Segment Wise Communication Delay Measurement for Managing Renewable Energy Sources in Smart Grid

Mohammad Abdul Ghani Sayani
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Segment Wise Communication Delay Measurement for Managing Renewable Energy Sources in Smart Grid

By

MOHAMMAD ABDUL GHANI SAYANI

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2014

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Segment Wise Communication Delay Measurement for Managing Renewable Energy Sources in Smart Grid

by

Mohammad Abdul Ghani Sayani

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March 28, 2014
DECLARATION OF ORIGINALITY

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In order to meet the communication delay requirements of various message types while developing applications for the Smart Grid (SG), selection of appropriate communication technology is crucial and requires network segment-wise delay characterization under different network conditions. Thus, this thesis presents a segment-wise communication delay measurement technique and experimental results for SG applications. In this technique, an Arduino based test bed is developed to characterize communication delays across multiple hops using different communication technologies such as Wi-Fi, Ethernet, and cellular communication. This test bed is customized for the measurement of the delay involved in several network segments between remotely deployed photovoltaic (PV) panels and monitoring locations. Extensive delay measurement tests are conducted with varying data packet sizes under various controlled background traffic conditions, including Internet traffic. The test results can be used to infer the suitability of various communication technologies under diverse network conditions.
DEDICATION

To Mom, Dad, Farha Sayani, Ahmed Sayani & Asra Sayani.
ACKNOWLEDGEMENTS

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<tr>
<td>AMI</td>
<td>Advance Meter Infrastructure</td>
</tr>
<tr>
<td>A/D</td>
<td>Analog to Digital</td>
</tr>
<tr>
<td>CMS</td>
<td>Central Monitoring System</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>CT</td>
<td>Current Transformer</td>
</tr>
<tr>
<td>DNP</td>
<td>Distributed Network Protocol</td>
</tr>
<tr>
<td>DCU</td>
<td>Data Control Unit</td>
</tr>
<tr>
<td>DA</td>
<td>Distributed Automation</td>
</tr>
<tr>
<td>EPROM</td>
<td>Erasable Programmable Read Only Memory</td>
</tr>
<tr>
<td>HEMS</td>
<td>Home Energy Management System</td>
</tr>
<tr>
<td>HAN</td>
<td>Home Area Network</td>
</tr>
<tr>
<td>iHEM</td>
<td>in-home Area Network</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>ICMP</td>
<td>Internet Control Message Protocol</td>
</tr>
<tr>
<td>IED</td>
<td>Intelligent Electronic Device</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>MC Unit</td>
<td>Monitoring and Controlling Unit</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute for Standards and Technology</td>
</tr>
<tr>
<td>PP</td>
<td>Packet Pair</td>
</tr>
<tr>
<td>QOS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RTT</td>
<td>Round Trip Time</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory control and Data Acquisition</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>SRAM</td>
<td>Static Random-access Memory</td>
</tr>
<tr>
<td>WICIP</td>
<td>Wireless Communication and Information Processing</td>
</tr>
<tr>
<td>YHDC</td>
<td>YaoHuadechang Electronic Co</td>
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1 INTRODUCTION

1.1 Motivation

Electricity is one of the major innovations that have changed the daily life of mankind. The entire world fundamentally runs on electricity in one form or another, and it is thus ingrained in modern life. Most modern energy alternatives are focused on creating electricity using renewable and non-renewable resources such as photovoltaic energy, fossil fuels, hydro-electric, nuclear, and wind energy etc.

The electric power industry consists of power generation stations, power transmission systems, power distribution systems and subsequent power retailing. The steadiness of electric distribution systems is integrally important for both utilities and customers. The conventional electrical grid needs to evolve if it is to serve the ever growing energy demand in the 21st century. Therefore, the Smart Grid (SG) concept is emerging with a vision to alleviate a number of challenges faced by conventional electrical grids. These challenges include accommodating a bidirectional flow of energy to provide better injection of renewable energy, facilitating a parallel bidirectional flow of information for monitoring and controlling infrastructure, and management and protection systems in the electrical grid.

Communication and information technology is the key to realize the SG vision. The advancements in information and communication technologies (ICT) over the years are employed by electrical firms to improve the efficiency, reliability, security and quality of
service (QoS) in electrical distribution. These progressive developments have led the evolution of smart grid to a research concept which aims to modernize the generation, monitoring, planning and distribution of electric power. Communication technology is crucial for grids in order to access distributed sensor information.

Through research work at the WICIP laboratory on monitoring and controlling solar panels and wind turbines in smart grid applications, it was observed that various types of communication and networking technologies are in use today. Monitoring and controlling power equipment requires different communication technologies and protocols depending on the application. These communication systems have to fulfill all of the requirements of the smart grid.

**Example:** A communication system is required for reliable and timely data collection from generators, transmission lines, transformers, points of interconnection, substations, smart meters, and sensors on renewable energy sources such as photovoltaic (PV) panels and wind turbines.

In view of such diverse monitoring and controlling requirements in the SG, selection of a communication technology is very important. Due to the presence of a large number of communication technologies and protocols, there is a lack of definitive information about which technologies should be used for a particular SG application. It is also observed that there is a lack of information with respect to the delay profiling of communication technologies for real SG application scenarios. Additionally, in absence of delay characterization, it is not possible to provide delay guarantees in real-time SG monitoring and controlling applications.
Therefore, during this thesis, a test bed is developed to characterize the delay experienced in commonly used communication technologies. This will facilitate better selection of appropriate communication technologies to create a static infrastructure for a SG application based on the delay requirements. The test bed results can also be used in dynamic decision making for communication gateways to select the most suitable interface for a given SG message type based on its remaining delay to reach the destination. In particular, the test bed is used to create various multi-hop communication scenarios for a PV monitoring and controlling application using combinations of Wi-Fi, Ethernet, and cellular technologies. The tests are conducted with varying data packet size and background traffic. This test bed can be extended to carry out delay measurements for other communication technologies.

1.2 Problem Statement

The objective of this research is to develop a test bed for the identification of appropriate communication technology using segment wise delay measurement under varying network conditions for various smart grid applications. The test bed should support the data transmission from geographically distributed energy resources to servers and vice versa using various communication technologies including Ethernet, Wi-Fi and GSM with varying background traffic, number of hops, and data transmission rate. Additionally, the delay characteristics while utilizing the Internet are to be examined.
1.3 Thesis Contribution

The research and documentation of the measured delay characteristics for various communication technologies will assist researchers in selecting best suited communication technologies for SG applications. Delay requirements, background traffic volume, number of hops, and data rate with the consideration of Internet traffic are the conditional parameters used in selecting appropriate communication technologies.

Once a strong sense of performance abilities have been understood, the ideal communication technologies to be used at different segments in the SG to achieve the best results, and thus smooth operation can be conveyed.

1.4 Background

The use of future and present communication technologies will be integral in achieving the requirements of SG monitoring and controlling applications. More than one type of communication technology can be deployed at any segment of the SG. Realizing, which technology will yield the maximum efficiency of the requirement, is important. Hence, in order to design a communication system for monitoring and controlling in smart grid applications, it is necessary to understand the different parameters and characteristics of communication technologies in terms of delay and time requirements.

1.5 Delay Requirements

The SG has two major types of messages which are to be transmitted or received for monitoring and controlling purposes. Delay requirements for monitoring and controlling packets are different. The application, where the packets are being used, also plays a
factor in determining delay requirements. Generally, it is trivial to determine the communication delay of sending a data packet over one hop without background traffic using a particular communication technology. However, as the number of hops, background traffic and the data packet size are increased, the packet transfer delay starts varying significantly across different communication technologies. Additionally, packet transfer delay cannot be guaranteed when the packet transfer involves Internet. Therefore, it is important to characterize the delay of various communication technologies under various SG network scenarios.

Smart Grid monitoring and controlling system developers have several options when selecting suitable communication technologies and protocols to be used in power systems. It is required for the developers to be familiar with the delay characteristics offered by different communication technologies that are to be used.

### 1.6 Interoperability

Interoperability is the major obstacle to overcome by the SG concept to interconnect energy distribution networks, power generation sources and energy consumers. Interoperability is an important issue in SG applications with plug and play enabled. The first contribution in SG interoperability research came from the National Institute for Standards and Technology (NIST) [1]. Standardized architecture development was needed to merge different communication technologies to co-exist simultaneously. Different vendors use different communication technologies in their system, hence the smart grid should be capable of operating with any type of technology or system used. For example, Home Area Network (HAN) technologies including Ethernet, ZigBee,
Bluetooth and Wi-Fi can be used to transmit data to the utility center. Provided that these messages can be read by utility center regardless of manufacturer. This can be achieved only if interoperability exists in the SG.

1.7 Thesis Organization

A description of the remaining part of the thesis is as follows: some related work in the field of SG and communication technologies delay are discussed in Chapter 2. The research work performed for this thesis and the description of designed system is covered in Chapter 3. Chapter 4 contains the analysis of the performance capabilities of Ethernet, Wi-Fi and GSM technologies. The thesis is concluded in Chapter 5.
2 LITERATURE REVIEW

2.1 Introduction

This chapter will expose different areas of research with respect to SG technology along with their suitability and application. The purpose of the beginning with a survey of SG technology is to convey the importance of the work and its current state. This chapter contains a study of different communication technologies used in SG applications such as Ethernet, Wi-Fi, ZigBee and cellular is present along with their respective specifications. An explanation of delay characteristics and the techniques used to measure them is provided, and finally the importance of delay measurement in SG applications is discussed.

2.2 Introducing Smart Grid

The concept of Smart Grid was developed to alleviate number of challenges in applications such as real-time equipment monitoring, smooth integration of renewable energy sources [2], and governing the supply and demand requirements of the grid to fulfill the present day energy needs. As the SG continues to evolve, future systems see progressive changes from the point of generation to the point of distribution and everywhere in-between [3]. In these next-generation power systems, there will be a significant contributions of energy from renewable energy resources. This integration becomes possible via SG deployments such as intelligent management and automated
systems [3-8]. Accurate and near to real-time data collection from generators, transmission lines, transformers, point of intersection and sub-stations are important for a successful implementation of the SG [9]. Integration of communication and information technologies is equally important as it will be the major contribution to conventional grids to make them intelligent [2, 3, 10, 11].

From technical point of view, the SG consists of three major systems: Smart infrastructure system, Smart management systems, and Smart protection systems [7].

- **Smart infrastructure system:** This system consists of energy, information and communication infrastructure. It has advanced energy generation and integration units, information collection and observation unit, and reliable communication systems with different interoperability options for information transmission and reception.

- **Smart management systems:** This system provides advanced monitoring and controlling services such as information analysis and energy generation control with advance algorithms. This makes the system intelligent by applying smart management and controlling techniques.

- **Smart protection system:** This system possesses all of the systems required for grid protection in terms of failure identification, diagnosis, system recovery, islanding, and network security to make the overall system reliable and secure.

Advance metering infrastructure (AMI) is used to promote the bidirectional flow of information in the SG, making it an automated energy delivery network and helping to implement real-time monitoring and managing of electrical usage for both utility and consumers [1, 7, 10, 12]. This data should be easily available to all the parties for their
own benefits [4, 13]. The SG should be able to respond to any event occurring anywhere in the grid, automatically or manually from the remote control center. The major functions of the SG are sensing, communicating, monitoring and controlling [12]. To have strong monitoring and controlling systems, a strong communication system is a necessity. The conventional grid lags advancement capability with respect to monitoring and controlling. Thus, lots of research and development is required on the existing control and monitoring systems in SG [14, 15] [3].

Sensors have been deployed in a variety of locations in the SG to measure voltage, sense the load current, and obtain many different parameters necessary for proper maintenance, configuration, and malfunction detections and self-monitoring [3, 6, 7, 16, 17]. These sensors require a communication medium to transmit their data to monitoring and control station. The output of these sensors is processed at the communication device and transmitted according to the communication protocol employed.

Actuators also play an important role in the SG, predominately in circuit breakers that connect and disconnect loads. The delay requirement of these actuator systems are generally very strict and any excessive delay can pose a harmful and dangerous situation to expensive equipment personnel in the immediate vicinity.

2.3 Smart Grid Communication

Equipping smart devices with communication interfaces is a paramount task in achieving the SG vision. Communication over power lines is not a new idea, and has existed since the evolution of SG began [18]. The bidirectional flow of energy and data in the SG differentiates it from the conventional grid. This two-way flow of information is
not possible without using communication technologies which supports various applications including AMI and Distributed Automation (DA) [10]. A strong communication architecture is a key requirement for the successful implementation of the SG application [19, 20]. Designing, developing, and integrating a high speed communication network are key focal points of a successful implementation of the SG [3, 21]. SG will need communication infrastructure at almost all the nodes of the system [12, 22]. Therefore, network architectures for Home Energy Management Systems (HEMS), Home Area Network (HAN) or in-Home Energy Management (iHEM) were introduced to collect and transfer data from energy consumption points [5, 23-25] to utility centers using low cost public networks such as Internet [26].

With respect to the SG, a number of communication technologies can be deployed ranging from wired to wireless. A Smart Grid can expand over large geographical areas, hence the communication technologies used in its implementation depend largely on the location, utility cost, accessibility, parameter requirements and available resources [3, 27].

Various communication technologies are being used at different segments of the SG. As any single technology will possess its own limitations, no one technology can fulfill all the imposed requirements. The choice of a communication protocol is dependent upon the selected communication technology. That stated, it is important to note that the system should be interoperable such that the evolution of new communication technologies and protocols may be accommodated in the present system, if needed.
The Distributed Network Protocol (DNP) was one of the forerunning standard protocols used for monitoring and controlling in sub-stations, but it cannot be used in the SG, because it has a deficiency in its communication standards [2]. In this situation, where a standard protocol cannot be customized for a particular application, a new protocol may need to be developed to improve performances [28]. A network failure occurs when there is a failure in any of the layers of the protocol suite used for communication.

Different wired and wireless communication technologies, which are useful for SG applications and their present specifications, are explained below.

- **Ethernet:** Wired LAN (i.e. Ethernet) is currently the most prominent technology used to transmit CMS/SCADA data locally in a single hop. A multi-hop Ethernet network is generally used for sending data over long distances (~ 70 kilometers). Ethernet technology is reliable and cost effective so a wide variety of devices come equipped with this interface. This provides a high data rate of up to 1 gigabit per second (Gbps), can support most SG data communication requirements, and is therefore considered sufficient for single-hop real-time communication purposes [28].

- **Wi-Fi:** Wi-Fi (i.e. IEEE 802.11) has become a widely used technology that has made wireless communication more approachable worldwide. It is suited for high data rate and large area application. Recent IEEE 802.11 compliant devices can transmit up to 150 Mbps for a 70 meter indoor range [28]. Additionally, Wi-Fi can be retrofitted to replace existing local wired LANs, accommodating the use of
popular wireless protocols which provide robust, high speed, point-to-point, and point to multipoint communication [27].

- **Cellular:** This technology represents a licensed frequency band with a data rate of up to 240 Kbps [27]. A significant advantage of cellular technology is that its service is widely available even at very distant and remote locations. Different types of cellular technologies such as 2G, 2.5G, 3G, GPRS, WiMAX, and LTE are available to be used in the SG application [4]. However, cellular technology experiences a lower data rate as compared to wired and wireless LAN technologies.

- **ZigBee:** ZigBee is an emerging and versatile short-range (30 – 50 meter) wireless communication standard with a typically low deployment cost. It is suitable for low energy applications and can transmit data from sensors to the nearest CMS or SCADA systems using multi-hop communication. ZigBee can provide a data rate of up to 250 Kbps [28], uses minimal power, is cost effective, and based on the IEEE 802.15.4 standards [29].

### 2.4 Smart Grid Communication Delay

A communication delay is defined as the time interval for an end-to-end process flow to transfer a message from the source to the destination. Proper end-to-end delay information is helpful for Quality of Service (QoS) Performance determination like protocol design, network monitoring, packet length, and data rate [30, 31]. Monitoring and controlling applications have different delay requirements and accurately determined values are required for controlling applications [16]. If the controlling system misses any
of the inputs from sensors or any other system in the SG, defective results could ensue [12, 32]. System performance can be negatively affected by network delay and amount of data it transmits [24, 33]. Different applications have their own delay requirements depending up on the type of response necessary with and the number of messages. These requirements are shown in table 1.[34]

**Table 1:** IEEE 1646 standard: communication timing requirements for electric substation automation [2].

<table>
<thead>
<tr>
<th>Information Type</th>
<th>Internal to sub-station</th>
<th>External to sub-station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection information</td>
<td>4ms (14 cycle of electrical wave)</td>
<td>8–12 ms</td>
</tr>
<tr>
<td>Monitoring and control</td>
<td>16 ms</td>
<td>1 s</td>
</tr>
<tr>
<td>Information</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations and maintenance</td>
<td>1 s</td>
<td>1 s</td>
</tr>
<tr>
<td>information</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Text strings</td>
<td>2 s</td>
<td>10 s</td>
</tr>
<tr>
<td>Processed data files</td>
<td>10 s</td>
<td>30 s</td>
</tr>
<tr>
<td>Program files</td>
<td>1 min</td>
<td>10 min</td>
</tr>
<tr>
<td>Image files</td>
<td>10 s</td>
<td>1 min</td>
</tr>
<tr>
<td>Audio and video data streams</td>
<td>1 s</td>
<td>1 s</td>
</tr>
</tbody>
</table>

As per Table 1, to accommodate the transmission time for data and control commands with in the sub-station, the delay should be less than 4 ms in communication networks and systems [35]. To provide this real-time data delivery, a fast communication infrastructure is necessary.
Reference [2] gives the classification of message exchange events for different applications of Smart Grids and power systems as shown in Table 2.

Table 2: IEC 61850 communication networks and systems in sub-stations: communication requirements for functions and device models [2, 8, 36].

<table>
<thead>
<tr>
<th>Message Types</th>
<th>Definitions</th>
<th>Delay requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Messages requiring immediate actions at receiving IEDs.</td>
<td>1A: 3 ms or 10 ms; 1B: 20 ms or 100 ms</td>
</tr>
<tr>
<td>Type 2</td>
<td>Messages requiring medium transmission speed.</td>
<td>100 ms</td>
</tr>
<tr>
<td>Type 3</td>
<td>Messages for slow speed auto-control functions.</td>
<td>500 ms</td>
</tr>
<tr>
<td>Type 4</td>
<td>Continuous data streams from IEDs</td>
<td>3 ms or 10 ms</td>
</tr>
<tr>
<td>Type 5</td>
<td>Large file transfers</td>
<td>1000 ms (not strict)</td>
</tr>
<tr>
<td>Type 6</td>
<td>Time synchronization messages</td>
<td>No requirement</td>
</tr>
<tr>
<td>Type 7</td>
<td>Command messages with access control</td>
<td>Type 1 or Type 3</td>
</tr>
</tbody>
</table>

As given in [37], three different techniques were used to measure the end-to-end delay and one-hop delay. First, adding the time stamp before the packet is sent and then subtracting this time from the received time. In this approach, the clocks should be synchronized. Second, a probing method, where the sender records the time until the packet, is received by assuming that the receiver responds immediately. This however is not possible in real-time. Finally, the Packet Pair (PP) method, where two packets are transmitted one by one to measure the transmission time by subtracting the differences of the reception times.

In [33], the synchronization procedure is used to measure the delay using IEEE 1588 protocol, where both end devices are synchronized. As Ethernet packets don’t have a
field for a time stamp, it uses IEEE 1588 protocol to attach one. Time stamped packets are transmitted from the sender side to receiver side and the difference between the transmitted and received time is calculated as delay.

In [31], the Ping utility tool is used to measure the RTT delay. Of two traces of delay one lasts for two minutes and the other lasts for one hour at an interval of ten milliseconds. Similarly in [38] the Ping tool is used again to measure RTT delay, but by sending Internet Control Message Protocol (ICMP) packets between two nodes for a duration of twenty-four hours at an interval of ten seconds.

Hence, a test bed was developed to measure the delay of different communication technologies. The delay has been documented when measured with different background traffic conditions including Internet characteristics.

2.5 Summary

Recent trends and developments in SG systems and the development of this test bed based on different applications have been discussed in this chapter. The availability of different communication technologies and use in different applications in view of the SG has also been discussed. Due to the large number of Internet technologies available and their usage depending on application, delay characteristics are important aspects to consider when deciding whether a specific communication technology will fulfill the required demand.
3 RESEARCH WORK

A prototype to measure the delay of the transmitted packet has been developed. Generally, it is trivial to determine the communication delay in sending a data packet over one hop without background traffic using a particular communication technology. However, as the number of hops, background traffic and data packet size are increased, the packet transfer delay starts varying significantly across different communication technologies. Additionally, packet transfer delay cannot be guaranteed when the packet transfer involves the Internet. Therefore, it is important to characterize the delay of communication technologies under diverse SG network scenarios.

The voltage and current across photovoltaic arrays and their grid interconnection is measured using voltage sensors and current sensors respectively. Initially, the data was transmitted using Ethernet. Data is collected from the sensors and connected to the Arduino board, which has an onboard analog to digital (A/D) converter in it. In post conversion, the digital values are encapsulated into Ethernet packets and prepared for transmission. These data packets are forwarded to the local router and then transmitted to the server via the internet. The delay of the packet incurred when traveling from data collection unit to the local router is measured. This route comprises a one hop delay. Similarly, the delay for two hops and three hops are measured via cascading routers. Using a LAN traffic generator, local traffic is generated, and the delay of the data packets during different local traffic loads is measured. Additionally, the delay of the packets
travelling through the Internet is calculated for different Internet characteristics. Similar delay measurements are carried out using Wi-Fi and GSM communication mediums.

When packet is transmitted from the monitoring and controlling unit, it usually takes a time span to reach the destination and this time span is mainly dependent on the communication technology being used and location of the monitoring and controlling unit.

In this chapter, the different hardware and software used in this thesis will be explained. A description of the working circuit and test scenarios will be given as well.

3.1 Arduino

The microcontroller used while developing this prototype was an Arduino board. This open-source hardware and the user-friendly software are based around the Atmel microprocessor which boasts built-in 10 bit analog-to-digital (A/D) convertors. The Arduino UNO board was deemed most appropriate for this prototype. This board has 32kB of flash memory, 2kB of SRAM and 1kB of EPROM. It requires an external power supply of 5V DC to operate. It can be programmed using the Arduino programming language, and there is an abundance of development environment for different functions and applications available. Arduino offers several different types of communication shields including Ethernet shield, Wi-Fi shield, ZigBee shield and GSM shield [39].

3.2 Arduino IDE

Arduino integrated development environment (IDE) is a cross-platform application written in Java which contains a text editor for writing code. Arduino programs are
written in C or C++. Software written using Arduino is called sketches and saved with the file extension .ino. It connects to the Arduino hardware to upload programs and communicate with them. The Arduino IDE uses the GNU tool chain and AVR Libc to compile programs, and uses avrdude to upload programs to the board [39].

3.3 HrPING

In regular practice, many ping utilities are available. However, for our unique SG application purpose, the best results acquired using HrPING. Similar to PING, HrPING sends ICMP echo request to remote devices, but what makes it different is that it yields the round trip time (RTT) in microsecond precision values. HrPING is able to provide this precision, because it uses the CPU’s timestamp counter, which is incremented with the CPU’s clock cycle. Additionally, HrPING can send more than one probe packet to a specified host without hearing the echo back from previously sent probe packets. Conversely, the Windows-based Ping application always waits for a reply before sending the next Ping packet [40].

3.4 LAN Traffic Generator

A LAN traffic generator creates packets for different protocols, and standards and performs transmission at a variety of data rates. This software has been used to generate local background traffic in different communication technologies to measure the delay of the packets by varying different background loads [41].
3.5 Block Diagram of a Monitoring and Controlling Unit

Figure 1 illustrates the Monitoring and Controlling Unit (MCU), which shows how the various components in the SG unit are arranged. The communication shield in the MCU is placed on the top of the Arduino microprocessor. It can be replaced with different communication shields including Ethernet, Wi-Fi, GSM and ZigBee enabled hardware.
Figure 2: Schematic Diagram of MC Unit

Figure 2 shows the schematic diagram of MCU. In this unit input values are coming from current and voltage sensors to the analog input pins of the Arduino board, and the control signal from the digital output pins of the Arduino board is given to the relay. Power supply is used to power Arduino board and voltage sensor. This blocks are described in details in the following sections.

3.7 Circuit Description

3.7.1 Current Sensor

The YHDC SCT-013 current transformer (CT) [42] is used to sense current non-invasively at the output of PV inverter between 0 and 100A AC. To connect this CT
sensor to an Arduino board, the output signal from this CT sensor is to be configured according to the Arduino board Analog input requirements.

**Figure 3: Current Sensor Block Diagram.**

The output from the current sensor is converted into a voltage signal by using a burden resistor. If the supply voltage from the Arduino board is 5V DC, a burden resistor of 33Ω must be used. Alternatively, if the supply voltage is 3V DC, burden resistor of 18Ω is used. The value of resistors, R1 and R2, should be of same values within the range of 10 to 470kΩ.
3.7.2 Voltage Sensor

A 60Hz CE-VJ03-32MS2-0.5 AC voltage transducer [43] is used to sense the AC voltage across the PV inverter output. It is powered by a 12V DC power supply and produces an output analog signal of 0-5V DC, which is linearly proportional to the AC voltage being measured. The output signal (0 to 5V DC) is given as an input to one of the Arduino analog input pins.

Figure 4: Voltage Sensor Block Diagram
3.7.3 Relay

Protective relay equipment plays an important role in power and automation systems [35]. Solid state relays [44] are used to control remote energy generators or other power electronics such as invertors. In the case of this prototype, the relay control voltage positive terminal is directly connected to a digital output pin on the Arduino board through a MAX232 inverting buffer IC to prevent damage of the digital output pin on the Arduino board.

![Relay Block Diagram](image)

Figure 5: Relay Block Diagram.
Whenever the control pin of the Arduino board is high, the digital output voltage will received at MAX232 integrated circuit(IC) which functions as an inverting buffer. If the output of the buffer is low, and the potential difference between pin 3 and pin 4 of the relay is low, the relay will be in a cutoff state, hence the generation unit or inverter will be turned off. Similarly whenever the digital pin is low, the output of the MAX232 IC will be high, and the relay will be in active state.

3.8 Summary

A flexible test bed, that is capable of determining many performance measurements, has been developed, and a detail description of its structure and operation is given. This test bed was used to measure the delay characteristic of different communication technologies such as Ethernet, Wi-Fi and GSM in different environmental conditions like varying background traffic and with different packet length.
4 RESULTS ANALYSIS

In order to find out the delay characteristics of different communication technologies, a setup has been developed to transmit ICMP probe packets from a laptop to an MC Unit using Ethernet, Wi-Fi, and GSM. By cascading multiple routers, different network hops are created as shown in Figure 7. Packet delay is measured using HrPING, and the required background traffic is generated using the LAN Traffic Generator software. The installation and working procedure for HrPING and LAN Traffic Generator are discussed in Appendix B and Appendix C.

The test for Ethernet and Wi-Fi was carried out for a sample of 50. Without background traffic and with a varying packet size of 50 bytes to 1500 bytes, the minimum RTT of the transmitted packets were recorded for one, two, and three hops respectively. Similarly, by varying the background traffic from 0.5 Mbps to 8 Mbps with a fixed packet size of 100 bytes, the minimum RTT of the transmitted packets were recorded for one, two, and three hops.

Finally, the minimum RTT of the transmitted packets were recorded - including the Internet characterization for the aforementioned communication technologies. Hence the delay of the packets under different test scenarios are plotted and compared.
4.1 Test Scenarios

4.1.1 Test Cases Using Ethernet

Ethernet cables are dedicated lines widely used for transmitting and receiving data that satisfy short range, high capacity, and minimum delay requirements. In a SG, the use of Ethernet links in LANs or connecting HANs to utility centers can be observed.

Figure 7 shows a scenario to measure Ethernet performance of a SG network. In this scenario, the MC Unit is comprised of an Arduino with an attached Ethernet shield. In order to use Ethernet shield, an “Ethernet.info” file had to be uploaded to the Arduino board. The “Ethernet.info” file has been provided in Appendix A.1. The data was transmitted or received via Ethernet technology.
4.1.1.1 Test Case 1: Ethernet with Varying Packet Size and No Background Traffic

In this case, the laptop and MC Unit are connected to the router using an Ethernet connection link. Data is transmitted or received using Ethernet technology in one, two, and three hops respectively as shown in Figure 7.

Figure 7: Network Structure with Ethernet Links

By fixing the background traffic to zero and varying packet sizes from 50 to 1500 bytes, initially a sample of 50 packets were transmitted using HrPING from the laptop to the MC Unit for one, two, and three hops respectively, and the minimum RTT of the packets was calculated. Subsequently, the minimum RTT values are collected for various packet sizes by increasing the packet size periodically and maintaining a fixed packet count.
4.1.1.2 Test Case 2 - Ethernet with Background Traffic and Fixed Packet Size:

In some cases, Ethernet links are used for the data transmission when there will be different background traffics induced from local or external networks in the Ethernet link. This traffic can cause packet delay, which is dependent on the load of the link. Since control data packets have limited delay requirements, these data packet delays under different load conditions are measured to calculate overall Ethernet packet delay.

Initially, a sample of 50 packets with a fixed packet size of 100 bytes and a maintained background traffic of 1 Mbps were transmitted using HrPING to calculate the minimum RTT for one, two, and three hops respectively. Sequentially, the minimum RTT values...
are collected and plotted for various background traffic values by increasing the background traffic periodically up to 110 Mbps, keeping the count and packets size fixed.

**Figure 9: Ethernet with Varying Background Traffic Results**

The profiling of the average delays provides insight about the performance of Ethernet technology for PV monitoring and controlling applications in a HAN. As shown in Figure 8, the average RTT increases to 4 milliseconds. Thus, the one-way delay is approximately 2 milliseconds for a 3 hop network with a packet size of 1500 bytes. Similarly, as shown in Figure 9, for 3 hops at a background traffic of 110 Mbps, the one-way delay is approximately 3.3 milliseconds. Therefore, as mentioned in Table I, 4
millisecond requirement of grid protection messages within substations can be achieved via Ethernet technology.

4.1.2 Test Cases Using Wi-Fi:

Wireless communication contributes an important role in the modernization of the SG. Wi-Fi is a powerful wireless communication technology. Generally, this technology is most preferred by residential and commercial users. Ethernet cable installation and setup is expensive and complex in contrast to deploying wireless networks. The application of wireless technology can be used in the SG for transmitting data from smart meters to utility centers or from utility centers to controlling and monitoring stations using Wi-Fi provided that the distance for communication is short and supported by using multiple hops.

In the setup shown in Figure 10, the MC Unit is equipped with a Wi-Fi shield. In order to use the Wi-Fi shield, a “Wi-Fi.info” file had to be uploaded to the Arduino board and this file has been provided in Appendix A.2. Data is transmitted or received in this case via Wi-Fi technology.

4.1.2.1 Wi-Fi with Varying Packet Size and No Background Traffic:

In this case, the laptop and MC Unit are connected to the router using a Wi-Fi connection link. Data is transmitted or received using Wi-Fi technology in one, two, and three hops respectively as shown in Figure 10.

By fixing the background traffic to zero and varying packet sizes from 50 bytes to 1500 bytes, a sample of 50 packets with a size of 50 bytes are transmitted using HrPING from the laptop to the MC Unit in one, two, and three hops respectively, and the average
RTT of the packets is measured with no background traffic. Sequentially, the average RTT values are collected and plotted for various packet sizes by increasing the packet size periodically and maintaining the fixed amount of packets.

![Network Structure with Wi-Fi Links](image)

**Figure 10:** Network Structure with Wi-Fi Links

### 4.1.2.2 Wi-Fi with Background Traffic and Fixed Packet Size:

After setting-up the Wi-Fi link, there can be background traffic from local or external networks depending on the time and the environment. For example, if all the smart meters are connected in one network and they try to transmit data to the utility center at the same time or there is ongoing local traffic in that network, there is a greater chance of increasing the congestion in the network and the delay of the transmitted data packets.
Therefore, it is important to know the delay characteristics of these Wi-Fi packets for different background traffic conditions.

**Figure 11: Wi-Fi Varying Packet Size Results**

Initially, in a sample of 50 packets with a fixed packet size of 100 bytes and constant background traffic of 0.5 Mbps, the packets were transmitted using HrPING to calculate the minimum RTT. Sequentially, the minimum RTT values were collected and plotted for various background traffic values. These background traffic values are increased periodically and maintained constant number and size of the packets are constant.
It is observed that when a Wi-Fi link is employed for the monitoring purpose, the increase in delay with increasing background traffic is not linear as in the case of Ethernet link. This unpredictability in Wi-Fi connections is a result of various unpredictable factors such as receiving network discovery packets by unauthorized Wi-Fi devices roaming in the vicinity of the experimental site.

Figure 12: Wi-Fi Varying Background Traffic Results

It is observed that when a Wi-Fi link is employed for the monitoring purpose, the increase in delay with increasing background traffic is not linear as in the case of Ethernet link. This unpredictability in Wi-Fi connections is a result of various unpredictable factors such as receiving network discovery packets by unauthorized Wi-Fi devices roaming in the vicinity of the experimental site.
4.1.3 Test Case Using GSM

4.1.3.1 GSM with Varying Packet Size:

GSM technology is the most widely used technology for both for voice and data communication. A GSM connection is useful for communicating with far away nodes, and cellular communication is widely available today. Therefore, it will be less expensive for a deployment of communication networks in the SG if GSM can be useful at the point of application. Since, SG is extended for wide geographical areas, this GSM technology can be used where other communication resources are not available. 2G, 2.5G, 3G, WiMAX, and LTE are the cellular communication technologies available to utilities for SG implementations [4]. The range for GSM communication is large, and it is now

![Figure 13: Internet Delay Characterization Using GSM Data based on Data Samples taken over 12 days in February 2014 in Windsor, Ontario](image-url)
increasingly available in remote locations. Due to its wide range, it can be used from generation point to the utility center even when generation points are located far from the city limits. Hence, this technology can be readily used where wired and other sources of wireless technology may be complex to implement and cost significantly more to install.

In the experimental setup, a GSM Internet USB stick is used. With the help of the HrPING application, the ICMP packets with a fixed packet size of 100 bytes are transmitted from the GSM device to the MC Unit using GSM data. Figure 13 shows that the majority of the packets took about 90 milliseconds to transfer. These packets were sent for a continuous period of 12 days with a group of 10 packets sent every 10 minutes (i.e. with 10 seconds between two consecutive packets).

4.1.4 Test Cases Using Combination of Ethernet and Wi-Fi:

Combinations of Ethernet and Wi-Fi technologies are widely used. For example, in a HAN, if Ethernet is used to transmit the data from the smart meter to the local data collecting unit, and then from the local data collection unit to a local router using Wi-Fi, the delay of the transmitted packet is varied when compared to when a single communication medium is used. If two types of communication technologies are used for different hops, and one hop has background load on the link, then the delay of the transmitted packets is increased depending on the load.

4.1.4.1 Ethernet and Wi-Fi with Varying Packet Size and No Background Traffic:

In this setup, the one-hop connection between the laptop and the router is via an Ethernet link, and the connection between MC Unit and router is through a Wi-Fi link. Similarly, the routers are cascaded to implement two and three hops as shown in Figure 14.
By fixing the background traffic to zero, and varying packet sizes from 50 bytes to 1500 bytes, a sample of 50 packets with a packet size of 50 bytes were transmitted using HrPING from the laptop to the MC Unit in one, two, and three hops respectively, and the minimum RTT of the packets was measured with no background traffic. Sequentially, the minimum RTT values were collected and plotted for various packet sizes by increasing the packet size periodically and keeping the count of packets fixed.

4.1.4.2 Ethernet and Wi-Fi with Fixed Packet Size and Varying Background Traffic:

Here, a combination of two technologies has been used; one is Ethernet and the other is Wi-Fi. For example, an Ethernet is used from a HAN to a data collection unit, and Wi-Fi is used from the data collection unit to the utility center. If there is background load in any of the networks, then the delay of the packet is increased depending on the network
load. If all the data starts flowing at the same time, then there will be huge load on the Ethernet link and the delay of the data packets will be large.

**Figure 15: Ethernet + Wi-Fi Varying Packet Size Results**

Initially, in a sample of 50 packets with a fixed packet size of 100 bytes and a maintained background traffic of 0.5 Mbps, packets are transmitted using HrPING to calculate the average RTT for one, two, and three hops respectively. Sequentially, the average RTT values are collected and plotted for various background traffic values by increasing the background traffic periodically and maintaining the count and packets size to be constant.
It is observed that when a Wi-Fi link is involved, the increase in delay with increasing background traffic is not linear as in the case of an end-to-end Ethernet link. This unpredictability in Wi-Fi connections is a result of various unpredictable wireless protocol overheads such as attending to network discovery packets by unauthorized Wi-Fi devices that are roaming nearby. However, the combination of Ethernet and Wi-Fi is still suitable for local SG applications that can tolerate delay up to 70 milliseconds. Additionally, the combination of Ethernet and Wi-Fi is important for rooftop deployed PV panels where the Wi-Fi router may be inside the building and can be used to transfer PV monitoring data to remote locations using the Internet.
4.1.5 Internet Characteristics Delay

As monitoring and controlling of remotely deployed PV panels often involves packet transfer through the Internet, the delay experienced by these data packets was characterized in this experiment. In order to accomplish this, ICMP probe packets were sent from a laptop through the Internet to a remotely deployed MC unit. These packets were sent for a continuous period of 22 days with a group of 10 packets sent every 30 minutes (with 10 seconds between two consecutive packets). Figure 17 shows that the majority of the packets took between 21 and 22 milliseconds to transfer. However, it should be noted that Internet delay is not guaranteed. It depends on various factors such as the geographical location and the time of the day.

![Figure 17: Internet delay Characterization Based on Data Taken Over 22 days in December 2013 in Windsor, Ontario](image-url)
5 CONCLUSION

In this thesis, a methodology for segment-wise delay characterization of various communication technologies is provided. The results of the experiments are valuable when selecting communication technologies that can meet the delay requirement of a particular SG application. It is observed that Ethernet technology can provide around 2 millisecond one-way delay for a three hop network with a packet size of 1500 bytes. Therefore, it is suitable for SG protection applications within a substation or locally at a photovoltaic installation. It is also observed that when a Wi-Fi link is involved, the increase in delay with increasing background traffic is not linear as in the case of an end-to-end Ethernet link. However, the combination of Ethernet and Wi-Fi is still suitable for local SG application such as monitoring and controlling rooftop deployed PV panels, where a delay up to 70 milliseconds is tolerable.

As monitoring and controlling of remotely deployed PV panels often involves packet transfer through the Internet, the delay experienced by these data packets is also characterized in this research. It was observed that majority of ICMP probe packets sent from a laptop through the Internet to a remotely deployed MCU took between 21 and 22 milliseconds to transfer in Windsor, Ontario between December 2013 to January 2014. This experiment provided an approximation of packet delay involving the Internet. It was shown that the Internet delay is not guaranteed as it depends on various factors such as the geographical location and the time of the day.
Cellular technology is useful for monitoring and controlling remote installations of PV panels, particularly in cases when Ethernet and Wi-Fi links may not be available. Therefore, ICMP probe packets were sent from a laptop to a remotely deployed MC unit to characterize the delay using GSM technology in Windsor, Ontario in January 2014. It was observed that the average RTT was 90 milliseconds for a packet size of 100 bytes. Similar to using the Internet, the delay in cellular technologies is not guaranteed and dependent on factors such as location and the time the packet is sent. However, if the application can tolerate delay to the order of 200 milliseconds as well as the occasional loss of packets, then cellular technology may be a candidate for remotely deployed devices.

The demonstrated test bed and delay characterization methodology can be used or easily extended to characterize the delay of other prospective communication technologies such as ZigBee and WiMAX for the SG. Such extended studies will help to facilitate better selection of one or more communication technologies to be used for a specific Smart Grid application.
6 REFERENCES


APPENDIX

A.1 Ethernet.info

#include <SPI.h>
#include <Time.h>
#include <Ethernet.h>

byte ArduinoMacAdress[] = ( 0xDE, 0xAD, 0xBE, 0xEF, 0xFE, 0xED );
byte ArduinoIP[] = ( 192, 168, 2, 1 );
byte Gateway[] = ( 192, 168, 2, 1 );
byte Subnet[] = ( 255, 255, 255, 0 );
byte MyServer[] = ( 192, 168, 2, 235 );

EthernetServer server(80);
EthernetClient client;
float current;
float voltage;

void setup()
{
  pinMode(8, OUTPUT);
  Ethernet.begin(ArduinoMacAdress, ArduinoIP, Gateway, Subnet);
  delay(1000);
  server.begin();
  Serial.begin(9600);
Serial.println("SetUp Sucess");

void loop()
{
    current = analogRead(0);
    voltage = analogRead(3);
    Serial.print("\nCurrent at Current Sensor : ");
    Serial.println(current);
    Serial.print("\nVoltage at Voltage Sensor : ");
    Serial.println(voltage);
    Serial.print("ARDUINO is attempting to connect... ");
    if(client.connect(MyServer, 84))
    {
        Serial.println("connected to the Myserver");
        Serial.println("ARDUINO: forming HTTP request message");
        client.print("GET /arduino/serverconnectingfile.php?current=");
        client.print(current);
        client.println(" HTTP/1.1");
        client.println();
        Serial.println("HTTP message sent");
        delay(3000);
        if(client.available())
        {
            Serial.println("HTTP message received");
        }
    }
Serial.println("printing received headers and script response...
");

while(client.available())
{
    char c = client.read();
    Serial.print(c);
}

else
{
    Serial.println("No response received / No response received in time");
}

client.stop();

else
{
    Serial.println("connection failure");
}

}
A.2 Wi-Fi.info

#include <SPI.h>
#include <WiFi.h>
#include <WiFiClient.h>
#include <WiFiServer.h>
char ssid[] = "wicip";       // your network SSID (name)
char password[] = "*******"; // your network password
int status = WL_IDLE_STATUS;
WiFiServer server(84);  //server port arduino server will use
WiFiClient client;
IPAddress MyServer(192,168,2,244); // (IP) web page server IP address
float current;
float voltage;
void setup()
{
  Serial.begin(9600);
  while (!Serial) {

  }
  if (WiFi.status() == WL_NO_SHIELD) {
    Serial.println("WiFi shield not present");
    while(true);
  }
  // attempt to connect to Wifi network:
  while (status != WL_CONNECTED) {
    Serial.print("Attempting to connect to SSID: ");
  //...
Serial.println(ssid);
    status = WiFi.begin(ssid, password);
    delay(10000);
}
Serial.println("Connected to wifi"); // you're connected now, it prints out the wifi status:
printWifiStatus();
}
void loop(){
    current = analogRead(0);
    voltage = analogRead(3);
    Serial.print("\n\nCurrent at Current Sensor : ");
    Serial.println(current);
    Serial.print("\nVoltage at Voltage Sensor : ");
    Serial.println(voltage);
    Serial.print(" attempting to connect... ");

    if(client.connect(MyServer, 80))
    {
        Serial.println("connected...");
        Serial.println(" Forming HTTP request message");
        client.print("GET /arduino/serverconnectingfile.php?");
        client.print("current=");
        client.print(current);
        client.print("&voltage=");
        client.print(voltage);
    }
client.println(" HTTP/1.1");
client.println();
Serial.println("HTTP message sent");
delay(3000);
if(client.available())
{
    Serial.println("HTTP message received");
    Serial.println("printing received headers and script response...
");
    while(client.available())
    {
        char c = client.read();
        Serial.print(c);
    }
}
else
{
    Serial.println("no response received / no response received in time");
}

client.stop();
}
else
{
    Serial.println("connection failure1");
}
void printWifiStatus() {

    // print the SSID of the network you're attached to:
    Serial.print("SSID: ");
    Serial.println(WiFi.SSID());

    // print your WiFi shield's IP address:
    IPAddress ip = WiFi.localIP();
    Serial.print("IP Address: ");
    Serial.println(ip);

    // print the received signal strength:
    long rssi = WiFi.RSSI();
    Serial.print("signal strength (RSSI): ");
    Serial.print(rssi);
    Serial.println(" dBm");
}

B - HrPING Setup and Working

- HrPING is a portable, command line utility no installation is required.
- To start the HrPING utility you must open the folder in the command prompt (in admin mode).
- Once the command prompt opens into the HrPING folder, type hrping on the command line to review the options as shown in the figure below.
For Example to ping 192.168.2.1 the following command is used “hrping 192.168.2.1”

In my experiment the following data options are used
- `-L` Total IP datagram size.
- `-n` Number of packets to send.
-s Interval in milliseconds between packet.

C – LAN Traffic Generator Software

- This software is to be installed on two systems on for transmission and the other for reception.
- Run the Setup_LanTrafficV2_Enhanced.exe File.
- Go to Start > Programs > LanTraffic V2 Enhanced>LanTraffic V2 Enhanced (Click to run the software).
- The following window will appear and click on YES

![Image of software window]

- Select I use two PC’s and the click on next step

![Image of software window]
• For Laptop 1 select Generate traffic and for Laptop 2 select receive traffic

![Diagram showing network traffic generation process]

• At the transmission side enter the destination IP address and Port number and click on generate traffic
• From the main window of the at the reception side enter the Port number same as transmission side and click on Ready to receive traffic.

• From the main window of the LanTraffic Generator click on the “Parameters #01” then the following window pops out and enter the back ground traffic value and click ok.
Then at the transmission side click on Start sender and receiver then both transmission and reception of the background traffic starts on both the sides.
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