DESIGN, SIMULATION, AND ANALYSIS OF SUBSTATION AUTOMATION NETWORKS

A Thesis

by

ELANGOVAN KEMBANUR NATARAJAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2011

Major Subject: Computer Engineering

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Approved by:

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ABSTRACT

Design, Simulation, and Analysis of Substation Automation Networks. (May 2011)

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Society depends on computer networks for communication. The networks were built to support and facilitate several important applications such as email, web browsing and instant messaging. Recently, there is a significant interest in leveraging modern local and wide area communication networks for improving reliability and performance in critical infrastructures. Emerging critical infrastructure applications, such as smart grid, require a certain degree of reliability and Quality of Service (QoS). Supporting these applications requires network protocols that enable delay sensitive packet delivery and packet prioritization. However, most of the traditional networks are designed to provide best effort service without any support for QoS. The protocols used in these networks do not support packet prioritization, delay requirements and reliability.

In this thesis, we focus on the design and analysis of communication protocols for supporting smart grid applications. In particular, we focus on the Substation Automation Systems (SAS). Substations are nodes in the smart grid infrastructure that help the in transportation of power by connecting the transmission and distribution lines. The SAS applications are configured to operate with minimal human intervention. The SAS monitors the line loads continuously. If the load values are too high and can lead to damage, the SAS declares those conditions as faults. On fault detection, the SAS must take care of the communication with the relay to open the circuit to prevent any damage. These messages are of high priority and require reliable, delay sensitive delivery. There is a threshold for the delay of these messages,

and a slight increase in the delay above the threshold might cause severe damages. Along with such high priority messages, the SAS has a lot of background traffic as well. In spite of the background traffic, the substation network must take care of delivering the priority messages on time. Hence, the network plays a vital role in the operation of the substation.

Networks designed for such applications should be analyzed carefully to make sure that the requirements are met properly. We analyzed and compared the performance of the SAS under different network topologies. By observing the characteristics of the existing architectures, we came up with new architectures that perform better. We have suggested several modifications to existing solutions that allow significant improvement in the performance of the existing solutions.

To My Family, Teachers and Friends

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CHAPTER I

INTRODUCTION

Computer networks have become an important backbone for today's society. In fact, economic activities and social life have seen huge evolution with new developments in computer networks. The traditional networks were designed to support several important user applications like email, web browsing and instant messaging. These networks were built with the notion of fairness i.e. the network should try to serve all the users with equal data rate. The users are provided with the type of service known as *the best effort service*. Best effort service does not guarantee Quality of Service (QoS) or data delivery to the users. It does not prioritize between the users as well. It tries to provide the best possible service to the user depending upon the load in the network. It also tries to ensure fairness to all the users in the network. However, with the introduction of multimedia messages, the concept of delay sensitive traffic came into play. These data types are provided with User Datagram Protocol (UDP) which sacrifices reliability and authentication for reduced delay.

Recently, there has been a significant interest in using the modern local and wide area communication networks in critical infrastructures to improve performance and reliability. These critical infrastructures require a certain degree of reliability and QoS. The network protocol that supports these applications should also provide guarantees for timely packet delivery and packet prioritization. These networks should also be interoperable with the traditional networks. With the growth of such infrastructures, the applications have increased requirements. However, these applications cannot deviate entirely from the traditional protocol if they are to achieve interoper-

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ability. In this thesis, we focus on designing networks to satisfy the requirements of one such critical infrastructure, *the smart grid*.

Smart grid is an electricity network that uses digital technologies to handle its communications. This network is used for monitoring line loads, transmission and distribution of power. The network comprises of substations and National Control Center (NCC). The substations are used for transmission and distribution of power. The NCC takes care of monitoring the operations of substations and the line loads in each substation. The older models of this network used telephone lines for communication between NCC and substations [1]. The components inside the substation were hard-wired for communication. However, these methods meant costly wiring, constant human intervention and slower performance. Recently, the smart grid network has moved to modern computer networks to handle the digital communication.

Among the smart grid applications, we focus particularly on communications within a substation. These substations have been designed to operate with minimal human intervention and hence they are known as the Substation Automation Systems (SAS). IEC 61850 protocol defines the requirements associated with the SAS application. The application has some time critical messages and a lot of less priority messages in the network. These time critical messages need a certain degree of reliability and QoS. One such time critical message is the *trip message* which informs the relays to open the breakers whenever there is a fault. The IEC protocol defines the threshold for the delay of these messages. However, it does not provide any guidance to guarantee the message delivery performance [2].

The delay of these time critical message is probably the most important aspect to make note of in the SAS application. If a trip message is lost or if it experiences excessive delay and exceeds the threshold, the relay will fail to open the breaker on time and this can lead to severe damage and financial loss. Hence, the entire architecture of the substation can be termed feasible only if it complies with the needs of the priority messages. Correspondingly, the substation network should be designed to guarantee all the requirements of these messages. The practical substations use bus ethernet and switched ethernet for communications. Reference [3] provides a difference in the requirements of the ethernet used in substation compared to the normal office ethernet. This clearly explains the need for a detailed design of the substation network.

Hence, the main requirements for the network include prioritization of messages, reliable and guaranteed delivery of the critical messages [3]. At the same time, the network should ensure that the number of components needed to build the architecture should be small because with the increase in the number of components, the reliability of the network decreases [4]. Another way of improving reliability is by introducing redundancies in the network. However, this increases the cost associated with developing the network. Hence, the ideal substation network should be reliable, provide packet prioritization, guarantee QoS and should be cost effective. In this thesis, we provide methods to improve the performances in the Bus ethernet model of the substation. By modifying the back off of the users based on their priority, the delay of the time critical messages can be significantly improved. We also provide new architectures using existing Wireless Local Area Network (WLAN) to ensure a better behavior than the practical models. By going with the wireless network, we achieved performance characteristics close to the wired networks. This means the delay performance of the WLAN model was comparable to the best topology with respect to delay and the reliability performance of the WLAN model was comparable to the best topology in terms of reliability. We did reliability studies on these models to confirm the results.

A. Motivation

Even though the analysis of delay in the substation network is important, until [3] there was no proper simulation method to analyze the delays in the network. The network designed by them was a futuristic approach which explored the possibilities of incorporating more messages in the network. However, even [3] does not provide an accurate model for implementing practical substations. Hence, we built a practical model of the substation in OPNET. While doing so, we realized the complexities in implementing the current network technologies in the substation and the importance of the trade-off between reliability and performance. This presented a significant challenge in designing substation network. The models built in this thesis are based on the practical substation model that was developed in OPNET.

B. Related Work

The related work for this thesis can be split into three categories:

1. Works related to the analysis of substation models.
2. Works related to the modifying backoff timer in bus ethernet
3. Works related to exploring the possibility of wireless models and reliability models in substations.

The whole idea of substation automation gained popularity with the introduction of IEC 61850 protocol. However, the feasibility of IEC 61850 was showed by [5]. This was the first paper to consider the requirements of the IEC 61850 and explored the protocol's feasibility. Ethernet was explored as a possibility for communications in substation in [6] and it was found to have sufficient performance characteristics to support substation communication. Reference [2] criticized the IEC 61850 protocol of providing no guidance to describe the characteristics of the delivery performance. None of the papers proposed a proper way to analyze the performance of the substations. [3] was the first work that provided a solid way to simulate substation network. The topologies for substations have not changed after these works.

The concept of modifying the backoff scheme of the bus ethernet has been explored by a lot of papers. Reference [7] looks at a bus ethernet in terms of it's multimedia traffic load and data traffic load. The paper proposes a backoff scheme to improve the overall performance based on these loads. Reference [8] assigns priorities to packets similar to 802.1p. Each packet has a weight associated with it and the weights play a role in modifying the backoff. However, this paper does not give analysis based on the number of users or traffic load. Reference [9] proposes a complete new mode it the network known as RETHER mode. The LAN switches from CSMA to RETHER mode to transmit real time traffic. Apart from these, a few papers analyze the possibility of backoff scheme in Wireless network. Reference [10] talks about schedulers based on the backpressure. Reference [11] talks about modifying the slot time dynamically based on the type and the length of the packets.

The idea of expanding smartgrid up to the consumer's home resulted in analysis of possibility of wireless protocols in smart grid. Reference [12] describes the requirements for implementing smartgrid over wireless network and also enlists a few of the wireless protocols that could be used in smartgrid. Reference [13] was one of the first papers to suggest using WLAN in substations. However, the author did not specify architectures for the wireless model. The ABB patent provided a very important breakthrough concerning implementation of wireless schemes in substation [13]. They came up with special waveguides to block electromagnetic disturbances to enable Wireless LAN to perform well.

The concept of reliability in substations has been explored in a lot of papers. Reference [14] looks at the architecture of the existing topologies and analyzes the reliability. The authors also look at the reliability of the substation in wireless ad-hoc model. However, the reliability analyses were simple without any actual numerical results. Reference [15] suggests architectures known as Reliability Block Diagrams to calculate the reliability of networks. This method is employed in [4] and an analysis of the effect of redundancies and simpler models are given. Reference [16] performs a more critical analysis by taking into effect the concept of repairable systems.

C. Outline of the Thesis

In Chapter II, we introduce the basics of substations and the components of the practical substation. We also mention the system model and the topologies that exist currently in substations. In Chapter III, we talk about the simulator, OPNET used in this thesis. We also talk about the models and nodes designed in the OPNET for simulation purposes.

In Chapter IV, we start to talk about the contributions of the thesis. We talk about the scheme used in the delay aware backoff and how we derive at the scheme. In Chapter V, we talk about the wireless architectures, their implementations, challenges and extensions. In Chapter VI, we talk about reliability technique and move on to propose the reliability block diagram for each architecture and evaluate them.

Finally in Chapter VII, we show the simulation results and compare the performances of different architectures. In Chapter VIII, we give the conclusion and the future work possible in this area.

CHAPTER II

SUBSTATION AUTOMATION SYSTEMS

Substations in electrical grids are devices which are used for connecting transmission and distribution lines. They are used in transmission and distribution of power. So a typical substation is supposed to receive the electricity and based on the location of the substations, it either needs to step up the voltage or step down the voltage and transmit the power down the line. Correspondingly, the substations have either a step up transformer or step down transformer and lines to distribute the load. Hence we can compare the substation to a router in a communication network. Both of them receive data, process them and send it to the destination. In case of anomalies, the router can just discard the data or perform some action but a substation cannot do such tasks. So with the involvement of power, a substation needs to have some kind of fault detection, fault tolerance and recovery mechanisms. This combined with the fact that some substations are deployed in rough and inaccessible terrains, Substation Automation Systems (SAS) was introduced.

A. IEC 61850

SAS uses Intelligent Electronic Devices (IEDs) to control it's functionalities. These IEDs are nothing but a microprocessor based controller that are capable of performing various functions. Various types of IEDs were designed to perform specific tasks. Each of these IEDs used to follow different protocols to communicate based on the type of task they were supposed to perform. This led to a lot of complexities when the IEDs tried to operate together. Costly protocol converters were used to ensure interoperability of IEDs [17]. These protocol converters also introduced delay in the network. To solve all these problems, a common protocol known as the IEC

61850 was introduced. This protocol has been standardized internationally and all the communication inside the substation follows this protocol including the digital communications that happen in the process level of the substation. IEC 61850 used ethernet based technology to be the communication network. This protocol also defines the requirements for various communication and even takes care of substation automation in terms of project management, conformance testing, etc [3]. Thus IEC 61850 reduces the cost of the substation by avoiding protocol converters. It also establishes interoperability with minimum delay.

B. Role of IEDs

There are many types of IEDs in the substation network. Some of the IEDs include the Merged Unit (MU) IED, Protection IED, Control IED and the Breaker IED. As said before, each type of IED has a specific set of tasks to perform. The MU IED is connected to the current and voltage transformers. The function of the MU IED is to receive the analog current and voltage values from the current and the voltage transformers. It then samples those values and sends the digitized values to the Protection IED. The protection IED monitors these values constantly and sends out a trip message if it detects any anomalies. These trip messages are sent to other protection IEDs and the corresponding breaker IEDs. The protection IEDs associated with the detected fault controls the relays to open the circuit to stop the current flow and hence prevent damage. The breaker IED sends out a Generic Object Oriented Substation Event (GOOSE) message to the entire system informing of the state change that has occurred in the network. All the three messages discussed here namely, the sample values, the trip message and the GOOSE message are all considered to be high priority and time critical messages. Excessive delays in these messages mean failure to detect fault or failure to open the circuit and so the consequences are severe. Apart from these IEDs, there is a Circuit Breaker Monitor (CBM) that monitors the breaker to see if they have been opened properly. These CBMs and the Protection IED records the event associated with the failure and sends out those records to the substation computer.

The MU IED and the Breaker IED belong to the lower level of the substation known as the process level. The protection IED, control IED and the CBM belong to the system level of the substation. In the practical substations, the process level is connected by copper wires and only the system level components of the substation are connected by the ethernet. Hence the sampled values and the GOOSE message occur in the hard wires network while the trip message alone occurs in the ethernet.

C. Substation Model

In the system model considered for this thesis, we take into consideration only the components that come under the ethernet network. The process level of the substation does not come under the ethernet communication network and hence it is not considered. So we assume that the priority messages like sampled values and GOOSE message are sent and received properly in the network. Among the system level components, we define the substation to be divided into three types of bays. They are the line bays, the bus bays and the transformer bays. Each bus bay and transformer bay unit consists of one CBM, one protection IED and one control IED. Correspondingly, each bay unit consists of one relay and breaker each. Since all the line loads are directly monitored by the line bay, it alone needs to have redundancy to ensure reliability. Hence, neighboring two line bays share three breakers among them. This model is known as the one and a half breaker model. In case of a fault, the line

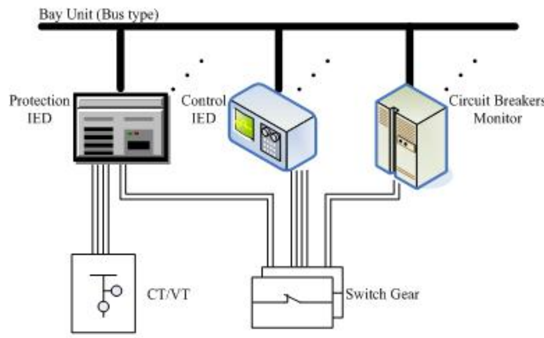

Fig. 1. Bus Bay Unit.

bay tries to open both the breakers associated with it. Since it has two breakers, it needs two CBM to monitor the breakers and so the line bay unit consists of one protection IED, one control IED and two CBMs. In the substation model considered, we have 16 line bays, 4 bus bays and 2 transformer bays. These bay units occur in the switchyard area of the substation. A sample bay unit for bus ethernet is shown in Fig. 1 and a sample bay unit for switched ethernet is shown in Fig. 2

Along with the switchyard area, the substation consists of the control center. This center, as the name implies controls the operation of the substation and provides configurations to the IEDs. This control center also is responsible for conveying the substation messages to the NCC. Hence the control center acts as the interface between NCC and the substation. The control center consists of the Human Machine Interface (HMI), Digital Fault Recorder (DFR), GPS receiver, a substation server and router. The HMI is nothing but a substation computer that is used to send configuration messages to the IEDs. It acts as the way for human intervention in the substation. The DFR receives the sampled values of the current and voltage from the MU IEDs directly through hardwire and stores them. Whenever there is a fault, the DFR compiles these values into a record and sends the record file to the HMI

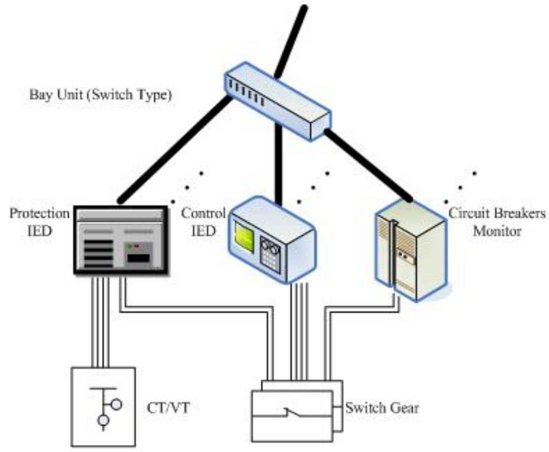

Fig. 2. Switched Bay Unit.

through a file transfer. The router is used to connect the substation to the Wide Area Network (WAN). A line diagram of the substation is shown in Fig. 3. The networking view of the substation is shown later in the Figs. 4, 5 and 6.

Apart from the trip message, the network also contains file transfer messages, time synchronization messages and configuration messages. A substation network is considered practically feasible only if the delay of the trip message lies under a certain threshold. Hence the primary objective when testing all the developed architectures is to note the delay of the trip message in that network.

D. Network Topologies in Practical Substation

The components of the switchyard and the control center are built using different topologies in the practical network. The substation might be connected in either bus ethernet or switched ethernet. Among the switched ethernet, the substation can be connected either in Ring topology or the star topology.

The bus ethernet in substation employs 10Mbps or 100Mbps ethernet bus. All

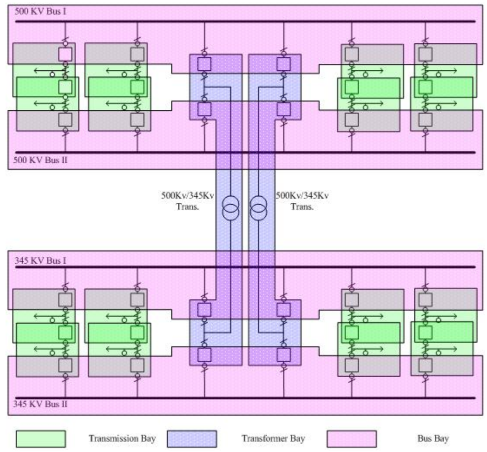

Fig. 3. Substation Line Diagram.

the bay units and the control devices are connected to the single bus. Since the bus connects all the station level components, it is known as the station bus. All the network messages are exchanged using this bus. The main delays experienced in the bus ethernet are due to collisions. However, since this model employs less number of components, it is significantly reliable [4]. The substation model for the bus ethernet is given in Fig. 4.

The ring and the star topology employs switched ethernet. The way the bay units are connected to one another varies based on the type of topology. The ring topology is given in Fig. 5. This topology defines two paths for each bay to communicate with every other bay. The presence of two separate paths ensures better reliability. However, the number of switches employed in this scheme is more and the path from one protection IED to another lies through many switches. Since queuing and processing at the switches constitute the main cause of delays in switched ethernet, the delay performance will be a little poor.

The star topology example is given in Fig. 6. This topology has less number

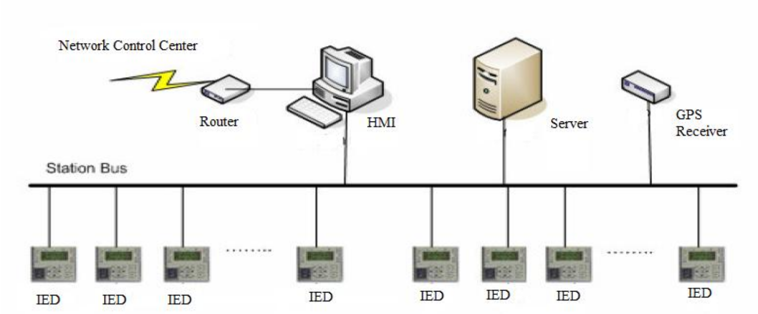

Fig. 4. Bus Ethernet Model.

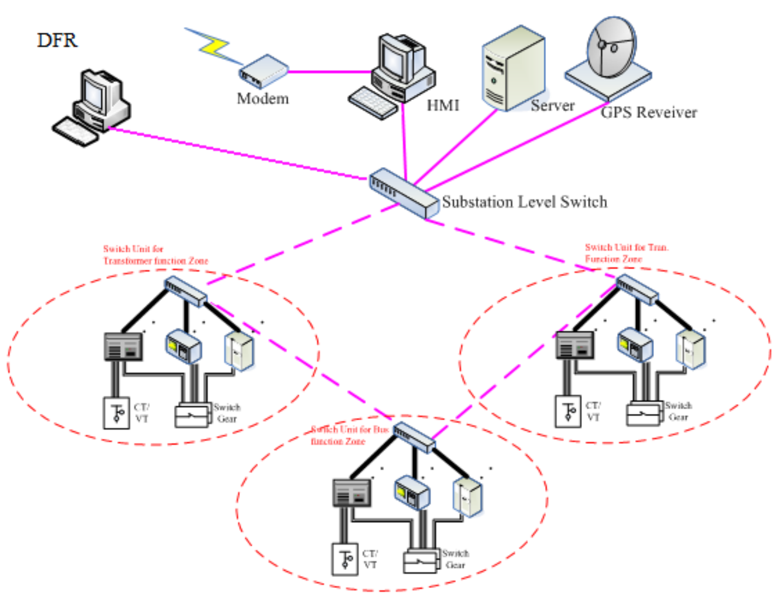

Fig. 5. Switched Ethernet-Ring Topology.

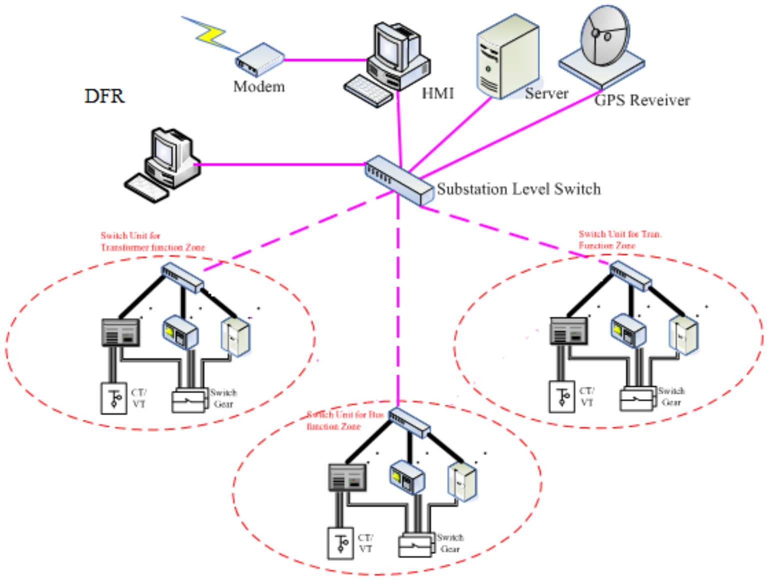

Fig. 6. Switched Ethernet-Star Topology.

of switches and has good performance in terms of delay. However, there is just one path between different nodes and so the reliability is less compared to ring topology. This is the most preferred of the three with respect to delay performance. However, practical substations prefer bus ethernet if reliability is the main concern and go for ring topology in cases where the tradeoff in reliability is not a huge issue.

E. Messages Exchanged

The messages considered in these network consists of the time critical message namely the trip message. This message is generated in the network whenever faults occur. This message is sent from the Protection IED which detects the fault to the corresponding protection IED which shares the breaker with the faulty line bay. If the breakers fail to open, the protection IED tries to open the entire bus bus associated with the faulty line. This trip message is 16 bytes in size. Once the trip message is sent, the protection IED and the CBMs of the bay unit in question sends error report to the HMI. These error reports are about 300KB in size and are sent using the File Transfer Protocol (FTP). Similarly, the DFR compiles a report of the values and sends a file of size 300KB to the HMI through FTP. Apart from these, the HMI sends a time synchronization message to all the components of the substation every second. This message is of size 16 bytes as well. Except for the trip message, the other messages are considered to be background messages.

CHAPTER III

OPNET MODELS

This chapter gives details about the modeling and simulation of the substation network in OPNET. By simulating different topologies, we can measure the delay performance and see if different models can be implemented without compromising the delay performance. OPNET can be established as a great way to compare the performances of these topologies. OPNET modeler is chosen over other simulators because of its extensive model library, user friendly interface and free-license for academic research. It is also the industry's leading environment for network modeling and simulation, facilitating in the design and study of various communication networks, models, protocols and applications with a lot flexibility and scalability. OPNET's library even includes models for devices based on companies like Cisco, Juniper, etc.

Apart from the extensive library, OPNET has different editors that form a hierarchy. This hierarchical series of editors enable easy modeling of new protocols and device models. The top most level of the editors is the project editor. This editor is used to develop the overall scenario of the communication network. All the devices and components of the network can be drawn here and the communication links can be specified. Apart from these, the standard application like FTP, E mail, etc can be defined in the project editor. The next level of editor is the node editor. This is used to modify the node models of the devices in the network. The node model of each device comprises a combination of process models that are cooperate with one another and together characterize the functions of the device. The node models contain the various attributes of the device and these attributes can be modified by the user.

The lower most level in the hierarchy of the editors is the process editor. This editor allows the modification of the process models. These process models comprises of a series of Finite State Machines (FSM). These FSMs together define the flow the process in the process model. The coding inside the process editor is done using C/C++. The editor defines places to write the Header block, Function block, State variables and the temporary variables used in the editor. The FSMs have blocks for enter executables and exit executables. Whenever the process enters or exits the FSM, the corresponding executables are executed. Hence they form the ideal tool to define new models. Along with the hierarchical series of editors, the OPNET modeler also has packet format editor to defines packet models, link and path editors to defines connectivity, etc.

A. IED Modeling in OPNET

Models were developed in OPNET for Protection IED, MU IED and Breaker IED. The models for CBM, Control IED and DFR and HMI were taken from existing models and modified accordingly. Although all these models were available for designing the substation, MU IED and breaker IED were not used in the simulations because they do not occur in the substation as a part of the network.

The node model of the protection IED consists of the normal OSI seven layers for specifying the FTP traffic in the IED. Along with the OSI layer, three specific process models were developed. These are the Trip source, eth_mac_intf_sas and the Sink processes. As the name suggests, the Trip source defines the generation of the trip messages. Since actual faults cannot be detected, the time points at which trip messages need to be generated are obtained from the user and trip messages are generated at those times. The trip messages are usually sent four times to make sure that at least one gets through [3]. The format of the packets were defined in

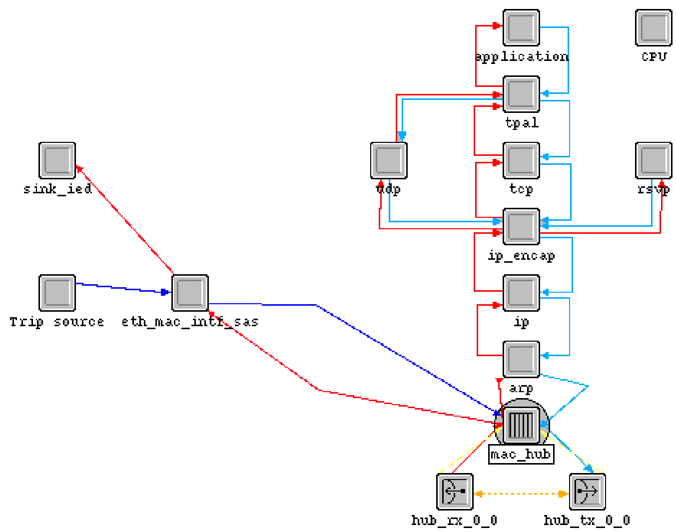

Fig. 7. Protection IED Node Model.

the packet editor and they are sent out four times on the specified times. The node model of the protection IED is shown in Fig. 7.

The process model of the trip message is shown in the Fig. 8. An initial state is defined where the time points given by the user are obtained. The process moves on to the OFF state and the timer is started for the first trip message during this time. As soon as the timer expires, the process moves to the ON state. In this state, the process generates and sends out four trip messages to the eth_mac_intf_sas model. The eth_mac_intf_sas receives the trip message and sends it out to the mac layer. So the priority messages are directly injected into the ethernet layer rather than going through the normal layers. The Sink process model is defined to receive the trip messages sent out by other IEDs. On receiving messages, the sink checks if it is a trip message. If so, it registers the end to end delay of the message. We note the end to end delay of all trip messages and give these values when the simulation ends.

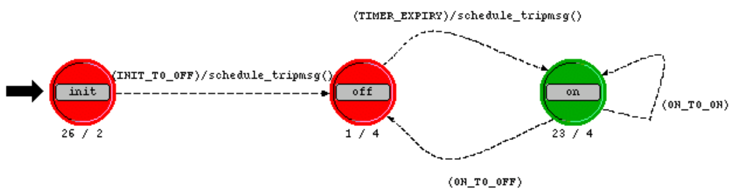

Fig. 8. Protection IED Process Model.

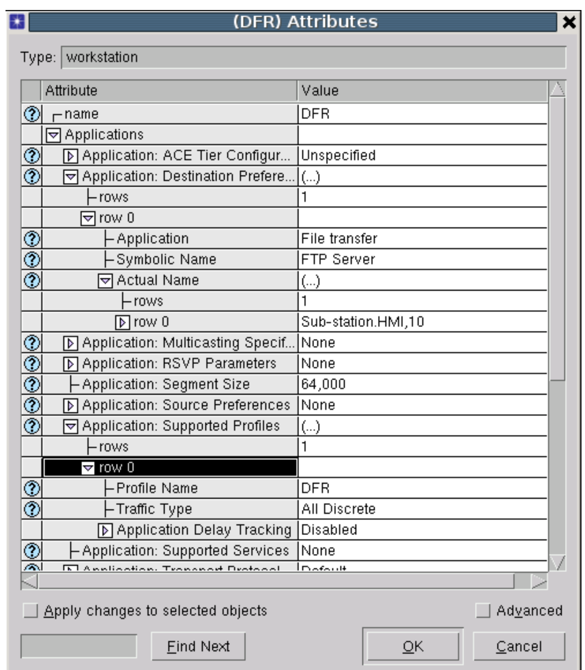

Fig. 9. DFR Attributes.

For the other IEDs, we define applications that specify the traffic they are supposed to generate. We create separate profiles for these applications. OPNET provides standard node models to create application and profile definitions. Once the profiles are created, the IEDs have to include these profiles in their attributes to generate traffic for the specified applications. The DFR and the HMI are similarly designed to generate necessary messages. A sample profile definition for the DFR is given in Fig. 9. The figure shows the DFR attribute which uses the profile defined for the file transfer procedure.

Similar process models were developed for Wireless LAN as well.

CHAPTER IV

DELAY AWARE BACKOFF

As mentioned in Chapter II, the bus ethernet model of the substation is the best model in terms of reliability. Some substations even prefer bus ethernet to the switched ethernet because of this reason. Hence improving delay performance of the bus ethernet would prove very useful if the network needs to support more messages. Reference [7] proposes a modified backoff scheme based on the ratio of multimedia traffic to the data traffic. By taking into account the rates and load of each type of traffic, the paper tends to improve the overall performance. In this thesis, the main concern is to improve the priority traffic irrespective of the network load, the load of the priority traffic or the number of stations.

A. Backoff Scheme

In bus ethernet, all the messages that go around the network use the single bus. In substation, this bus is the station bus. All the IEDs and the control center devices are connected to each other through the station bus. The main cause of delays in bus ethernet is due the collisions. Whenever a packet experiences collision, the sender starts a timer. The packet is retransmitted after the timer expires. The timer uses random exponential backoff scheme to make sure that the devices perform well even if there are many users in the system. The main characteristics behind the backoff of the bus ethernet is that the whole scheme is decentralized i.e. there is no centralized coordinator to inform the devices when to send packets. Hence whenever there is a collision, the devices do not know with whom they have collided and with how many users they collided.

If performance of the bus ethernet is to be improved, improving the backoff scheme is the way to go. The devices in the network should be termed as either a priority user (real time user) or a non-priority user (best effort user). The basic idea behind providing priority to the real time users is to decrease the backoff timer for these users at the cost of increasing the timer for the best effort users. However, care should be taken to ensure that the delay of best effort users do not increase too much. Also, if the number of priority users are more in the system, decreasing the backoff too much would mean increased number of collisions and increased delay among the real time users. Hence an optimal scheme is needed to ensure proper backoff.

B. System Model and Assumptions

Since we are building the scheme to improve the substation performance, the system model is taken from the substation network. The trip message is the only high priority message. Hence only the protection IEDs that sends the trip message are considered to be real time users. In substations, the occurrence of fault is a fairly rare event and occurrence of two faults in two separate lines is rare. Any further cases are assumed almost impossible. So we take only two priority users in our consideration. In bus ethernet, the backoff and the wait times are based upon the slot times. The slot time is the time taken for a message to be sent from one end to other of the ethernet. We assume our system to be discrete for simplicity and that each slot is twice the slot time. This ensures proper delivery of the message and the sender confirms the successful delivery within the slot. As we are trying to improve the backoff scheme, we assume that our system always starts with a *one time* collision and that the users start their backoff timer. The one time collision implies that the users do not have any other high priority message than their single trip message.

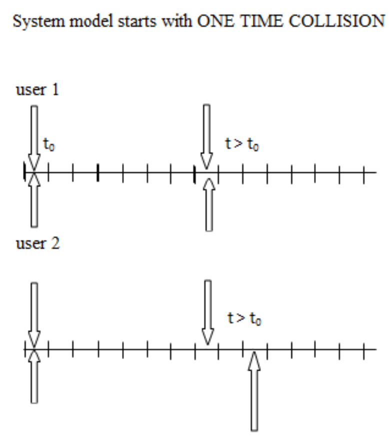

Fig. 10. Backoff Cases.

C. Delay Calculation

First, let us look at what the optimal strategy would be for a system with just two users. We assume that this is a *onetime* event. We assume that the users are user 1 and user 2. Let us assume that both the users have some message to send. At time t_0, both users try to send the message in the next slot. Collision occurs and both users backoff to a random future slot. Let us consider the probability mass function of the two users to be $p_1(i)$ and $p_2(i)$. When the two users send the message again, there may either be another collision or the packet might be sent successfully as shown in Fig. 10. As the priority users are concerned only with reducing their own delays, we take into consideration reducing the delay of each individual user rather than observing the entire system's delay.

Let us take user 1 into consideration. The Expected number of slots in which the user 1 sends the message is given by,

$$E_1(i) = \sum_{i=1}^{\infty} i \cdot p_1(i) \tag{4.1}$$

The probability of the two users colliding again is given by,

$$\eta = \sum_{i=1}^{\infty} p_1(i) \cdot p_2(i) \tag{4.2}$$

Let $E[T_1]$ be the average time taken to retransmit. It is given by,

$$E[T_1] = \sum_{i=1}^{\infty} p_1(i)[(1 - p_2(i))i + p_2(i)(i + E[T_1])] \tag{4.3}$$

If the left hand side is expanded and Equations on (4.1) and (4.2) are applied, the equation can be simplified. On simplifying, Equation (4.3) becomes

$$E[T_1] = \sum_{i=1}^{\infty} E_1 + \eta \cdot T_1$$

This further reduces to

$$E[T_1] = \frac{E_1}{1 - \eta} \tag{4.4}$$

The expected delay for the second user, user 2 can be similarly derived to be

$$E[T_2] = \frac{E_2}{1 - \eta}$$

If we assume that both the users are priority users, we can say that $p_1 = p_2$. Hence the Equation (4.1) becomes

$$E = E_2 = E_1 = \sum_{i=1}^{\infty} i \cdot p(i) \tag{4.5}$$

Correspondingly, Equation (4.2) becomes

$$\eta = \sum_{i=1}^{\infty} p^2(i) \tag{4.6}$$

D. Optimization

The objective we are trying to achieve is to minimize $E[T]$. So the original optimization equation is given by,

Minimize,

$$E[T] = \frac{E}{1-\eta} \tag{4.7}$$

such that

$$\begin{aligned} \sum_{i=1}^{i=\infty} p(i) &= 1 \\ p(i) &\geq 0 \qquad \forall i \end{aligned}$$

Since the Equation 4.7 is non linear, we solve the optimization in a different way. For all values of $E = \alpha \in [1, \frac{n(n+1)}{2}]$, we define the minimum collision probability for each value of α as η_α, where $\eta_\alpha = \eta|_{E=\alpha}$. So the objective now reduces to minimizing η_α. Finally, we choose optimal α that minimizes the expected delay, $E[T] = \frac{\alpha}{1-\eta_\alpha}$.

1. The Inner Loop

To minimize the packet collisions i.e. η_α, we can define the conditions for the minimization to be;

1. Choose a value $E = \alpha$ from $[1, \frac{n(n+1)}{2}]$.
2. The summation of all the probability values that the slots can take should be equal to one.

We have represented E in Equation (4.5) and η in Equation (4.6). Since we cannot take the summation till ∞ in these equations, we assume limited support and let the summations to go on till n. This makes the calculation easier. Having established all the conditions, the optimization equation is given as the following.

Minimize,

$$\eta_\alpha = \sum_{i=1}^{i=n} p(i)^2 \tag{4.8}$$

such that

$$\begin{aligned} \sum_{i=1}^{i=n} i \cdot p(i) &\leq \alpha \\ \sum_{i=1}^{i=n} p(i) &= 1 \\ p(i) &\geq 0 \qquad \forall i \end{aligned}$$

For simplicity, we rewrite the Equations. Minimize,

$$\sum_{i=1}^{i=n} x_i^2 \tag{4.9}$$

such that

$$\begin{aligned} \sum_{i=1}^{i=n} i \cdot x_i &\leq \alpha \\ \sum_{i=1}^{i=n} x_i &= 1 \\ x_i &\geq 0 \qquad \forall i \end{aligned}$$

2. KKT Conditions

To solve the optimization Equation 4.8, Karush-Kuhn-Tucker (KKT) conditions are used. To express the optimization problem in KKT conditions, the problem is modified as Minimize,

$$\sum_{i=1}^{i=n} x_i^2 \tag{4.10}$$

such that

$$\begin{aligned}\sum_{i=1}^{i=n} i \cdot x_i &\leq \alpha \\ \sum_{i=1}^{i=n} x_i &\leq 1 \\ -\sum_{i=1}^{i=n} x_i &\leq -1\end{aligned}$$

Based on Lagrange multiplier method, the dual can be given as

$$L(x) = \sum_{i=1}^{i=n} x_i^2 + v_1(\sum_{i=1}^{i=n} i \cdot x_i - \alpha) + v_2(\sum_{i=1}^{i=n} x_i - 1) + v_3(-\sum_{i=1}^{i=n} x_i + 1) \tag{4.11}$$

Here v_1, v_2 and v_3 are dual variables such that $v_1, v_2, v_3 \geq 0$. Differentiating Equation (4.11) with respect to x_i we get,

$$x_i = \frac{v_3 - v_2 - i \cdot v_1}{2}$$

Assuming $v_3 - v_2 = v_{32}$ we get,

$$x_i = \frac{v_{32} - i \cdot v_1}{2} \tag{4.12}$$

Differentiating Equation (4.11) with respect to v_1, v_2 and v_3 we get,

$$\begin{aligned}\sum_{i=1}^{i=n} i \cdot x_i - \alpha &\leq 0 \\ \sum_{i=1}^{i=n} x_i - 1 &\leq 0 \\ -\sum_{i=1}^{i=n} x_i + 1 &\leq 0\end{aligned}$$

Based on KKT conditions, multiplying the equations with v_1, v_2 and v_3 gives

$$v_1(\sum_{i=1}^{i=n} i \cdot x_i - \alpha) = 0 \tag{4.13}$$

$$v_2(\sum_{i=1}^{i=n} x_i - 1) = 0 \tag{4.14}$$

$$v_3(-\sum_{i=1}^{i=n} x_i + 1) = 0 \tag{4.15}$$

In Equation (4.15), v_3 cannot be 0 because if v_3 is zero, all other variables in Equation (4.12) should be zero to make sure that the random variables x_i are positive. In Equation (4.13), if v_1 is zero, all the x_i's will have the same value according to Equation (4.12). This case occurs only when the value of α is high i.e. when $\alpha \geq \frac{n\cdot(n+1)}{2}$.

On applying Equation (4.12) and the conditions that $v_1, v_3 \neq 0$ and $v_3 - v_2 = v_{32}$, we get

$$-v_1/2\sum_{i=1}^{i=n} i^2 + v_{32}/2\sum_{i=1}^{i=n} i - \alpha = 0 \tag{4.16}$$

$$v_1/2\sum_{i=1}^{i=n} i - v_{32}/2 \cdot n + 1 = 0 \tag{4.17}$$

Solving these two equations with $\alpha = 3$,$n = 10$, we get $v_1 = 2/33$ and $v_{32} = 8/15$. Applying these values in Equation (4.12) and applying the condition that $x_i \geq 0$, we get the values of x_i as $x_1 = 0.2364$, $x_2 = 0.2061$, $x_3 = 0.1757$, $x_4 = 0.1455$, $x_5 = 0.1152$, $x_6 = 0.0848$, $x_7 = 0.0545$, $x_8 = 0.0242$ and $x_9 = x_10 = 0$.

This result has been confirmed by using the same optimization Equation (4.8) in the CPLEX optimization software of MATLAB. The optimization distribution according to MATLAB was the plot shown in Fig. 11. So we can imply that the optimal distribution for backoff timer for the priority users is a linear distribution. The probability of retransmission linearly decreases with the increase in slot numbers.

Since the optimization equation is convex, the minima given by the MATLAB is the optimal minimum. In CPLEX, the quadratic optimization function is used to solve the problem.

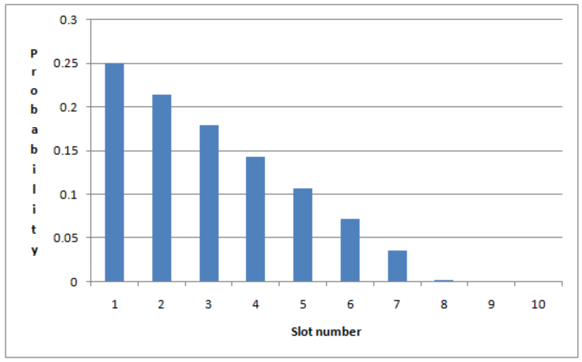

Fig. 11. Optimal Distribution for Backoff.

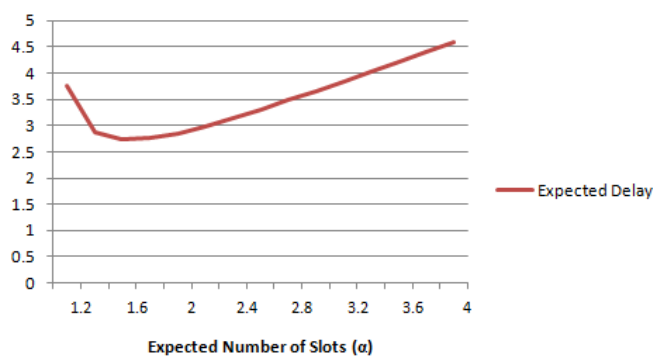

Fig. 12. Alpha vs. Expected Delay.

3. The Outer Loop

Optimizing η still leaves the question of optimum value of α. The optimization of η is run for various values of α from $[1, \frac{n(n+1)}{2}]$ to determine the optimal value of α for which the delay is minimum. This experiment is shown in Fig. 12.

The Optimal value for α was thus found to be 1.6. The corresponding probability distribution was found for this value of α and this gives the optimal backoff distribution for the system model.

CHAPTER V

WIRELESS MODELS

In Chapter 2, we mention that the substations are deployed in rough terrains. The terrain along with the fact that there are a lot of wired connection means that the cost of wiring is quite high in substations [13]. The wiring between the switchyard and the control center is particularly costly because of the distance between them. Hence by moving to wireless network, the cost of wiring in the substation can be significantly reduced. WLAN is the wireless substitute for ethernet network. So we explore the possibility of employing WLAN based substations.

A. Challenges

Security is one of main issues in any network. By going for WLAN network, there is a possibility of third party users getting access to the messages transferred. To avoid these situations, Wi-Fi Protected Access (WPA) can be included to improve security in WLAN. Also, WLAN networks are sensitive to ElectroMagnetic (EM) disturbances. Considering that the substations hold power lines and power devices, the possibility of EM disturbances are quite high. However, Reference [13] talks about a waveguide specifically developed by ABB for industrial purposes such as these. These waveguides block the EM disturbances and the WLAN can operate without any disturbances.

WLAN employs Access Points (AP) as the coordinator for the systems in the network. The range of the typical AP is about 100m. Substations usually cover a distance of around 125m. However this varies with substation capabilities. The range of WLAN might decrease if there are surrounding devices using the same frequency. Hence the area around the substation should not have any other antenna based equipments that operate in the same frequency as the AP. However, since the substations usually occur in remote areas, this should not be a huge factor.

B. Architectures

One of the basic architecture that can be used for wireless scheme is to use a single AP to connect all the devices in the substation. So all the devices in the model given in Figs. 5 and 6 need to have wireless transceivers. In single AP model, the reliability will be comparable to bus ethernet. However, the delay will not be as worse as bus model because WLAN uses centralized scheme to transmit messages with reduced collisions. The layout of the single AP model is shown in Fig. 13. Apart from the changes in the physical channel, there is no other change in the network. The messages that occur in the network and the conditions during which each message occur remain the same in wireless model as well.

C. Model Extensions

The wireless model has advantages like reduced cost, better reliability-delay tradeoff and ease of deployment. Still the architecture can be improved further by going for multiple APs or a partial wired-wireless network. If multiple APs are used, the traffic load can be divided between the access points and the delay can be improved further. Since each AP can cover the entire substation, they can also be considered as the redundant device in the network. Thus the reliability is improved as well but there is a small delay when the network is reconfigured to figure out the new paths to each device. An example for multiple AP network is given in Fig. 14. As shown in the figure, we connect the components of the control center through a switch directly to the two APs. This reduces the delay for the messages sent by the HMI to the devices.

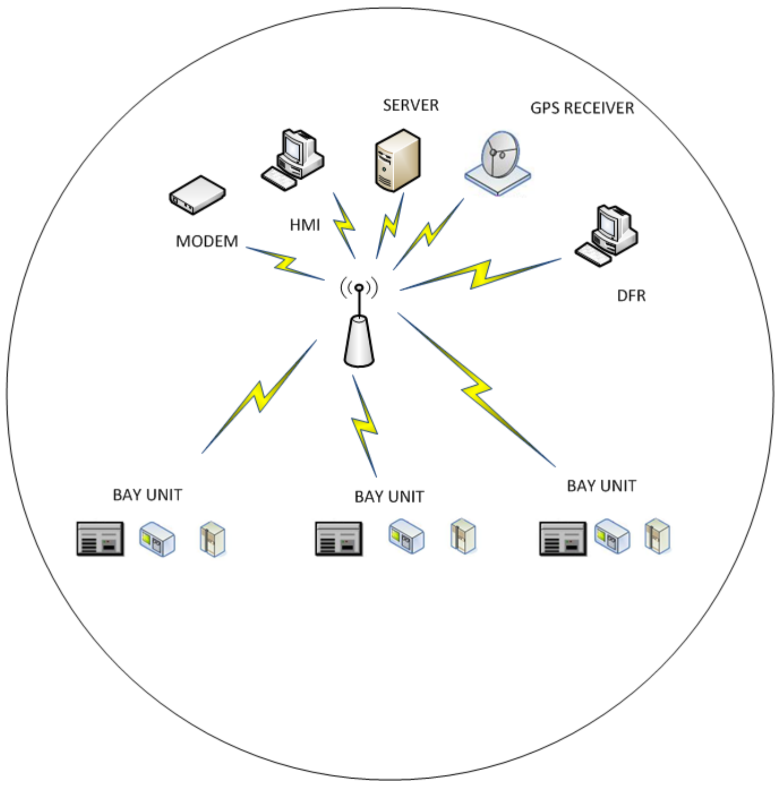

Fig. 13. Single AP Model.

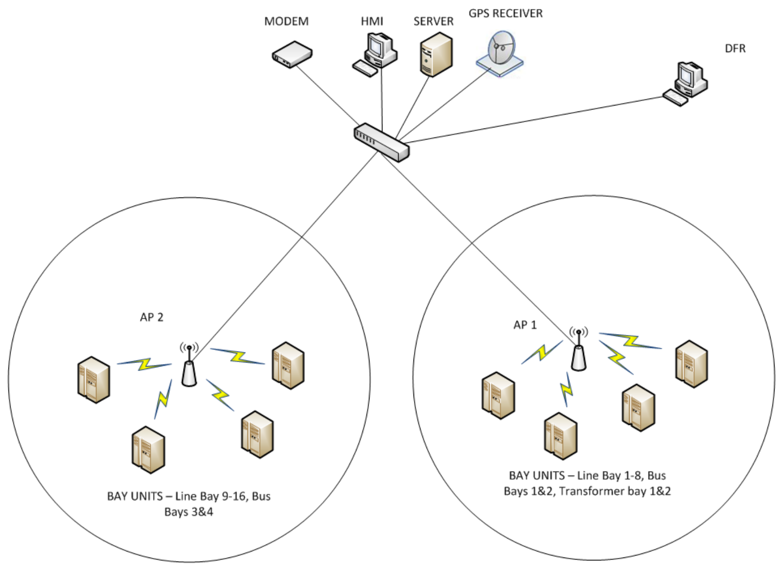

Fig. 14. Multiple AP Model.

We cannot afford to have too many APs in the system which will decrease the range of each AP and increase the cost of implementation as well.

Even by going with multiple APs, the delay performance cannot be better than the star topology. To match the performance of star topology and still keep the wiring cost to a minimum, a partial wired/wireless topology is developed. The architecture for the wired/wireless topology is given in Fig. 15. This topology has the switchyard connections the same as in the star topology. However, the switches are connected to an AP rather than the control center. All the devices in the control center connect to the AP. This ensures that the high priority messages occur through the wired network and the low priority messages occur through the wireless medium. The delay performance is improved for this model but the reliability is compromised. Thus the only advantage of implementing wireless in this architecture is the decrease of implementation cost.

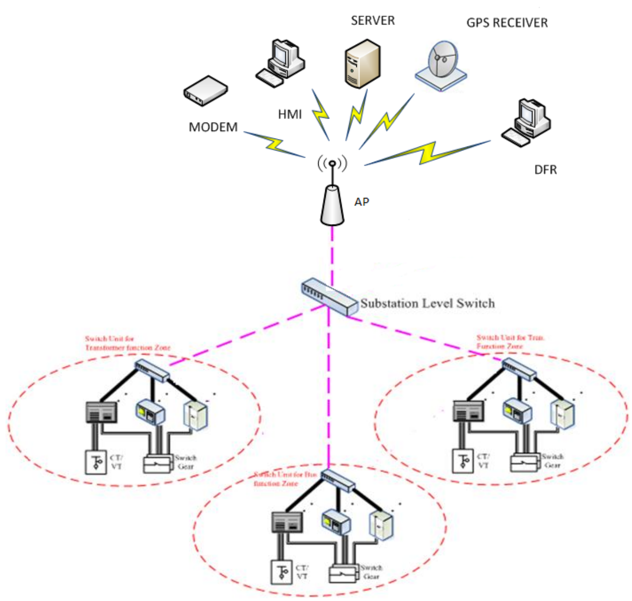

Fig. 15. Wired/Wireless Model.

CHAPTER VI

RELIABILITY STUDIES

Reliability is one of the important aspects of the substations. According to Reference [18], the reliability in substations is divided into two aspects namely dependability and security. Dependability is defined as the degree of certainty with which the relay can be said to operate correctly. Security on the other hand is the degree of certainty with which the relay will not operate incorrectly. Lack of either dependability or security could compromise the system. If the substation is not dependable, the circuits will not be opened during faults resulting in severe damage and financial loss. If the substation is not secure, the circuits will be opened even during normal operation and this could result in power loss.

Since we are dealing with only the network aspect of substation, we are not simulating actual fault occurrences and fault detection. So there is no way to calculate the degree of security in our model. However, we could calculate the dependability of the system we design based on the delay performance and system failure.

- If the delay of the trip message crosses the threshold, then the trip message does not reach the protection IED in time and so relays are not opened in time.
- If there is a failure in a switch or link, the trip message does not reach the destination and so the relays do not open.

So we can assume that these are the two cases under which the dependability of the system is compromised. The failure probability of the entire network can be calculated, the increase of delay in the trip message can only be noted from the simulations.

A. Reliability Block Diagram

Reliability Block Diagram (RBD) [19] gives the overview of the devices in the network which need to perform correctly for the system to succeed. Based on redundancies and the paths defined from the sender to the destination, the RBD of the network varies. By drawing the RBD of each architecture, the system reliability can be determined. [4] assumes a few general architectures of substation network and calculates the system reliability.

Once the RBD is derived, we can use the network reduction procedure [15] to find out the failure rate, repair rate, system unavailability and system availability. Since we are concentrating only on the network aspect of the substation, we derive the RBD model by including only the networking components of the substation. If we take $R_{sys}(t)$ be the reliability of the system and $Q_{sys}(t)$ be the unreliability of the system, we can say that

$$Q_{sys}(t) = 1 - R_{sys}(t)$$

$p_i(t)$ is the reliability and λ_i is the constant failure rate of a component i. $p_i(t)$ is given by,

$$p_i(t) = e^{-\lambda_i t}$$

The failure rate of all the ethernet media are taken as $0.003 year^{-1}$ and the failure rate of the rest of the components are taken to be $0.01 year^{-1}$ [4]. The time period is chosen as 1000 hours.

1. Bus Topology

In bus topology, the trip message from one protection IED reaches the other protection IEDs through the bus alone. Hence the RBD consists of the bus and the taps used to connect the sender IED to the bus and the receiver IED to the bus. The RBD is

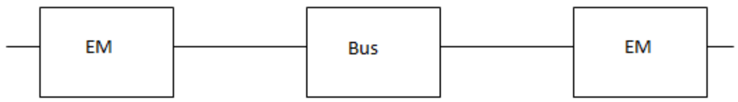

Fig. 16. RBD for Bus Topology.

shown in Fig. 16. The reliability of the tap is p_{tap} and the reliability of the bus is p_{bus}. The system reliability is given by,

$$R_{sys} = p_{bus} \cdot p_{tap}^2 \tag{6.1}$$

Applying the failure rates of the individual components, the system reliability is found to be, $R_{sys} = 0.9982$.

2. Ring Topology

The topology for ring network is shown in Fig. 5. In this topology, the trip message can have two paths to reach a protection IED from another. So irrespective of the protection IED chosen, the RBD have to include all the switches and their connecting links. The RBD diagram for the ring topology is shown in Fig. 17. As we can see, the backup path is drawn in parallel to the original path and the system failure happens only if both the paths fail. The reliability of the ethernet media is p_{em} and the reliability of the switch is p_{sw}. The system reliability is given by,

$$R_{sys}(t) = p_{em}^2 \cdot p_s w^2 (p_{em}^n \cdot p_{sw}^n + p_{em} - p_{em}^{n+1} \cdot p_{sw}^n)$$

$$R_{sys} = p_{em}^{n+2} \cdot p_{sw}^{n+2} + p_{em}^3 \cdot p_{sw}^2 - p_{em}^{n+3} \cdot p_{sw}^{n+2} \tag{6.2}$$

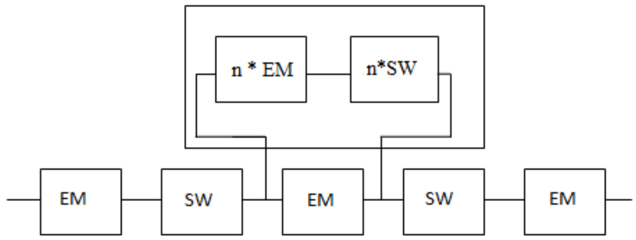

Fig. 17. RBD for Ring Topology.

For the assumed model with 23 switches in the ring, the reliability equation is as follows,

$$R_{sys} = p_{em}^{24} \cdot p_{sw}^{24} + p_{em}^{3} \cdot p_{sw}^{2} - p_{em}^{25} \cdot p_{sw}^{24} \tag{6.3}$$

Applying the failure rates of the individual components, the system reliability is found to be, $R_{sys} = 0.9970$.

3. Star Topology

In star topology, the protection IEDs of the similar bay units are connected by a single switch. However, the protection IEDs of the other bay units are connected through a series of 3 switches. So the RBD considers the worst case and includes the 3 switches and their connecting links. The RBD is shown in Fig. 18 and the corresponding system reliability is given by,

$$R_{sys} = p_{em}^{4} \cdot p_{sw}^{3} \tag{6.4}$$

Applying the failure rates of the individual components, the system reliability is found to be, $R_{sys} = 0.9952$.

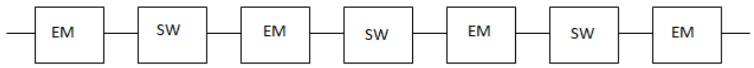

Fig. 18. RBD for Star Topology.

4. Wireless Models

The subsections 1, 2 and 3 give the reliability of the exiting models. Now we focus on the wireless models built for this thesis and calculate their reliability.

For the single AP model, the trip message has to travel through AP to the destination. Since the IEDs use a wireless card to connect to the AP, a failure in the wireless card might prevent the protection IED from sending the message. So we include the possibility of failure in the IED itself. The RBD model for the single AP is shown in Fig. 19. The reliability of AP is p_{ap} and the protection IED is p_{pr}. So the system reliability can be given as

$$R_{sys} = p_{ap} \cdot p_{pr}^2 \tag{6.5}$$

Applying the failure rates of the individual components, the system reliability is found to be, $R_{sys} = 0.9982$.

For the second architecture with two APs, the architecture is designed such that the trip message need only be sent to the protection IED of the same AP. Also, the second AP can be taken as the redundant network and hence it is drawn parallel to the original AP. The RBD is shown in Fig. 20. The reliability of the system is given by,

$$R_{sys} = p_{pr}^2(2p_{ap} - p_{ap}^2)$$

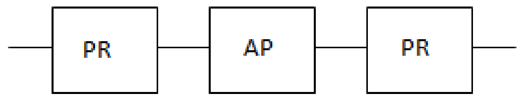

Fig. 19. RBD for Single AP Model.

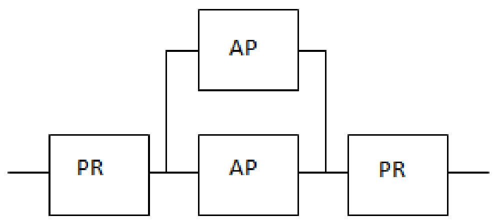

Fig. 20. RBD for Multiple AP Model.

$$R_{sys} = 2p_{ap} \cdot p_{pr}^2 - p_{ap}^2 \cdot p_{pr}^2 \qquad (6.6)$$

Applying the failure rates of the individual components, the system reliability is found to be, $R_{sys} = 0.9993$.

Finally we have the architecture which combines the wired and wireless scheme. This topology is the same as the star topology in terms of the path traveled by the trip message. Hence the reliability of the system is the same as Equation 6.4. The final system reliability is also the same as star topology.

CHAPTER VII

SIMULATION RESULTS

In this chapter, we look at the results of various types of simulations performed. Three kinds of studies were performed in this thesis, namely delay performance, delay aware backoff and reliability. So we present these three observations in separate sections.

A. Delay Performance

For the study of delay performance, we take in to consideration the following scenario. The simulation is performed for 20s. The HMI sends out time synchronization messages to all the devices once every second. One of the protection IEDs of the line bay is made to send a trip message at the 10th second of the simulation time. The protection IED and the corresponding CBMs associated with it sends out files of size 300kb to the HMI after the trip message is sent. The DFR also sends a file of size 300kb to the HMI. The trip message delay is noted for the different topologies under these circumstances. The delay performance of the bus topology, ring topology, star topology, single AP model, multiple AP model and wired/wireless architecture are given in Fig. 21. As we can see, the delay of the star topology and the wired/wireless topology are similar. Also, these delay values are the best performing ones. Also, we can see that the delays of the wireless model are comparable to the ring topology in terms of delay. The bus topology is the worst performing one. Even though the delays of wireless architecture are not equal to star, they provide an architecture which combines the reliability of the bus model and the performance of the ring topology.

Architecture	Measure Delay (ms)
Bus Topology	1.4
Ring Topology	0.66
Star Topology	0.26
Single AP Model	0.76
Multiple AP Model	0.4
Wired/Wireless Model	0.26

Fig. 21. Trip Message Delays.

B. Delay Aware Backoff

For testing the delay aware backoff, a discrete model was built in MATLAB. The scenario consists of 10 users out of which 2 users are assigned as priority users. These priority users follow the delay aware backoff for $\alpha = 1.6$. The best effort users follow the normal random exponential backoff scheme. In each slot, all the users decide on generating packets using a probability value assigned. Since the priority packets occur rarely in the network, we assign the probability 0.1 for the priority packets. The normal users generate packets at probability 0.7. These packets are queued up by the user and they are sent one after another similar to normal ethernet. This system was run for 100,000 slots and the delay for the real time users and the best effort users are determined. The result of this simulation is shown in Fig. 22.

As we can see, the priority users perform very well when compared to the best effort users. This model introduces more priority packet in to the network than a practical substation. Still the delay aware backoff scheme performs well. Hence implementing this strategy in bus ethernet will improve delay significantly.

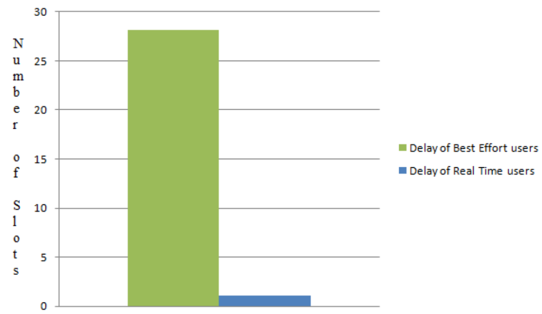

Fig. 22. Delay Aware Backoff Performance.

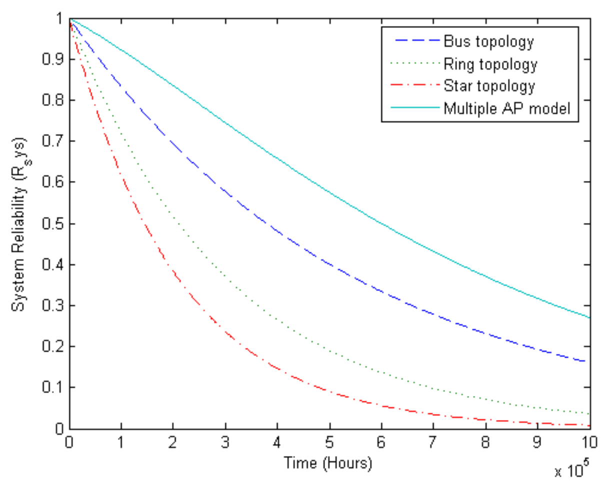

Fig. 23. System Reliability of Various Models vs. Time.

Architecture	Measure Delay (ms)	Reliability (t=1000hrs)
Bus Topology	1.4	0.9982
Ring Topology	0.66	0.9970
Star Topology	0.26	0.9952
Single AP Model	0.76	0.9982
Multiple AP Model	0.4	0.9993
Wired/Wireless Model	0.26	0.9952

Fig. 24. Comparison of Performances for Various Architectures.

C. Reliability

In chapter VI, we analyzed the reliability of different topologies for mission time of 1000 hours. To obtain a more comprehensive result, the reliability values were calculated for various mission times. The simulation was performed in MATLAB. The reliability of the various topologies is noted for each time and are plotted. As the performance of single AP model and the bus topology are same and the performance of the wired/wireless architecture and star topology are same, we plot only one instance for these architectures. The result obtained for the system reliability is shown in Fig. 23

As we can see, the reliability of the wireless architectures are better than the ring and star topology. So the wireless architectures have a better delay-reliability tradeoff than the traditional architectures. This is shown in the Fig. 24.

CHAPTER VIII

CONCLUSION AND FUTURE WORK

In this thesis, we looked at the performance of the substation under different topologies. We focused on the delay characteristics of the priority message and the reliability of the substation and proposed new architectures which perform well in both the attributes. We could say that the multiple AP model could very well replace ring or bus topology because it has better performance both in terms of delay and reliability. When we compare the multiple AP model with the star topology, it performs a lot better in terms of reliability but at a slight increase in delay. However, the cost of implementation of the multiple AP model is significantly reduced because of minimal wiring. So it could very well replace star topology.

IEC 61850 is a vast protocol and implementing substation over ethernet is a relatively new concept. So there are numerous possibilities for future work. We analyzed only the communication inside the substations. However, smart grid network comprises of numerous substations exchanging data with one another and with NCC. So the model can be expanded to communication outside the substation. Even within the substation, the practical implementation does not include all the messages in the ethernet network. For example, the sampled values from MU IED could very well be a part of the network. Similarly the GOOSE message can also be incorporated into the network. To implement these, the designed models need to be expanded. Since these messages are also priority messages, their delay characteristics need to be studied thoroughly before implementation.

The time synchronization designed in all the models in this thesis uses simpler protocol like Network Time Protocol. Studies are made regarding implementing IEEE 1588, Precision Time Protocol in the substation. Our design can be modified to implement 1588 as well. Finally, the wireless models specified uses WLAN for communication. However, other wireless technologies like Zigbee, WIMAX and LTE could be explored.

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VITA

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