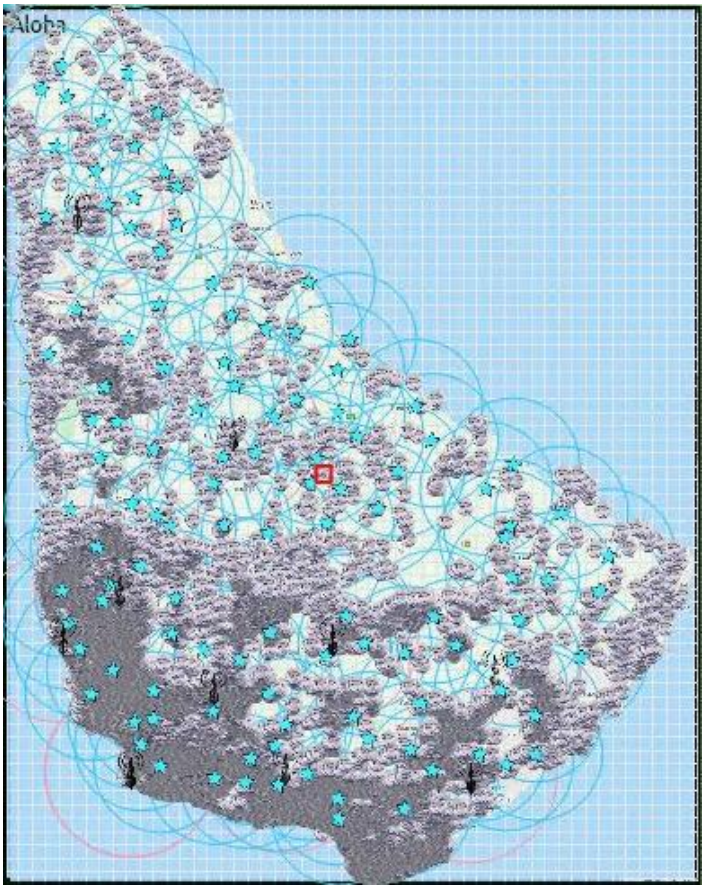
This information is used in our AMI simulation to ensure an accurate representation of device distances, meter density, router/collector locations and future deployment strategies.

3. 3. Network Simulator

The test simulation framework is based on OMNeT++, a discrete event simulator that allows modeling of all required AMI components. A simulation-based experiment is well suited to study the BLPC AMI network performance since we will be working with tens of thousands of communication nodes. The simulation software was selected based on its ability to satisfy the following requirements:

- Ease of installation, use, and stability
- Scalability of multiple end devices and ability for aggregation
- Capability to model modern communication channels (e.g., wireless, fiber, etc.)
- Library coverage and ability to write dedicated models

OMNeT++ [22] provides built-in libraries and modules to incorporate geometrical positions of the communication nodes to enable a close to real-world scenario evaluation. It also allows model development in C++ but uses a Network Description language (NED) with graphical design for an easier view of results and debugging. It should be mentioned that OMNeT++ has the capability to perform parallel simulations in Windows and Linux OS and thus has the ability to handle large simulation runs.



Source: OMNeT++ Simulator Environment

Figure 4: BLPC AMI network.

The test network shown in Figure 4 is built with BLPC information using the OMNeT++ network simulator. Although the individual smart meters are not clearly delineated, this image shows the density of smart meters across the island and the location

of routers and collectors. As expected, a high density of meters and collectors are seen in the capital city of Bridgetown region located near the southwest corner. Blue stars and black antenna represent routers and collectors respectively.

It is expected that the high density of smart meters in the Bridgetown region can have a drastic impact on the performance of the overall network and strategic placement of routers in these high traffic areas will enhance the performance of the network. The relocation of routers from scarcely populated areas to the high traffic areas can also be considered when faced with limited network resources. This research focuses on analyzing these concepts with respect to the AMI network performance.

3. 4. Simulation parameters

Table 1 describes the communication parameters used in the BLPC simulation. These specifications are based on the Landis & Gyr Focus residential AMI system and are made configurable in the simulation to model different operational scenarios. Meter endpoints operate on low power with transmission ranges typically limited to hundreds of meters whereas routers and collectors have a higher communication range due to higher transmit powers. All the RF mesh network channels are assumed to be in the standard ISM frequency band and the random access protocol implemented in the MAC layer is slotted ALOHA with slot time of 700ms.

Parameter Name	Range
Carrier Frequency	902-928 MHz
Transmission Rate	115.2 kbps
Transmission range of meter	300 m
Transmission Range of Router	2500 m
Transmission Range of Collector	3218 m
ALOHA-Slot Time	0.7 s
Transmitted Packet Length	1000 bits
Number of Meters	63122
Number of Routers	117
Number of Collectors	11

Table 1: Simulation Parameters

The simulations are performed for multiple iterations using different scenarios based on the router locations and numbers for our research. Batch simulations are executed using the same configuration multiple times with a different set of parameters to assess the performance metrics of a particular scenario. Various scenarios based on optimized router locations and numbers will be compared against the original distribution of the communication devices currently deployed by BLPC.

The test AMI network is evaluated in terms of average end-to-end delay, percentage packet losses and packet hop counts. The end-to-end delay of a packet is defined as the total time taken for a packet to reach the collector from its starting point. It is closely related

to the total number of hops a packet takes to reach the target (i.e., packet hop counts). The percentage of packet losses in a network is defined as the percentage of packets that are lost during transmission. The simulations are carried out for different scenarios using actual router positions and those based on the selected clustering algorithm. The number of routers is also varied to determine the impact of network performance as a function of meter-to-router ratios. Alternative router positions and numbers are then used in the OMNeT++ to obtain the AMI network metrics. The network performance is compared between the different scenarios to determine the optimal position of interconnecting devices in a network.

Chapter IV

Clustering algorithms

Clustering algorithms are used to find the optimal positions of the interconnecting devices or routers in the AMI network through different mechanisms. Background information, algorithm implementation and mathematical preliminaries of the two selected clustering algorithms are provided in this chapter.

4. 1. Introduction

Clustering algorithms cluster a set of data points into groups with similar characteristics so that the intra-cluster standard deviation is minimized while the inter-cluster differences are maximized. The end goal is to cluster data points, or in our case smart meters, into optimal groupings to be serviced by a single router. The clustering algorithms attempt to form these groupings so that the inter-cluster communication is done through a minimum number of smart meter hops to reach collectors faster. In this thesis, the optimization of the router positions is determined by using two well-known clustering algorithms mentioned earlier: MDAV and Lloyd's algorithm [17-21]. These are commonly used by the research community because of their ease of implementation and numerous application capabilities. After the clustering of smart meters has been achieved, the centroid value of a group is considered as the best location of the single router serving the

end nodes or smart meters associated with that group. The cluster centroid and regional boundaries are calculated iteratively achieving minimum standard deviation in the centroid value.

4. 2. Mathematical description of the clustering algorithms

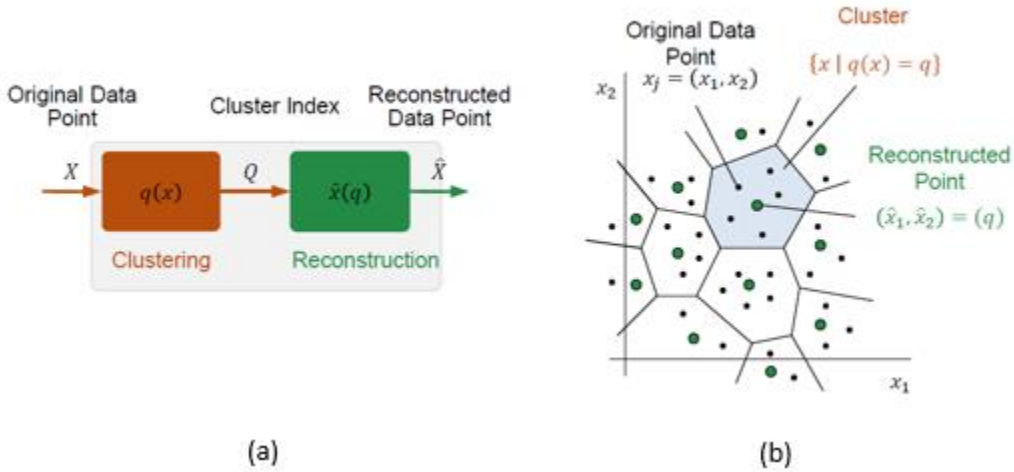
The alphabet in this section corresponds to a measurable space that contains random variables representing possible router positions. $|\Gamma|$ is the cardinality of a set Γ. We convene to use uppercase letters for random variables, and lowercase letters for particular values they take. This means that the notation X = x represents the event when the random variable X takes the value x ϵ Γ. Additionally, E[.] represents the expectation operator. Thus, the expectation of X over a finite set of data points $\{x_1, \ldots, x_n\}$ is $E[X] = \frac{1}{n}\sum_{i=1}^{n} x_i$.

4. 3. Background on the traditional k-means method (Lloyd)

A clustering method is defined as a function able to partition a range of values x of a random variable X, approximating each resulting cluster by a value $\hat{x}$ of a discrete random variable $\hat{X}$. The clustering map $\hat{x}(x)$ consists of two steps. First, to assign data points of X to a cluster Q based on a clustering function $q(x)$ and secondly, to use a reconstruction function $\hat{x}(q)$ to map the index Q into a value $\widehat{X}$ that approximates the original data, leading to $\hat{x}(x) = \hat{x}\big(q(x)\big)$. Clustering could be referred to as $\hat{x}(x)$ or $q(x)$. Two-dimensional clustering is represented in Figure 5 where the random variable takes values in $\mathbb{R}^2$.

Cluster indices $Q = q(x)$ take values in a finite alphabet $\Gamma = \{1, \ldots, |\Gamma|\}$. The size of the alphabet $|\Gamma|$ (i.e., the number of clusters), should be given with the application requirements. A certain amount of distortion is incurred between the original data X and

its reconstructed version $\widehat{X} = \hat{x}(Q)$, due to clustering. A distortion measure is defined as a nonnegative function $d(x, \hat{x})$ where the expected distortion can be computed as $D = Ed(x, \hat{x})$. A commonly used distortion measure is the mean squared error (MSE).



Source: "Optimized Routers Positions for Large-Scale RF Mesh Networks based on Clustering Algorithms" Ad Hoc Networks (2019)

Figure 5: Example of two dimensional clustering

Optimal clustering is achieved when the minimum distortion is obtained for a given number of possible indices. Two conditions must be satisfied to be on an optimal clustering [3, 4]. First, the *nearest-neighbor condition*, where the optimal clustering $q^*(x)$ is given by,

$$q^*(x) = \arg\min d\big(x, \hat{x}(q)\big)\,, where\ q = 1, \dots, |\Gamma| \qquad (1)$$

which means that each value x of the data is allocated to an index that corresponds to the nearest reconstruction value.

Second, the *centroid condition*, which affirms that the optimal reconstruction function $\hat{x}^*(q)$ is given by,

$$\hat{x}^*(q) = E[X|q] \quad (2)$$

This means that each reconstructed value is the *centroid* of that cluster. The algorithm requires an initialization step to select initial cluster centroids that will be optimized. One of the most common ways to choose the initial centroids is by assigning the reconstruction points randomly at first. The criterion to stop the algorithm could be either by limiting the maximum number of iterations or by limiting the relative distortion value change given a small threshold. The specifications of Lloyd's Algorithm is given below in table 2.

Algorithm A: Lloyd's Algorithm
function Lloyd **input** *Stop*, $(x_j)_{j=1}^{n}$ *Number of iterations before stopping, quasi-ID portion* $x_1, \ldots . x_n \in R^m$ *of a dataset of n records* **output** q *Assignment function from records to microcells* $j \rightarrow q(j)$ 1. Define randomly the initial centroids. 2. Assign each point to the cluster that has the closest centroid (in terms of MSE) using Equation. 1. 3. Recalculate the values of the centroids using Equation. 2. 4. Repeat steps 2 and 3 until the number of iterations *Stop* is reached.

Table 2: Lloyd's Clustering Algorithm

4. 4. Background on the traditional k-micro aggregation algorithm (MDAV)

Micro-aggregation is also similar to a quantization problem. The algorithm finds a partition of the set by quasi-identifying tuples of cells with k elements, while concurrently

trying to reduce the distortion incurred by replacing each cell element by the cell representative. A common measure of distortion for the MDAV algorithm is the mean-squared error (MSE) similar to Lloyd's algorithm.

The clustering algorithm is adapted to our application by applying the k-Anonymous aggregation to the meters. The representative value, AKA the centroid in each cell, is considered the router position for the specific cluster. The specifications of MDAV algorithms used in this work are given in Table 3.

Algorithm B: MDAV Clustering Algorithm [18]

function MDAV

input k, $(x_j)_{j=1}^{n}$ *Anonymity parameter k, quasi-ID portion*

$x_1, \ldots . x_n \in R^m$ *of a dataset of n records*

output q *Assignment function from records to microcells* $j \rightarrow q(j)$

1. **While** $2k$ points or more in the dataset remain to be assigned to microcells **do,**
2. Find the centroid (average) C of those remaining points.
3. Find the furthest point P from the centroid C, and the furthest point Q from P.
4. Select and group the $k-1$ nearest points to P, along with P itself, into a microcell, and do the same with the $k-1$ nearest points to Q.
5. Remove the two microcells just formed from the dataset.
6. **If** there are k to $2k-1$ points left **then** form a microcell with those and finish.
7. **Else**, *At most* $k-1$ *points left, not enough for a new microcell*
8. Adjoin any remaining points to the last microcell. *Typically the nearest microcell*

Table 3: MDAV Clustering Algorithm

It is worth mentioning that this work normalizes each quasi-identifier to zero mean and unit variance. Zero-mean normalization is just a convenience that facilitates the computation of variances. The unit-variance normalization is crucial for perturbation errors inherent in the micro aggregation process. This is very important to remain invariant to

different choices of units, such as kilograms for weights, and meters for heights, etc. Even though in our case we have only one attribute (i.e., position of meters) and two dimensions (i.e., x-axis and y-axis), it is important to apply zero-mean and unit-variance normalization so that values of the computed distortions are between zero and one.

Clustering algorithms are used to find the optimal positions of the routers in smart grid applications. This is then applied to the case study and the BLPC test AMI network. The corresponding results and performance analyses are presented in the following chapters. First, a case study is performed to validate the strategy. The outcomes of the case study are then used to recommend the use of clustering algorithms to position the devices in the BLPC RF mesh system.

Chapter V

Optimization of key device positions

We have put forth the idea of using clustering algorithms to find the optimal positions of devices in a mesh network. This is carried forward by first conducting a detailed case study with a publicly available data set. This ensures the proposed algorithm is standardized and can be reproduced in the future if needed. The following section discusses how the strategy is implemented for the Montreal city dataset that is publicly available. The results of the simulations and conclusions on the optimal positions and number of devices for that network are also presented.

5. 1. Introduction

The optimization of the positions of the interconnecting devices in a RF mesh network using clustering algorithms is applied to a publicly available dataset. The performance of the network is evaluated in terms of average end-to-end delay and packet losses. The smart meters used in this case study are obtained from a dataset of residential addresses in the Montreal city. The dataset contains 335297 smart meters distributed over an area of, approximately, 431 km^2.

5. 2. Strategy to optimize key devices in RF Mesh network

This section presents the design strategy to optimize the positions of key devices in RF Mesh networks. Key devices, in this case, refer to router and collectors, as the positions of the meters cannot be changed in an AMI infrastructure. The Montreal AMI deployment differs from that of BLPC as collectors are assumed to have flexible install locations. As routers ensure that the information sent by the meters reaches the collectors, it can be concluded that the information exchange between meters and collectors will have the lowest number of hops if router positions are optimal with respect to meter and collector positions.

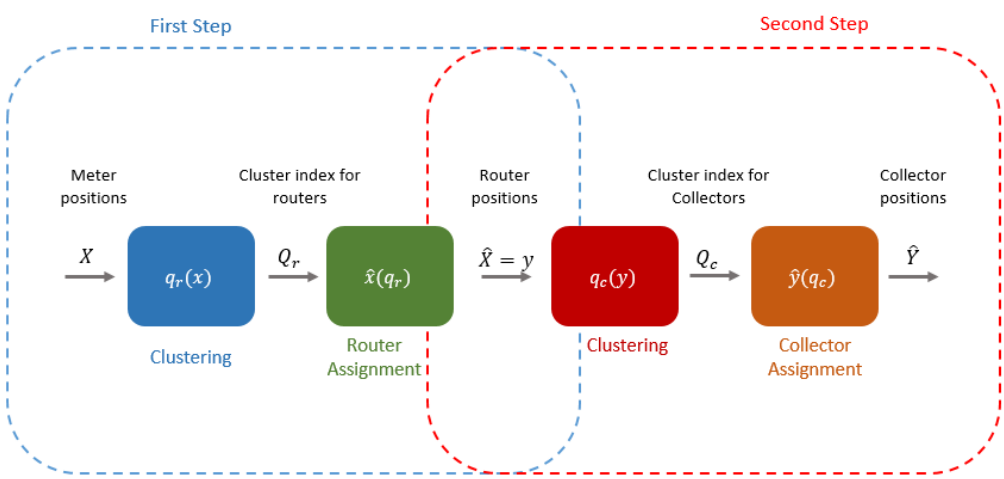


Figure 6: Optimization of key devices in large-scale RF mesh networks

Figure 6 presents the two-layer hierarchical clustering to optimize router and collector positions. The first step consists of applying clustering algorithms on the meter positions X to obtain the router positions $\hat{X}$. The second step consists of applying clustering algorithms on the router positions $\hat{X} = y$ to compute the collector positions $\hat{Y}$. The RF mesh network is simulated with the newly available device positions and the performance

of the network is studied. This case study offers insights on the number of iterations, errors and other simulation parameters required by the clustering algorithms to find optimal positions of the interconnecting devices and how the network behaves when the positions are modified.

5. 3. Experimental results

Simulations are carried out using OMNeT++ with the simulation parameters mentioned in Table 4. The number of collectors used in the case study is 40 and it is based on the study conducted in [23]. This paper concludes that the average number of meters a collector can serve is approximately 8971. Therefore, for the Montreal city of 335297 meters, the total number of collectors in the test network is calculated to be 40. The number of routers required for this large scale RF mesh network is studied with a series of experiments using 100, 150, 200 and 250 routers. The percentage of the total number of meters τ_h that can reach at least one of the available routers is computed based on the router positions found using the particular clustering algorithm. Likewise, the percentage of the total number of routers δ_h that can reach at least one of the available collectors is computed based on the collector positions obtained from implementing the previously described design strategy. The following equations provide the definition of τ_H and δ_h.

$$\tau_H[\%] = \frac{100 \times \sum_{i=1}^{h} P_{m_i}}{m} \tag{3}$$

where m is the number of total meters and

$\sum_{i=1}^{h} P_{m_i}$ is the sum of meters that can reach at least one of the available routers with $h, h - 1, h - 2, \ldots, 1$ hops where $h \in H = \{1,2, \ldots ,10\}$.

$$\delta_h[\%] = \frac{100 \times \sum_{i=1}^{h} P_{r_i}}{r} \quad (4)$$

where r is the number of routers and

$\sum_{i=1}^{h} P_{r_i}$ is the sum of routers that can reach at least one of the available collectors with $h, h - 1, h - 2, \ldots, 1$ hops where $h \in H = \{1,2,3\}$.

Figures 7 and 8 show analytical results. It can be observed that the percentage of the total meters that can directly reach a router increases correspondingly with the total number of routers (as expected). The τ_h values for 100, 150, 200 and 250 routers are 7.8%, 12.4%, 17% and 21.6% respectively. The connectivity between nodes is increased when the total number of routers is increased in a network and, thus, the percentage of meters that can directly connect to a router increases. The results show that almost 80% of the total number of meters can reach a router with maximum of three hops in all the cases.

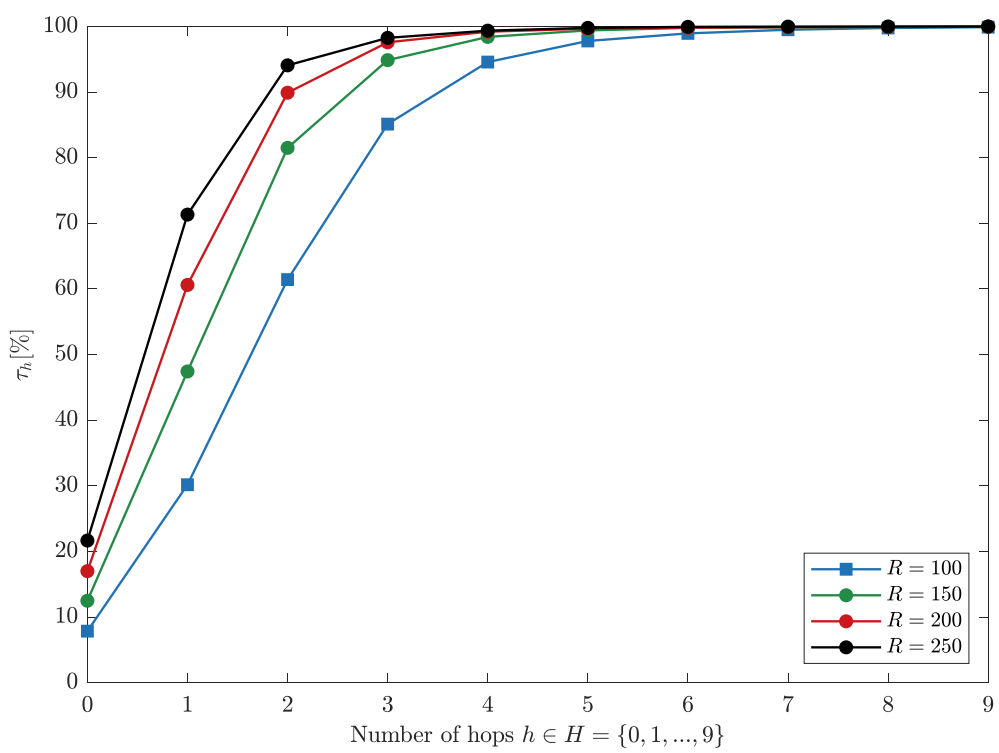


Figure 7: Percentage of total number of meters that can reach one of the routers

Figure 8 shows the case of δ_h where more than 89% of the total number of routers can reach a collector directly in all the cases. OMNeT++ simulations are carried out to evaluate the average end-to-end delay and packet losses to further verify these analytical results and to conclude the optimal number of routers needed in the Montreal Case study. This is done for two configurations, one with 100 routers and the other with 200 routers in the network.

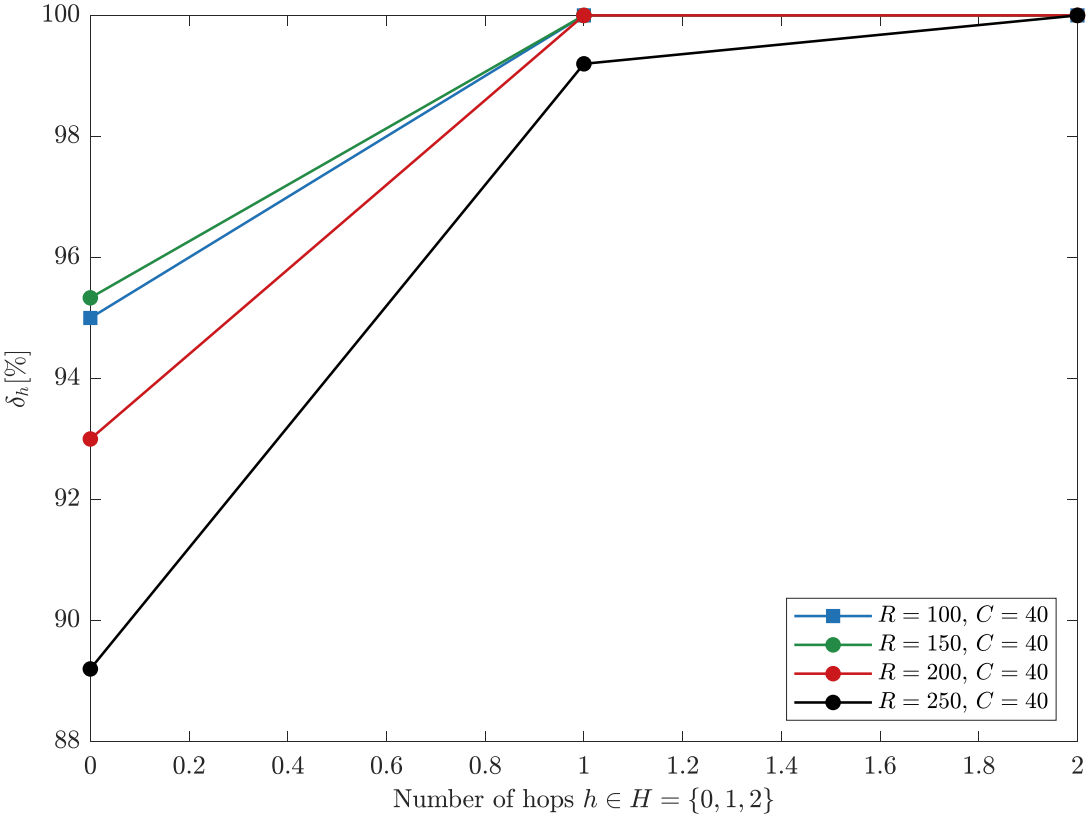


Figure 8: Percentage of total number of routers that can reach one of the collectors

5. 4. Packet losses and average end-to-end delay in RF Mesh network

The simulation settings of the smart grid scenario for the case study are shown in Table 4. All results are obtained from 3 simulations per point.

Parameters	Values
Area	**431 km^2**
Number of smart meters	**335297**
Number of routers	**100/200**
Number of collectors	**40**
Transmission range of meters	**300m**
Transmission range of routers	**2500m**
Transmission range of collectors	**3218m**
MAC specification	**IEEE 802.15.4**
Carrier frequency	**915 MHz**
Transmission bit rate	**115.2 kbps**
Simulation time	**18000 s**
Routing protocol	**Geographical routing**

Table 4: Simulation parameters for the Montreal case study

Figure 9 illustrates the router and collector positions after applying Lloyd's clustering algorithm. The blue star represents the location of meters and the positions of routers and collectors are shown as orange and yellow triangles, respectively.

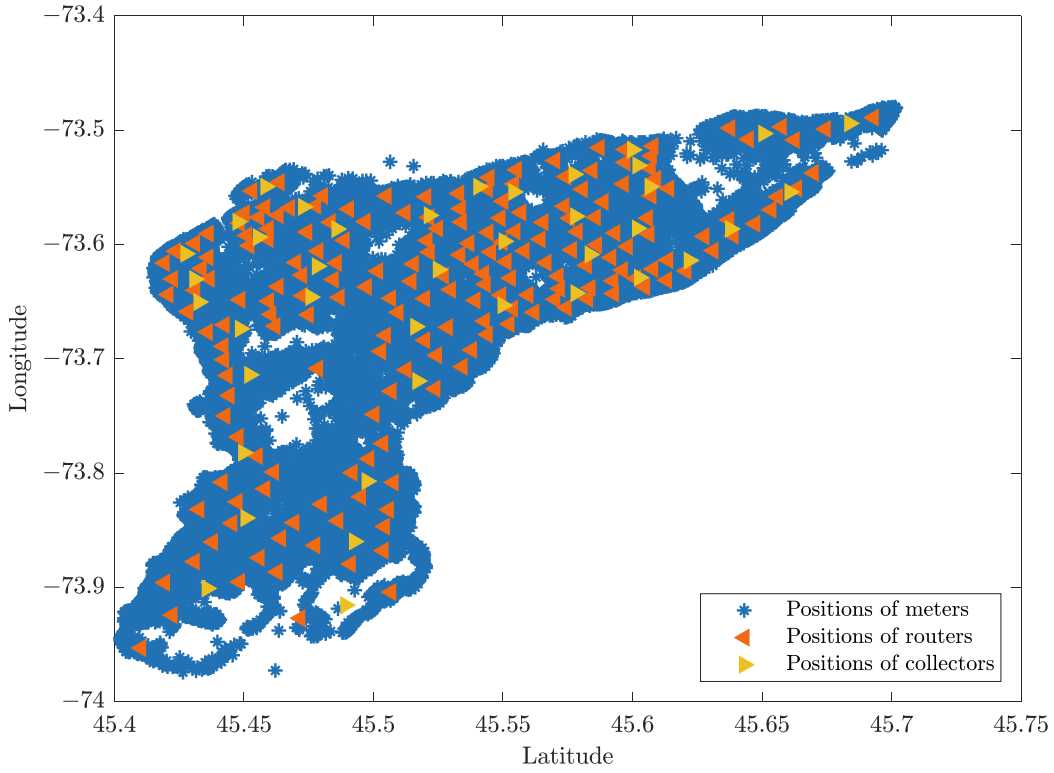


Figure 9: Meters along with optimized router positions and optimized router and collector positions for case study

Table 5 shows the simulation results obtained after positioning the routers and collectors in the RF mesh network using Lloyd's clustering algorithm in OMNeT++ [11]. It can be observed that the average percentage of packet losses, with 100 and 200 routers leads to similar results (i.e., 3.63% and 4.86%, respectively). It can also be seen that the average end-to-end delay value is decreased by increasing the number of routers (18.7s and 16.2s respectively). This is expected as an increase in the number of routers allows packets to reach their destination faster. However, doubling the number of routers does not offer a huge improvement in the delay indicating the law of diminishing returns. Hence, it can be

concluded that 100 routers are enough to achieve a good performance in terms of packet losses and end-to-end delay without the additional cost of extra routers.

Performance Metrics	With 100 Routers	With 200 Routers
Average percentage of packet losses	**3.63%**	**4.86%**
Average end-to-end delay	**18.7s**	**16.2s**

Table 5: Simulation results for the Montreal case study using OMNeT++

This study is concluded with the network performance findings shown in Table 5 and how the positions and the number of key devices impact the network. This validation is then utilized to recommend the use of our hypothesis in finding optimal device positions for the BLPC. This case study serves as a standard and verifiable source for our hypothesis.

Chapter VI

Optimization of Router Positions in BLPC network

The findings of the previous chapter verify the recommendation to use clustering algorithms to find optimal positions for the routers in a mesh network. The following sections provide information on the optimized router positions based on MDAV and Lloyd's algorithm in BLPC network. The analytical and experimental results using OMNeT++ is also presented to validate the hypothesis of improved AMI network performance using clustering algorithms.

6. 1. Introduction

The positions of end nodes (i.e., smart meters) are fixed while the interconnecting devices (i.e., the routers) can be repositioned in our BLPC test framework. The design and development of an efficient routing protocol in a RF Mesh network to connect the smart meters and collectors highly depends on the positions of the routers. The focus of this work is to optimize the positions of the available routers to bring out the highest possible connectivity between smart meters and collectors. The same clustering algorithms described in Chapter 4 are used with the BLPC data. Extensive simulations are carried out to evaluate the improvements in the performance metrics.

The following experiments use the actual geographical locations of 63122 smart meters, 117 routers, and 11 collectors distributed throughout Barbados. This area includes both rural and non-rural areas, some of them heavily populated.

6. 2. Analysis of the number of hops from a meter to a collector in RF Mesh network

Our study is based on the hypothesis that optimized routers positions will lead to fewer packet hops in a network. This is done by computing the percentage of total meters that can reach at least one of the available routers, $\tau_H[\%]$ for the original distribution of routers and optimized positions of routers. $\tau_H[\%]$ is defined in Equation 3 as the percentage of total meters that can reach at least one of the available routers with maximum number of hops h.

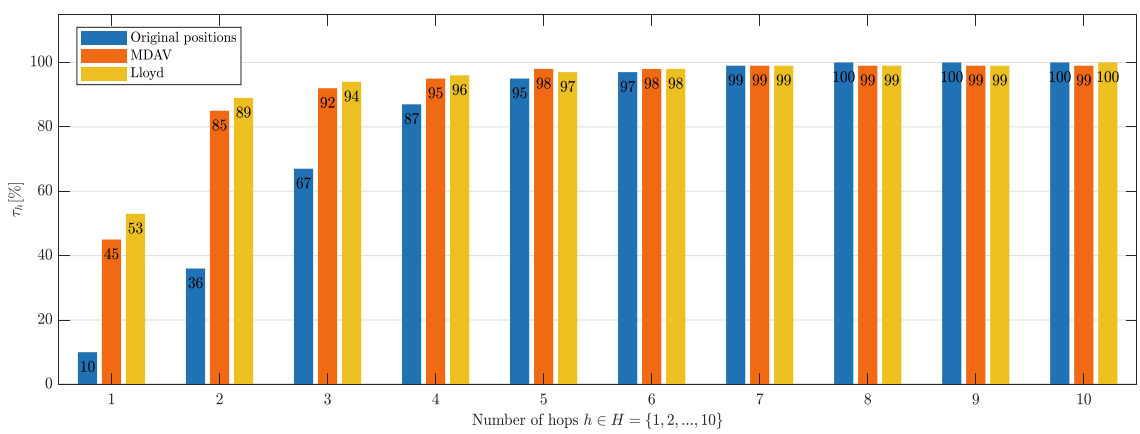


Figure 10: Percentage of total meters that can reach a router through maximum number of hops h

Figure 10 shows the number of hops a packet goes through to arrive at the closest router. It is significantly reduced in the case of modified router positions using MDAV and Lloyd's algorithms. Approximately only 10% of meters can reach a router with one hop on

the original distribution of routers; however, with the new distribution of routers, approximately 45% and 53% of meters can reach a router with one hop. Also, 85% and 89% of the total meters can reach a router with maximum of two hops in optimized distributions but only 36% can make it using the original router positions. This clearly shows the effectiveness of applying MDAV and Lloyd to allocate routers in optimized positions.

As the final packet destination is the collector, it is quite important to compute δ_h , as defined in Equation 4, representing the percentage of total routers that can reach at least one of the available collectors, with h hops. δ_h is computed for the original distribution of routers positions as well as for the optimized distribution of routers.

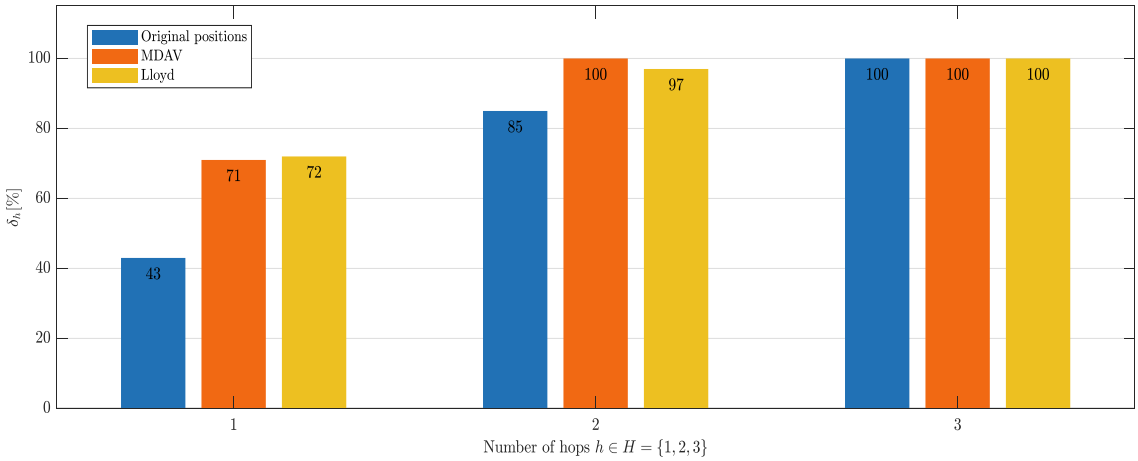


Figure 11: Percentage of total routers that can reach a collector through maximum number of hops

Figure 11 shows a reduction in the number of packet hops from router to collector when MDAV and Lloyd's algorithms are used. This means that, in total, the number of hops a packet goes through to reach a collector is significantly reduced. Around 43% of total routers can reach a collector with one hop in the original distribution of routers; however, 71% and 72% respectively for MDAV and Lloyd's algorithms can reach a

collector with one hop. Almost 100% and 97% of the total routers can reach a collector with a maximum of two hops using MDAV and Lloyd router positions, while only 85% can make it using the original router positions. We can also see that all routers are able to reach a collector with three hops. Results clearly show the effectiveness of applying MDAV and Lloyd to allocate routers in optimized positions, which reduce the total number of hops a packet needs to reach a collector.

6. 3. Packet losses and average end-to-end delay in RF Mesh network

The simulation settings for this smart grid scenario are shown in Table 1. All results are obtained from 3 simulations per point. First, the positions of the 117 routers of the BLPC network are optimized, based on the two clustering algorithms to show the overall performance improvement. Then, the number of routers is reduced from 117 to 105 (10% less), 93 (20% less), and 81 (30% less) respectively to check whether this reduction would affect the network performance and also to verify if allocating fewer routers in optimized positions gives similar or different results. A determination of an optimal number of routers may result in fewer routers than currently deployed resulting in a decrease in capital cost for the BLPC AMI network.

Network performance is evaluated in terms of average end-to-end delay and average percentage packet losses. The relative average end-to-end delay in the network is calculated between the original and the optimized configurations. This is defined in Equation 5

$$\tau_D \stackrel{\text{def}}{=} \frac{t}{t'} \tag{5}$$

where t = Average end-to-end delay in the network with original router positions

And t'= Average end-to-end delay in the network with new router positions.

The relative packet loss in the network is also computed between the original and optimized configurations and is defined as,

$$\tau_L \stackrel{\text{def}}{=} \frac{L}{L'} \tag{6}$$

where L= packet loss with original router positions

L'= packet loss with optimized router positions.

Table 6 gives the improvement in the performance metrics after applying the clustering algorithms for optimized router positions.

Parameter	MDAV based positions	Lloyd based positions
$\boldsymbol{\tau_D}$	1.92x	2.15x
$\boldsymbol{\tau_L}$	1.02x	1.09x

Table 6: Improvement in metrics after optimization of router positions

The above table shows that when the router positions are optimized, the improvement factor is approximately twice that of the original router positions in case of end-to-end delay in the network. Though the improvement in packet losses is only slightly higher than the original network, we get almost 200% performance improvement for the end-to-end delay. For instance, if the average end-to-end delay in the network with the original distribution of routers is 10 seconds, then after optimizing the router positions, the average end-to-end delay will be reduced to almost 5 seconds. The delay is computed based on those packets that successfully arrive at the destination. This enhancement is due to the new distribution of router positions which makes the packets reach the destination with

fewer hops. Finally, this result confirms the improvement obtained analytically by applying MDAV/Lloyd algorithm shown in Figures 10 and 11. We should stress that the average end-to-end delay is an extremely important parameter in smart grid communications and due to that, the problem of where to place routers in RF Mesh network has become an important task to be solved.

Further analysis is carried out using the same number of smart meters and collectors but reducing the total number of routers in the network. The positions of this reduced number of routers are then obtained by using MDAV and Lloyd's Algorithm. The new total number of routers is 10%, 20%, and 30% less than the original number of routers. The following tables (7 and 8) show τ_D and τ_L parameters obtained using fewer routers than the original configuration.

Parameter	10% less No. of Routers	20% less No. of Routers	30% less No. of Routers
$\boldsymbol{\tau_D}$	1.06x	0.85x	0.76x
$\boldsymbol{\tau_L}$	0.63x	0.66x	0.61x

Table 7: Improvement in metrics after reducing the number of routers and using MDAV algorithm for distribution

Parameter	10% less No. of Routers	20% less No. of Routers	30% less No. of Routers
$\boldsymbol{\tau_D}$	0.73x	0.83x	0.81x
$\boldsymbol{\tau_L}$	0.75x	0.74x	0.65x

Table 8: Improvement in metrics after reducing the number of routers and using Lloyd algorithm for distribution

It can be observed from both these tables that the improvement factor for τ_D and τ_L is significantly lower when compared to their original values with all 117 routers present. This means the average end-to-end delay of the network is increased if the number of routers is reduced. For instance, if the average end-to-end delay is 10 seconds in the network, with 20% fewer routers, the average end-to-end delay will be increased to 11.75 seconds. This is expected as less routers in a given network lead to worse overall performance of the RF Mesh network as shown in Tables 5 and 6. It can be concluded that the initial number of routers is enough however the initial positions were not optimal in terms of our performance metrics. The simulations and analytical results indicate that there is room for improvement in the BLPC network. These results suggest that there is a benefit on using the clustering algorithms to find optimized positions of the interconnecting devices in the BLPC network.

A deeper analysis of the currently deployed BLPC AMI network highlights the presence of dead-end meters and isolated clusters. Dead-end meters are those that cannot communicate with any devices in the network, thus packets from these devices do not flow to the collector. Isolated clusters are defined as a group of devices that can communicate among themselves but none of them can connect to a device in the mesh network, hence the packets from these devices are not received at the collector. It should be noted that the nominal device transmission ranges were used in the RF mesh simulation and higher transmit powers would reduce the number of isolated clusters and dead-end nodes.

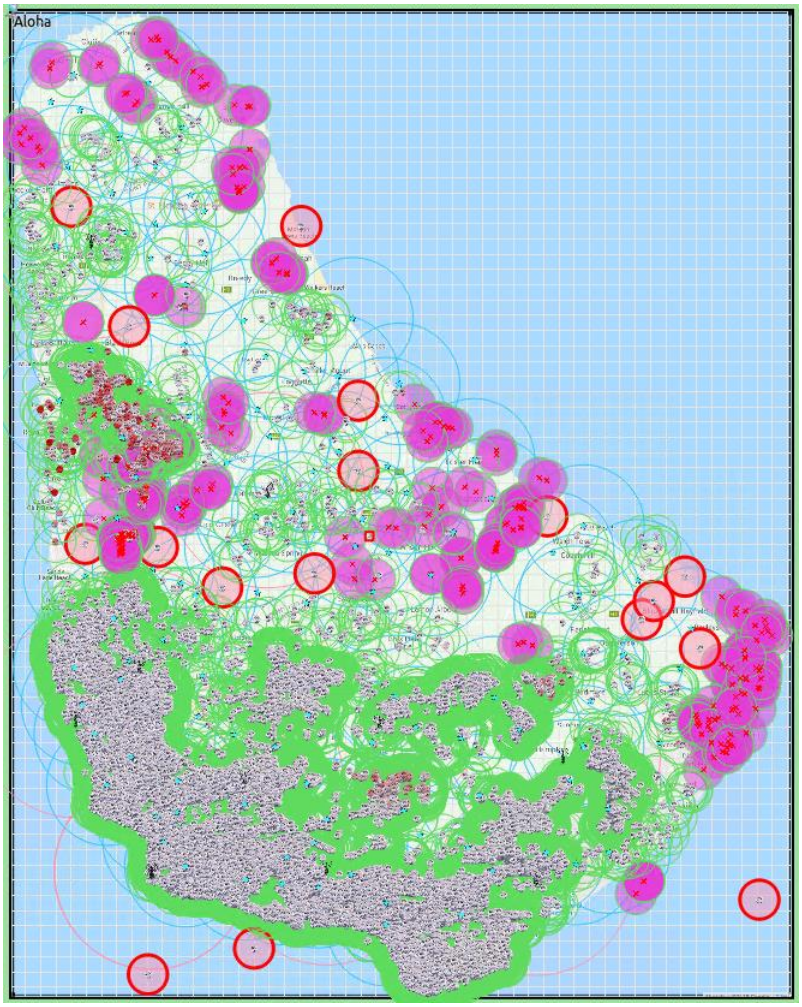


Figure 12: Barbados Map showing the dead end meters and isolated clusters

Figure 12 shows the existing dead-end meters and isolated clusters. The devices with red circles are dead-end meters and those with pink shades are the isolated clusters. Further network design information from the industry vendor, Landis & Gyr, is required to determine the validity of this result in the actual BLPC deployment scenario.

Chapter VII

Conclusions and future work

7. 1. Conclusions

The main objective of this research was to optimize the positions of interconnecting devices, routers, and collectors, in a RF mesh AMI network. The optimization techniques, based on two well-known clustering algorithms, were evaluated using extensive OMNeT++ simulations. This hypothesis of optimal router and collector positions was initially validated by a case study on Montreal city data and provided insights on the network performance and the impact of the positions of the interconnecting devices. This case study dealt with optimizing both the router and collector positions, since both were flexible in terms of installation locations. The study verified the effectiveness of the AMI design strategy based on clustering algorithms. The results for the case study were presented and discussed in detail.

A baseline test AMI network was then built using actual deployment information provided by BLPC on the location of smart meters, routers, and collectors. This AMI network was evaluated in terms of metrics such as end-to-end delay, packet losses, and packet hop count. The results confirm the Montreal study that optimal positioning of the routers in the RF mesh network leads to better overall performance. Also, we analyzed the

optimal number of routers required for this AMI network implementation. The results provided confirmation that the existing number of routers is sufficient, but they can be repositioned to offer an overall better performance. This research also presented a background survey of routing protocols for smart grid applications. The geographical routing protocol is used throughout this study due to its most likely utilization by the Landis & Gyr AMI system used by BLPC. Extensive research and simulations are needed in the future to select an optimal routing protocol suitable for this application.

7. 2. Research papers published as a result of the thesis work

The consolidated study and experimental results for the Barbados test AMI network were published as a research paper titled "**Optimized Routers Positions for Large-Scale RF Mesh Networks based on Clustering Algorithms"** in the Elsevier Journal named **Ad-hoc Networks** with impact factor 3.1. It was reviewed and accepted for publishing in April 2019. Another paper titled," **Optimization of Key Devices Positions in Large-Scale RF Mesh Networks",** was submitted to the conference **PEWASUN'19** and was accepted. This paper presents the case study with Montreal city data and applying the clustering algorithms to get the optimal positions for routers and collectors to form the RF mesh network.

7. 3. Future Work

Further study should be carried out to analyze the reasons for the presence of dead-end meters and isolated clusters. One of the reasons for the existence of these dead-end nodes could be the fact that the test AMI network does not contain all the devices that will

be part of the mesh network in the real-world scenario. The following results are from 63122 smart meters placed in the test network. BLPC estimates a total of around 120000 smart meters would eventually be part of the RF mesh network. The connectivity will be much improved once all the devices are incorporated, even with using nominal transmit power levels.

Future study to determine the optimal routing protocol for this application based on the expected traffic in the completed network should be evaluated. Further improvement when determining the optimal positions of interconnecting devices can be done by using not only the distance but also taking into consideration other metrics such as transmitting power, noise cancellation in the devices, etc. The real-world implementation of interconnecting devices in their optimal positions should also include a study on possible terrain modeling for multipath effects and RF interference from other wireless emitters.

References

[1] Bill Lichtensteiger, Branko Bjelajac, Christian Mueller, Christian Wietfeld, "RF Mesh Systems for Smart Metering: System Architecture and Performance", *2010 First IEEE International Conference on Smart Grid Communications*, Gaithersburg, MD, USA, Oct 2010, ISBN 978-1-4244-6512-5.

[2] Ian F. Akyildiz, Xudong Wang, Weilin Wang," Wireless mesh networks: a survey", *Computer Networks*, Vol 47, Issue 4, March 2005.

[3] Gopalakrishnan Iyer, Prathima Agrawal, Emmanuel Monnerie, Ruben Salazar Cardozo," Performance analysis of wireless mesh routing protocols for smart utility networks", *2011 IEEE International Conference on Smart Grid Communications* (SmartGridComm), Brussels, Belgium, Oct 2011, ISBN 978-1-4577-1702-4.

[4] Filippo Malandra, Brunilde Sansò, "Analytical performance analysis of a large-scale RF-mesh smart meter communication system", *2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference* (ISGT), Washington DC, USA, Feb 2015, ISBN 978-1-4799-1785-3.

[5] S. Valuiskyi, V. Novikov, T. Pryshchepa, A. Romaniuk, "Improved Algorithm for Real Time Search of WSN Routers Placement", *2016 4th International Conference on Methods*

and Systems of Navigation and Motion Control (MSNMC), Kiev, Ukraine, Dec 2016, ISBN 978-1-5090-1053-0.

[6] Emilio Ancillotti, Raffaele Bruno, and Marco Conti, "The Role of the RPL Routing Protocol for Smart Grid Communications", *IEEE Communications Magazine*, Vol. 51, pp. 75-83, 2013.

[7] Filippo Malandra, Brunilde Sansò, "Performance analysis of large scale RF-mesh networks for smart cities and IoT", *2017 IEEE International Conference on Smart Grid Communications* (SmartGridComm), Dresden, Germany,Oct 2017, ISBN 978-1-5386-09439.

[8] Zhutian Yang, Rui Han, Yunfei Chen, Xianbin Wang, "Green-RPL: An Energy-Efficient Protocol for Cognitive Radio Enabled AMI Network in Smart Grid", *IEEE Access* (Vol 6), March 2018, ISBN 2169-3536.

[9] Leonard Kleinrock and John Silvester," Optimum Transmission Radii for Packet Radio Networks", *Proceedings of the IEEE National Telecommunications Conference*, Birmingham, Alabama, December 1978, pp. 4.3.1–4.3.5.

[10] Tadashige Iwao, Kenji Yamada, Masakazu Yura, Yuuta Nakaya, Alvaro A. Cardenas, Sung Lee, Ryusuke Masuoka, "Dynamic Data Forwarding in Wireless Mesh Networks",

2010 First IEEE International Conference on Smart Grid Communications, Oct 2010, Gaithersburg, MD, USA.

[11] Stephen Dawson-Haggerty, Arsalan Tavakoli," HYDRO: A Hybrid Routing Protocol for Low-Power and Lossy Networks", *Proceedings of the IEEE National Telecommunications Conference*, 2010, pp 268-273.

[12] Hiertz, G. R., Max, S., Zhao, R., Denteneer, D., & Berlemann, L. (2007, August). "Principles of IEEE 802.11 s", *2007 16th International Conference on Computer Communications and Networks* (pp. 1002-1007).

[13] Robertsingh, A., Devaraj, D., & Narmathabanu, R. (2015, December). "Development and analysis of wireless mesh networks with load-balancing for AMI in smart grid", *2015 international conference on computing and network communications* (CoCoNet) (pp. 106-111).

[14] Gharavi, H. and Hu, B.," Multigate communication network for smart grid". *Proceedings of the IEEE*, 99(6), pp.1028-1045, 2011.

[15] Kim, Jaebeom, Dabin Kim, Keun-Woo Lim, Young-Bae Ko, and Sang-Youm Lee. "Improving the reliability of IEEE 802.11 s based wireless mesh networks for smart grid systems." *Journal of Communications and Networks 14*, no. 6 (2012): 629-639.

[16] Farooq, Hasan, and Low Tang Jung. "Health, link quality and reputation aware routing protocol (HLR-AODV) for Wireless Sensor Network in Smart Power Grid." *2012 International Conference on Computer & Information Science* (ICCIS), vol. 2, pp. 664-669, 2012.

[17] J. Domingo-Ferrer, A. Martínez-Ballesté, J. M. Mateo-Sanz, and F. Sebé, "Efficient multivariate data-oriented microaggregation," *VLDB J., vol. 15*, no. 4, pp. 355–369, 2006.

[18] J. Domingo-Ferrer and V. Torra, "Ordinal, continuous and heterogeneous k-anonymity through microaggregation," *Data Min., Knowl. Discov*., vol. 11, no. 2, pp. 195–212, 2005.

[19] A. Hundepool, A. V. de Wetering, R. Ramaswamy, L. Franconi, A. Capobianchi, P.-P. de Wolf, J. Domingo-Ferrer, V. Torra, R. Brand, and S. Giessing, "μ-ARGUS version 3.2 software and user's manual", *Stat. Neth., Voorburg*, Netherlands, 2003. [Online]. Available: http://neon.vb.cbs.nl/casc.

[20] M. Templ, "Statistical disclosure control for microdata using the R-package sdcMicro," *Trans. Data Priv*., vol. 1, no. 2, pp. 67–85, 2008. [Online]. Available: http://cran.r-project.org/web/packages/sdcMicro.

[21] S. P. Lloyd, "Least squares quantization in PCM," *IEEE Trans. Inform. Theory*, vol. IT-28, pp. 129–137, Mar. 1982.

[22] Varga, András, and Rudolf Hornig. "An overview of the OMNeT++ simulation environment." *Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops*, p. 60. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008.

[23] "Hydro Québec, May 2012, Remote meter reading project phase 1." [Online]. Available: *http://publicsde.regie/energie.qc.ca/projets/34/DocPrj/R-3770-2011-B-0157-TRAD-DOC 2012_05_23.pdf.*

[24] Shaukat, N., S. M. Ali, C. A. Mehmood, B. Khan, M. Jawad, U. Farid, Z. Ullah, S. M. Anwar, and M. Majid. "A survey on consumer's empowerment, communication technologies, and renewable generation penetration within Smart Grid." *Renewable and Sustainable Energy Reviews* 81 (2018): 1453-1475.

[25] Malandra, Filippo, and Brunilde Sansò. "A Markov-Modulated End-to-End Delay Analysis of Large-Scale RF Mesh Networks With Time-Slotted ALOHA and FHSS for Smart Grid Applications." *IEEE Transactions on Wireless Communications 17*, no. 11 (2018): 7116-7127.

[26] S. Rogai, "Telegestore Project - Progress and Results", *IEEE International Symposium of Power Line Communications and its Applications*, Pisa/Italy, March 2007.

[27] R. M. Fujimoto, "Large-scale network simulation: how big? how fast?," *Modeling, Analysis and Simulation of Computer Telecommunications Systems*, MASCOTS 11th IEEE/ACM International Symposium, 2003.

[28] R. D. L. Engle, "Modeling Quantum Optical Components, Pulses and Fiber Channels Using OMNeT++," *Proceedings of the "OMNeT++ Community Summit*, 2015.

[29] Huang, Xinxin, Shaowei Wang, and Chonggang Wang. "Aggregation points planning for smart grid communications: Wired and wireless cases." *2015 IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6, 2015.

[30] Kong, Peng-Yong. "Cost efficient data aggregation point placement with interdependent communication and power networks in smart grid." *IEEE Transactions on Smart Grid 10*, no. 1 (2017): 74-83.

[31] Mohammadali, Amin, Mohammad Sayad Haghighi, Mohammad Hesam Tadayon, and Alireza Mohammadi-Nodooshan. "A novel identity-based key establishment method for advanced metering infrastructure in smart grid." *IEEE Transactions on Smart Grid 9*, no. 4 (2016): 2834-2842.

[32] Mustapa, Muslim, Mohammed Y. Niamat, Atul Prasad Deb Nath, and Mansoor Alam. "Hardware-oriented authentication for advanced metering infrastructure." *IEEE Transactions on Smart Grid 9*, no. 2 (2016): 1261-1270.

[33] Rolim, Guilherme, Diego Passos, Igor Moraes, and Célio Albuquerque. "Modelling the data aggregator positioning problem in smart grids." *2015 IEEE International Conference on Computer and Information Technology; Ubiquitous Computing and Communications; Dependable, Autonomic and Secure Computing; Pervasive Intelligence and Computing*, pp. 632-639. IEEE, 2015.

[34] Wang, Guodong, Yanxiao Zhao, Yulong Ying, Jun Huang, and Robb M. Winter. "Data aggregation point placement problem in neighborhood area networks of smart grid." *Mobile Networks and Applications 23*, no. 4 (2018): 696-708.

[35] Zhang, Chen, Cheng Li, and Yuanzhu Chen. "A markov model for batch-based opportunistic routing in multi-hop wireless mesh networks." *IEEE Transactions on Vehicular Technology67*, no. 12 (2018): 12025-12037.

[36] Xu, Yuanhuizi, Kwan-Wu Chin, and Sieteng Soh. "A Novel Distributed Pseudo-TDMA Channel Access Protocol for Multi-Transmit-Receive Wireless Mesh Networks." *IEEE Transactions on Vehicular Technology 67*, no. 3 (2017): 2531-2542.

[37] Shaukat, N., S. M. Ali, C. A. Mehmood, B. Khan, M. Jawad, U. Farid, Z. Ullah, S. M. Anwar, and M. Majid. "A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid." *Renewable and Sustainable Energy Reviews 81* (2018): 1453-1475.

[38] Seggelmann, Robin, Irene Rüngeler, Michael Tüxen, and Erwin P. Rathgeb. "Parallelizing OMNeT++ simulations using xgrid." *Proceedings of the 2nd International Conference on Simulation Tools and Techniques*, p. 69. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2009.

[39] Liu, Qiong, and Peng Li. "Backoff algorithm optimization and analysis for IEEE 802.15. 4 wireless sensor networks." *2014 9th International Symposium on Communication Systems, Networks & Digital Sign* (CSNDSP), pp. 411-416, 2014.

[40] Sekercioglu, Yasar Ahmet, András Varga, and Gregory K. Egan. "Parallel simulation made easy with OMNeT++." *European Simulation Symposium 2003*, pp. 493-499. SCS Europe Publishing House, 2003.

APPENDIX

The network simulation is carried out in OMNeT++ using the following code. The code has two parts. The initialization and the modeling. The initialization file contains the values for the parameters defined in the modeling. This file can be configured with a different set of values for each parameter to simulate different scenarios. The different components of the network such as meters, routers, collectors are individually modeled using the Network Description language (NED). The NED files define the graphic properties of the individual modules while the functions of each module are programmed using C++. Figure 13 shows the OMNeT++ framework with the command and console view.

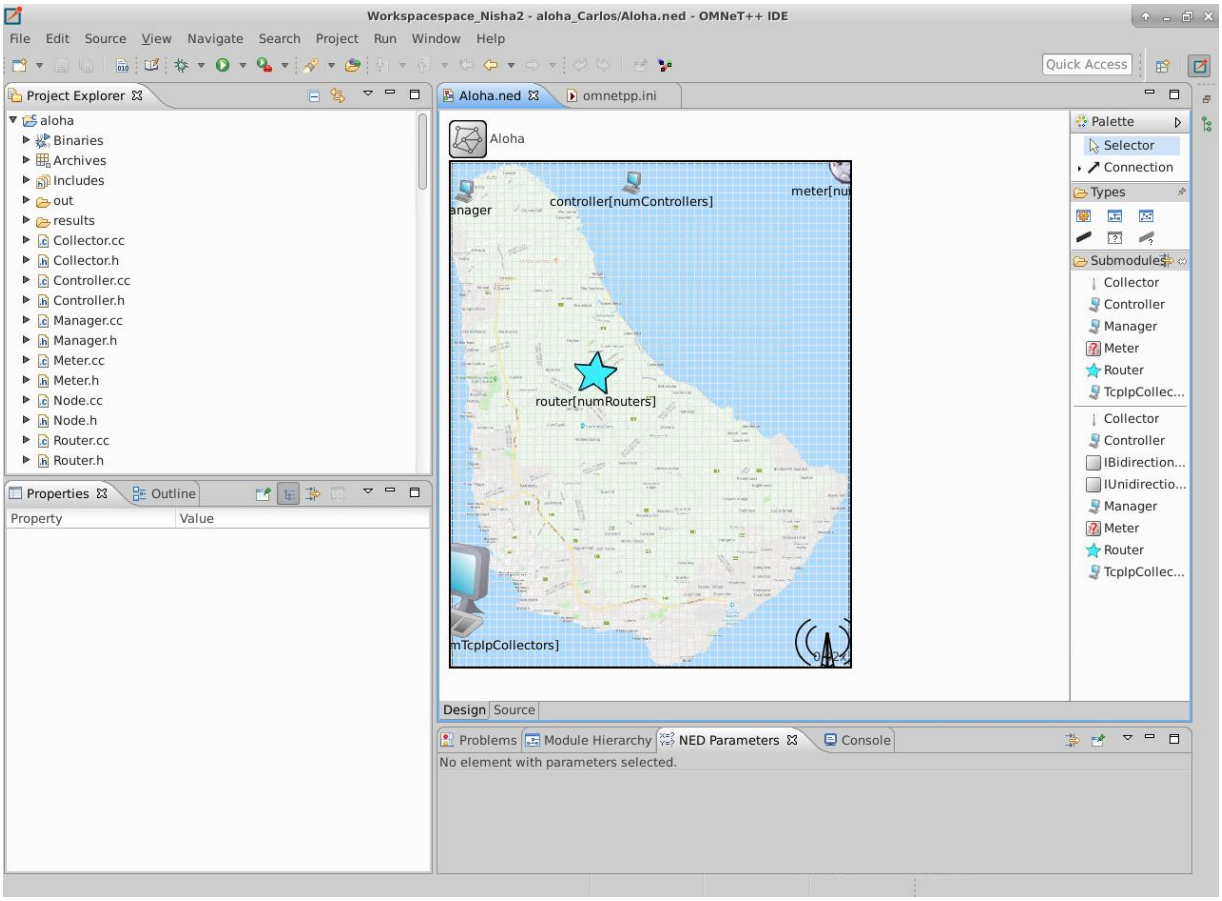


Figure 13: OMNeT++ Network Simulator Console

The .ned files contain the graphical and geographical information of each module.

(i) Aloha.ned (For the BLPC AMI network simulation)

```
// Copyright (C) 1992-2015 Andras Varga
// The Aloha network consists of hosts which talk to the central
"server" via
// the Aloha or Slotted Aloha protocol
//
network Aloha
{
    parameters:
        bool saveData;
        bool GIS;
        int BackOffMethod;
        double BackOffTime @unit(s);
        int macMinBe;
        int macMaxBe;
        int macMaxFrameRetries;
        int numUsageSent;
        int numUsageReceived;
        int numRouters;
        int numMeters;
        int numControllers;
        int numCollectors;
        int numTcpIpCollectors;
        int length @unit(m);
        int width @unit(m);
        double txRate @unit(bps);  // transmission rate
        double slotTime @unit(s);  // zero means no slots (pure
Aloha)
        double ackTimeout @unit(s);
        bool isRandomlyGenerated;
        string DispOption;
        string Algorithm_option; //For Various Router positions
algorithm NR
        int Run; //For Batch Simulations NR
        // Display for Barbados BPLC

@display("bgi=background/Barbados,s;bgg=500,0,grey90;bgb=25592,32
280");
    submodules:
        // Ranges updated from L&G
```

```
        // device            min(/m)            ave
max
        // meter                                1400f/426.7m
        // router-meter
2300f/701.4m
        // router-router     0.5mile/804.672m
2mile/3218.69m
        // router-collector  0.5mile/804.672m
2mile/3218.69m   C6000 collector
        // router-collector  1mile/1609.34m
3mile/4828.03m   C7000 collector

        //DO NOT CHANGE NAME OF SUBMODULE AS THE EXACT STRING IS
USED TO IDENTIFY THEM
        // disable Tx Range display when simulating scenarios
with large number of endpoints:
            meter[numMeters]: Meter {
            txRange = 300m;     // Originally 300m, 210m for
ALPHA, 300 for BETA, from L+G docs 700.72m
            //rangeBorderColor = "#lightgray";   //light GREEN
            rangeBorderColor = "#5fdc5f";   //light GREEN
                    }
        //similar to a meter but usage generation and less likely
to bounce data
        controller[numControllers]: Controller {
            txRange = 400m;      // Originally 300m
            rangeBorderColor = "";
                    }
        router[numRouters]: Router {
            txRange = 2500m;     // 1650m for ALPHA, 2000 for
BETA, BETA works with 2500m, from L+G docs 2011.68m
            rangeBorderColor = "#32c8ff";   //light BLUE
        }
        collector[numCollectors]: Collector {
            txRange = 3218m;     // 2100 for ALPHA  same for
BETA, works with 2500m, from L+G docs 3218m
            rangeBorderColor = "#ff96b4";   // light RED
        }
        tcpIpCollector[numTcpIpCollectors]: TcpIpCollector;
        manager: Manager;}
```

(ii) Meter.ned

```
// Copyright (C) 1992-2015 Andras Varga
//
```

```
// This file is distributed WITHOUT ANY WARRANTY. See the file
// `license' for details on this and other legal matters.
simple Meter
{
    parameters:
        double animationHoldTimeOnCollision @unit(s) =
default(0s); // in animation time

        double txRange @unit(m);
        string rangeBorderColor;
        volatile int pkLenBits @unit(b);    // packet length in
bits
        volatile double usageTxPeriod @unit(s);// packet arrival
time
        double x @unit(m);            // the x coordinate of the
meter
        double y @unit(m);            // the y coordinate of the
meter
        double idleAnimationSpeed;   // used when there is no
packet being transmitted
        double transmissionEdgeAnimationSpeed;  // used when the
propagation of a first or last bit is visible
        double midTransmissionAnimationSpeed;     // used during
transmission
        bool controlAnimationSpeed = default(true);
        int numChannels;
        int numRxCh = default(1);
        bool isSharedRadio = true;
        @display("i=device/FocusAXRe_SD_s");
    gates:
        input in @directIn;      //messages (both self and inter
module non-manager)
        input dataIn @directIn;  //from manager to generate usage
data
}
```

(iii) Router. ned

```
simple Router
{
    parameters:
        double animationHoldTimeOnCollision @unit(s) =
default(0s); // in animation time
```

```
        double txRange @unit(m);           // transmission range
        string rangeBorderColor;
        double x @unit(m);                 // the x coordinate of
the meter
        double y @unit(m);                 // the y coordinate of
the meter
        double idleAnimationSpeed;         // used when there is
no packet being transmitted
        double transmissionEdgeAnimationSpeed; // used when the
propagation of a first or last bit is visible
        double midTransmissionAnimationSpeed; // used during
transmission
        bool controlAnimationSpeed = default(true);
        int numChannels;
        int numRxCh = default(1);
        bool isSharedRadio = false;
        @display("i=abstract/bstar_n1");
            gates:
        input in @directIn;
}
```

(iv) Collector.ned

```
// Copyright (C) 1992-2015 Andras Varga
//
// The central computer in the ALOHAnet network.
//
simple Collector
{
    parameters:
        double animationHoldTimeOnCollision @unit(s) =
default(0s); // in animation time

        double txRange @unit(m);        // transmission range
        string rangeBorderColor;
        volatile int pkLenBits @unit(b);   // packet length in
bits
        volatile double controlSignalPeriod @unit(s);   //
control interarrival time: 0 implies no control signal
        double x @unit(m);        // the x coordinate of the
collector
        double y @unit(m);        // the y coordinate of the
collector
```

```
        double idleAnimationSpeed; // used when there is no
packet being transmitted
        double transmissionEdgeAnimationSpeed; // used when the
propagation of a first or last bit is visible
        double midTransmissionAnimationSpeed; // used during
transmission
        bool controlAnimationSpeed = default(true);
        int numChannels;
        int numRxCh = default(4);
        bool isSharedRadio = false;
        @display("i=device/antennatower_vl");

        @signal[arrivalR](type="simtime_t"); //Signal Declaration

@statistic[delayFirstNewMessageR](title="delayFirstNewMessageR";
source="arrivalR"; record=vector,stats; interpolationmode=none);
    gates:
        input in @directIn;
        input dataIn @directIn; //used to receive control events
}
```

(v) Manager.ned

```
simple Manager
{
    parameters:
        string host;
        string user;
        string password;
        string database;
        int port;
        @display("i=device/pc_s");

}
```

(vi) Omnetpp.ini

The Initialization file “omnetpp.ini” contains the values of parameters for each run instance.

```
[General]
network = Aloha
#sim-time-limit=10000s  # Original
```

```
sim-time-limit=14400s   # 4 hours
cmdenv-express-mode=true

# Before simulation observe the following parameters in Aloha.ned
# Background picture
# Transmission ranges

# Geographical information for devices positioning
Aloha.GIS = false
# Backoff Algorithm for retransmision management
Aloha.BackOffMethod = 0 # 0 : no backoff, 1 : uniform in
backofftime, 2: uniform in backofftime/2
Aloha.BackOffTime = 100s # time period to retransmit
#TSCH-CSMA-CA parameters. refer to table 8-83 in IEEE 802.15.4-
2015
Aloha.macMinBe = 1
Aloha.macMaxBe = 7
Aloha.macMaxFrameRetries = 3

#device counts
Aloha.numCollectors = 1
Aloha.numMeters = 1000
Aloha.numRouters = 500
Aloha.numControllers = 5000
Aloha.numTcpIpCollectors = 1

#indicates if the generation is randomly sent
Aloha.isRandomlyGenerated = true
Aloha.saveData = false #will save if not random and is set to
true

#slotted aloha parameters
Aloha.slotTime = 0.7s                       #slot time
Aloha.ackTimeout = 0.3s                    #Original #0 implies
timeout occurs just before next slot
#Aloha.txRate = 300kbps                      #max speed (BLPC
info doc)
Aloha.txRate = 115.2kbps                      #max speed (updated
BLPC info doc)
Aloha.collector[*].controlSignalPeriod = 0s #0 implies not
control events
Aloha.collector[*].pkLenBits = 50b          #number of bits per
control signal
Aloha.meter[*].usageTxPeriod = 86400s       #every day
```

```
Aloha.meter[*].pkLenBits = 20000b           #data size (2.5kB per
day)

#data collection
Aloha.numUsageSent = 0                       total number of
packets Sent??
Aloha.numUsageReceived = 0                   total number of
packets received

#system parameters. location set at random for now
Aloha.length = 10000m
Aloha.width = 8000m
Aloha.meter[*].x = uniform(0m, 10000m)                  #spacing
at random to get started
Aloha.router[*].x = uniform(0m, 10000m)                  #spacing
at random to get started
Aloha.controller[*].x = uniform(0m, 10000m)
#spacing at random to get started
Aloha.meter[*].y = uniform(0m, 8000m)                  #spacing
at random to get started
Aloha.router[*].y = uniform(0m, 8000m)                 #spacing
at random to get started
Aloha.controller[*].y = uniform(0m, 8000m)
#spacing at random to get started
**.numChannels = 80                        #80 was the original
based on BLPC info doc
#Aloha.meter[*].numRxCh = 80
#Aloha.router[*].numRxCh = 1
#Aloha.router[*].numChannels = 1
# ...MZA
Aloha.collector[*].numRxCh = 80              #4 number of
channels to rx on per slot

#animation params that depend on data and rate
**.animationHoldTimeOnCollision = 0s        #text bubble delay
time
**.idleAnimationSpeed = 1                   #speed of animation
while not sending
**.transmissionEdgeAnimationSpeed = 1e-6    #speed of packet
after tx befor rx
**.midTransmissionAnimationSpeed = 1e-1     #speed during
transfer

#db connection parameters
```

```
Aloha.manager.host = "192.168.122.18"
Aloha.manager.user = "dbuser"
Aloha.manager.password = "passw0rd"
Aloha.manager.database = "WaterHeaters"
Aloha.manager.port = 3306

#paticular test cases
[Config Barbados01]

Aloha.GIS = true
# Geograpical information for devices positioning is in the
files:
# metersCSVomnetpp.csv
# routersCSVomnetpp.csv
# collectorsCSVomnetpp.csv
Aloha.DispOption="Batch"

#Aloha.Algorithm_option=${M="Original","MDAV","LLYOD"} # Analysis
of new positions
#Aloha.Run=${N=1,2,3}
#Analysis of number of routers

Aloha.Algorithm_option="Original"
Aloha.Run=1
#Aloha.Run=${N=1,2,3}
Aloha.length = 25592m
Aloha.width = 32280m
description = "Barbados01"
sim-time-limit=5h  #5h
# number of devices, equal or less that the data stored at csv
files.
Aloha.numCollectors = 11
Aloha.numRouters = 117
Aloha.numMeters = 63123
Aloha.numControllers = 0

Aloha.isRandomlyGenerated = true
Aloha.saveData = false #will save if not random and is set to
true
Aloha.slotTime = 0.7s    # worked with 0.1, no stats though
Aloha.ackTimeout = 0.3s                        #timeout occurs
just before next slot
Aloha.collector[*].controlSignalPeriod = 0s     #0s  #control
event every 100 seconds
```

```
Aloha.meter[*].usageTxPeriod = 2h               #tx every 1000
secs
Aloha.meter[*].pkLenBits = 1000b                  #number bits
stored by the meter during usage period
Aloha.collector[*].x = 7693m
Aloha.collector[*].y = 25170m
Aloha.meter[*].x=0m
Aloha.meter[*].y=0m
Aloha.router[*].x=0m
Aloha.router[*].y=10000m
Aloha.BackOffMethod = 0# 0 : no backoff, 1 : binary uniform

[Config Montreal]

Aloha.GIS = true
# Geograpical information for devices positioning is in the
files:
# metersCSVomnetpp.csv
# routersCSVomnetpp.csv
# collectorsCSVomnetpp.csv
Aloha.DispOption="Batch"

#Aloha.Algorithm_option=${M="Original","MDAV","LLYOD"} # Analysis
of new positions
#Aloha.Run=${N=1,2,3}

#Analysis of number of routers

Aloha.Algorithm_option="Original"
Aloha.Run=${N=1,2,3,4,5}
#Aloha.Run=${N=1,2,3}
Aloha.length = 32280m
Aloha.width = 25592m
description = "Montreal"
sim-time-limit=5h  #5h
# number of devices, equal or less that the data stored at csv
files.
Aloha.numCollectors = 40
Aloha.numRouters = 200
Aloha.numMeters = 335297
Aloha.numControllers = 0

Aloha.isRandomlyGenerated = true
```

```
Aloha.saveData = false #will save if not random and is set to
true
Aloha.slotTime = 0.7s    # worked with 0.1, no stats though
Aloha.ackTimeout = 0.3s                        #timeout occurs
just before next slot
Aloha.collector[*].controlSignalPeriod = 0s     #0s  #control
event every 100 seconds
Aloha.meter[*].usageTxPeriod = 2h               #tx every 1000
secs
Aloha.meter[*].pkLenBits = 1000b                  #number bits
stored by the meter during usage period
Aloha.collector[*].x = 7693m
Aloha.collector[*].y = 25170m
Aloha.tcpIpCollector[0].x = 0m
Aloha.tcpIpCollector[0].y = 0m
Aloha.meter[*].x=0m
Aloha.meter[*].y=0m
Aloha.router[*].x=0m
Aloha.router[*].y=10000m
Aloha.BackOffMethod = 0# 0 : no backoff, 1 : binary uniform
```

Curriculum Vitae

Candidate's full name: Nisha Rajendran

Undergraduate Degree: Bachelor of Engineering in Electronics & Instrumentation

University attended: Anna University, Chennai India- Bachelor of Engineering, 2012

Undergraduate Thesis:

ARM based Reconfigurable Wireless Network for Industrial Automation, 2012

Publications:

1. Mezher, Ahmad Mohamad, Julián Cárdenas-Barrera, Nisha Rajendran, Julian Meng, and Eduardo Castillo Guerra. "Optimized Routers Positions for Large-Scale RF Mesh Networks based on Clustering Algorithms." Ad Hoc Networks (2019): 101901.

2. Mezher, Ahmad Mohamad, Julián Cárdenas-Barrera, Nisha Rajendran, Julian Meng, and Eduardo Castillo Guerra, "Optimization of Key Devices Positions in Large-Scale RF Mesh Networks", PEWASUN'2019 Conference.