Design and Analysis of Hybrid Wireless Mesh Networks for Smart Grids

Philip Huu Huynh and C. Edward Chow

Department of Computer Science, University of Colorado at Colorado Springs, Colorado, USA
{phuynh,cchow}@uccs.edu

Abstract. In this paper the use of a Hybrid Wireless Mesh Network (HWMN) technologies for the smart grid of Advanced Metering Infrastructure (AMI), which enables the collecting of meter data in real-time, was proposed and analyzed. A Google Maps mashup was developed to read the real GIS data from a local utility company and display the locations of the meters and light poles, which can be selected for mounting the WiMAX or Wi-Fi network devices. A NS-3 simulator was developed to simulate the network traffic of meter data collection over the HWMN and to allow us to evaluate different topologies and to see if their capacities are adequate to report all meter values to the data center within one second. The preliminary simplified simulation results show that with the proper antennae selection for the HWMN, it is feasible to collect meter data from hundreds of thousands smart meters within one second.

Keywords: AMI, WiMax, Wi-Fi, Smart Grid, Simulation, Network Planning.

1 Introduction

Recently many utilities deployed smart grids for collecting meter data [1]. The main reasons are to reduce the cost by not sending people to read the meter data and by avoiding generating excess power through correct prediction of the load profile using the aggregated meter values. To correctly predict the load profile and perform load forecasting, utilities need to collect meter data in real time.

Utilities have hundreds of thousands of meters installed in their service areas, and want to network these meters for metering collection. The wireless communication technologies have been popularly deployed in the local areas and the metropolitan areas because of their conveniences in the cost, network installation and maintenance. Taking advantages of the wireless technologies, utilities can network their meters and the data center for data communication. However, if the underlined wireless technologies do not provide enough bandwidth, then the meter data cannot be delivered to the data center in time. The WiMAX technology allows us networking the meters and the data center with the broadband data transmission at long distance and higher bandwidth [2, 3]. Therefore, the wireless networking solution for real-time metering collection is feasible. The important question is to design of the wireless infrastructure and their topology so that it can be scaled up and meet the cost and real-time perfor-

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mance requirements, given huge wireless meters to be served in large areas. For example, The Wi-Fi mesh technology can be employed as part of a hybrid wireless infrastructure with WiMAX and Wi-Fi to allow the deployment at the reasonable low cost [4].

The wireless technologies such as WiMAX, and Wi-Fi are high performance, scalable, and secured [4]. Taking the advantages of these network technologies, utilities can deploy the smart grid wireless communications infrastructure for the real-time metering collection. The real-time meter data can save the operation costs and reduce the electricity market price.

When the WMN technology is applied in AMI solutions, it can bring new components to the electrical grids, such as self-managing and self-healing mesh networking, intelligent meters, and bridging to Home Area Networks (HAN) [5] for connectivity with energy consuming appliances. The real time communication between the smart meters and the utility's data center provides detailed usage data while also receives and display Time-of-Use (TOU) pricing information, and offers other on-demand abilities such as remote connect or disconnect, unrestricted monitoring and control, etc. Customers are able to access the usage data for tailoring consumption and minimizing energy expenses while helping balance overall network demand.

When WMNs are used in the AMI, they can provide the following features [6, 7]:

- *Low cost of management and maintenance* - WMNs are self-organizing and require no manual address/route/channel assignments. It is simple to manage thousands or millions of devices resulting in the lowest total cost of ownership.
- *Increased reliability* – The WMN routing mechanisms provide the redundant paths between the sender and receiver of the wireless connection. Communication reliability is significantly increased because of the eliminations of single point failures and potential bottleneck links. Network robustness against potential problems, e.g., node failures and path failures due to RF interferences or obstacles, can also be ensured by the existence of multiple possible alternative routes.
- *Scalability, flexibility and lower costs* - WMNs are self-organizing and allow true scalability. Nodes and gateways are easily added at a very low cost with:
  - No limitation on number of hops
  - No network address configuration
  - No managed hierarchical architecture
  - No hard limitation on number of nodes per gateway
- Robust security – WMNs have the security standards that allows all communications in AMI are protected by mutual device authentication and derived per-session keys using high bit rate AES encryption. This hardened security approach allows for authentication as well as confidentiality and integrity protection in each communication exchange between every pair of network devices – Smart meters, Relays, or Wireless Gateways.

In this paper, we focus on the AMI solutions using the hybrid wireless mesh network technologies such as WiMAX and Wi-Fi that are capable of collecting data in real-time. A wireless network planning tool was developed based on the existing utility infrastructure and GIS information and the performance of the large wireless network infrastructures was evaluated using the network simulation software NS-3. Section 2 shows the design and implementation of the smart grid wireless planning tool. Section 3 shows the simulation results of the HWMN for smart grids. Section 4 is the conclusion remarks.

2 Smart Grid Wireless Infrastructure Planning (SG-WIP) Tool

The SG-WIP is a wireless network topology planning application. We have developed this planning tool to assist the planning and designing phase of the AMI wireless network infrastructure. Figure 1 shows the GUI of SG-WIP.

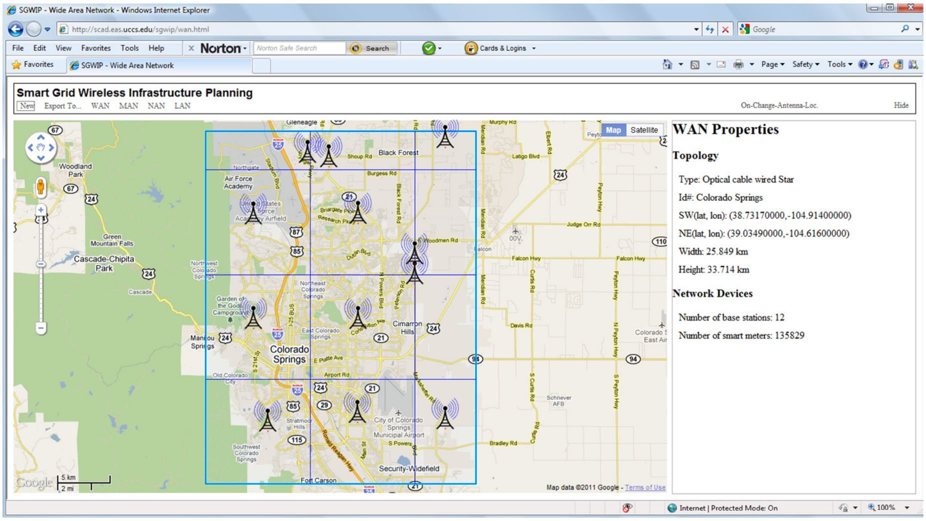

Fig. 1. SG-WIP tool for planning AMI wireless infrastructure network in Colorado Springs

The SG-WIP is a Google Maps mashup [8, 9]. It reads in the GIS data of a utility company and provides the information about the geographical locations of the network topologies, network devices, and the residential housing units in the service areas of a utility. Real data were provided by a local utility and used in this study.

With the real utility GIS data, we also conducted related researches that use the SGWIP tool, including antenna placement problem and housing unit density statistics.

The research for antenna placement of the WiMAX/Wi-Fi networks utilizes the SG-WIP platform as a tool to extract information of the geographical network topologies such as housing unit locations, or street light poles. Utilities typically use their street light poles for installing wireless base stations if they own and manage them. It turns out some light poles were not suitable as antennae placement locations due to their structure and power source limitation. Therefore logistically they can not be used in real situations.

Figure 2 shows the planning antennae placement for the smart meters and the WiMAX/Wi-Fi gateway on the Google Maps. The Google Maps with satellite images help verify the locations of wireless devices and related placement decisions.

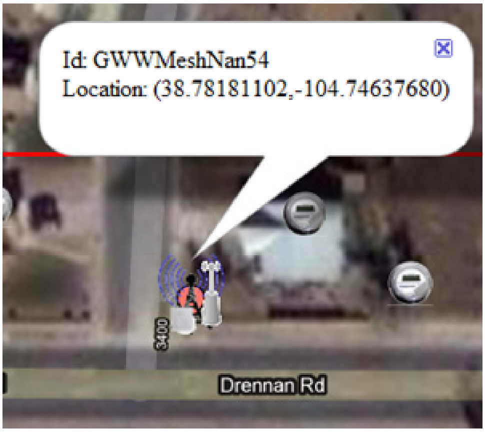

Fig. 2. Using SG-WIP tool for planning the antennae position. A WiMAX/Wi-Fi gateway was placed on a streetlight pole.

The research about housing unit density of the designing wireless networks also used the SGWIP tool to gather the distribution of the housing units. It enables us to consider smart meter density as a factor in our simulation studies.

Table 1 shows the range of number housing units in the LAN, NAN, WAN topologies. The dimensioning information is helpful for the designing of smart grid network simulation. For example, it helps deciding the sizes for the grids.

Table 1. The ranges of housing unit density of the LAN, NAN, MAN topologies in Colorado Springs

	Low Bound (housing units)	High Bound (housing units)	Simulation
LAN	0	51	50
NAN	0	1,054	950
MAN	0	40,501	27,000

Figure 3 shows the WLAN topology size 100x100 square meters that has fifty one housing units. The SIGWIP tool overlays the meter symbols on the houses based on the GIS locations of the meters.

The information about the network topologies from SG-WIP tool, as well as the research results about the housing unit density, and the antenna locations can help the AMI network infrastructure researchers and designers in their simulation and analysis of the wireless network infrastructure of the AMI.

The SG-WIP will be made available for academic research.

Fig. 3. The WLAN topology (100x100 square meters) has a high density of resident housing units (51)

3 HWMN Simulation

In the proposed HWMN network, we assume Wi-Fi base stations (BS) are used to collect meter data from the smart meters, On top of that, WiMax gateways (GW) are used to provide routing paths from these Wi-Fi base stations to a group of "take-out" points. From the handful of take-out points, the huge volume of meter data are sent over high speed optical fiber communication links to the utility data center (DC).

In this simplified hierarchical network simulation study, we assume the whole metro area served by the utility were divided into layers of regular square areas. NS-3 simulation studies were conducted on Wi-Fi network with each Wi-Fi network served a small number smart meters based on the house density statistics collected with network planning studies conducted with SG-WIP. We then feed the traffic statistics to simulate the WMAN network with variable GWs servicing a region of the metro area. We also investigated the impact of fiber cable length from the take-out points to the Data Center. Here are some of the simulation results.

In Figure 4, the number of the UDP packets sent and received in every one second for the simulation duration versus the number of GWs for different simulation experiments. The total processing delay is also plotted on the chart.

We can see that the network has successfully transmitted the UDP packets in every one second from the senders (or GWs) to the receiver (or BS).

Moreover, we can see that the total processing delay is between 930 and 960 milliseconds. It does not increase with the number of the GWs. This is due to the WiMAX network or 802.16d standard has a fixed frame time (5ms) that is independent to the number of the subscribers.

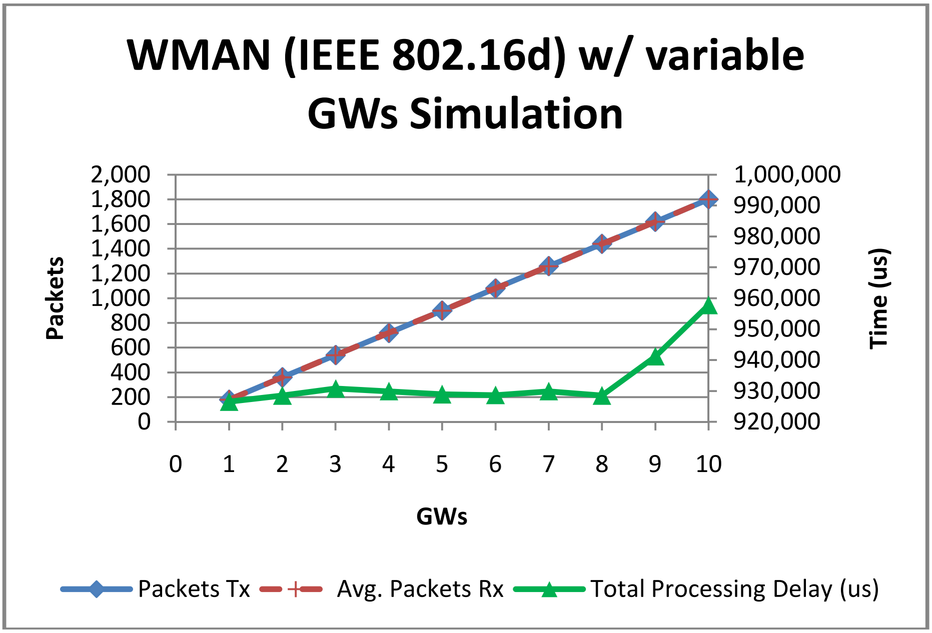

Fig. 4. The simulation results for the WMAN topology. The number of GWs is assigned from one to ten in the experiments to evaluate the changing of total processing delay at the GWs.

3.1 Impact on the Network Performance by Aggregating Meter Data

Figure 5 shows the simulation results for the WMAN point-to-multipoint topology from many experiments. There are one BS and ten GWs in the network. Each GW sent 180 packets to the BS in every second. The number of meter data packets put in a transmitted UDP packet was assigned from the one to seventeen packets to evaluate the changing of total processing delay at the BSs in the experiments. Figure 5 shows the improvement of network performance when the number of meter data packets are aggregated in a transmitted UDP packet or the length of loaded data in one WiMAX frame. The number of meter data packet was increased until the network going to the overloaded state. As we can see on the chart, when the number of meter packets is less than 16, the network successfully transmitted all of the UDP packets. This is due to the sending UDP packet that contains a designated number of meter data packets, is not fragmented in the transmission. Moreover, the traffic application was programmed to send out in every second the number of UDP packets that can be delivered completely by the network in one second.

However, the network is overloaded when the number of embedded meter data packets is equal or greater than 16. This is due to the UDP packets were fragmented in the transmission. That caused the number of received packets in one second to be less

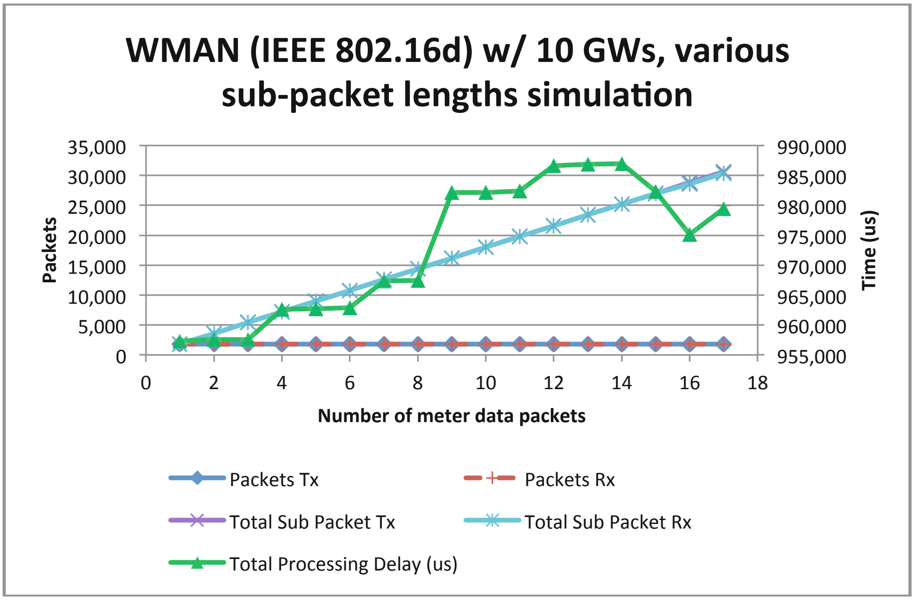

Fig. 5. Impact on the network performance by aggregating meter data

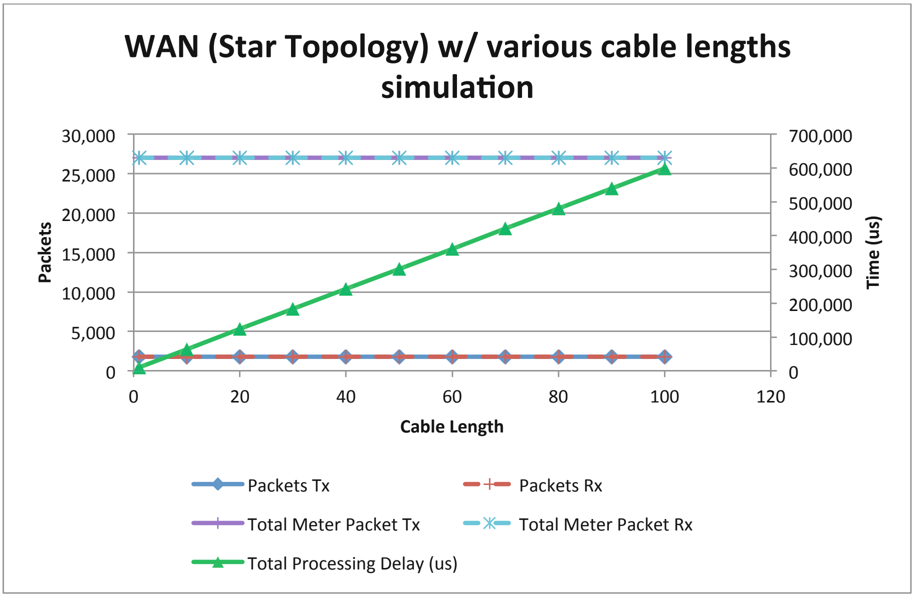

Fig. 6. The simulation results for the WAN star topology with one DC and one BS. The length of the optical fiber cable was assigned from one to 100 km.

than the number of sent packets. As a result, the average transmission delay of a packet was increased.

It is also observed that the total processing delay is independent from the number of the BSs. This is due to the BSs were connected to the data center in the point-to-point connections. The network can transmit over 180,000 meter data packets that sent from seven BSs, and the total processing time at each BS is less than 600 milliseconds. However, the average delay is affected by the distribution of the BSs around the data center (DC).

Figure 6 shows the simulation results for the WAN star topology from many experiments. There was one DC and one BS in the network. GW sent 1,800 packets to the DC in every second. The length of the optical fiber cable that connects the DC and BS was assigned from the one to 100 kilometers to evaluate the changing of total processing delay at the BS in the experiments. We can see that the total processing time was linearly increased with the length of the optical fiber cables that connect the BSs and the data center.

4 Simulation Limitations and Future Work

In this simplified simulation study, we did not include the 3D model and terrain information into the considerations for signal interference and degradation. Future work includes better integration of SG-WIP with the NS-3 simulation modules. Demand response is one of the important goals of the AMI deployment. In contrast to the metering collection, the demand response supporting applications will request the meter data from the data center for the consumer's demand analysis. It is expected that the demand response applications can help the consumers utilize their energy more efficiently. Although this subject is out of the scope of this paper, it is an important area of research, where the AMI researcher community can contribute through the design and performance evaluation of the HWMN infrastructure.

5 Conclusion

AMI is being implemented by many utilities around the world. AMI contributes the benefits not only to the utilities but also to the consumers. AMI real-time meter data collection can give the utilities and consumers the ability to access the real-time meter data. Consumers are benefits from the sharing real-time meter data because they can monitor and actively adjust their demand of electric, gas, and water to save money. Utilities are benefits from the real-time meter data because they can use the real-time meter data to improve the quality of load profile charts, and load prediction. So the utilities can save the fuel usage of power plants and reduce the price of electricity.

Many utilities have implemented the AMI wireless infrastructures for collecting meter data automatically. However, most of the deployed wireless infrastructure did not support or have not supported yet the real-time meter data collection. The intervals for meter data collection are typically higher than one minute. The current meter data collecting period is often in the range between fifteen and forty five minutes.

We have developed a software tool SG-WIP for planning and designing the AMI wireless infrastructure using the real utility light poles and meters GIS data from the city of Colorado Springs, Colorado. SG-WIP allows us to examine the actual geographical distribution of smart meters and a real utility. It also served as an education and training tool for discussing the smart grids and related issues.

We proposed a parameterized WiMAX/Wi-Fi network model and implemented it in the NS-3 platform. Experiments were conducted using the network simulation process, including the WLAN (Wi-Fi) simulation, the WNAN (Wi-Fi Mesh) simulation, the WMAN (WiMAX) simulation, and the WAN (optical fiber point-to-point connection) simulation. The simulation results show that the proposed WiMAX/Wi-Fi Hybrid WMN infrastructure can transport the meter data from 160,000 smart meters in the CSU service areas to the data center in one second.

From the simulation result analysis, we can conclude that the high scalability property of WiMAX/Wi-Fi WMN helps flexibly extend the coverage area of the AMI wireless infrastructure without degrading the network performance.

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