Converged IP-over-Standard Ethernet Process Control Networks for Hydrocarbon Process Automation Applications Controllers

A Thesis submitted for the degree of Doctor of Philosophy

by

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ABSTRACT

The maturity level of Internet Protocol (IP) and the emergence of standard Ethernet interfaces of Hydrocarbon Process Automation Application (HPAA) present a real opportunity to combine independent industrial applications onto an integrated IP based network platform. Quality of Service (QoS) for IP over Ethernet has the strength to regulate traffic mix and support timely delivery. The combinations of these technologies lend themselves to provide a platform to support HPAA applications across Local Area Network (LAN) and Wide Area Network (WAN) networks. HPAA systems are composed of sensors, actuators, and logic solvers networked together to form independent control system network platforms. They support hydrocarbon plants operating under critical conditions that — if not controlled — could become dangerous to people, assets and the environment. This demands high speed networking which is triggered by the need to capture data with higher frequency rate at a finer granularity. Nevertheless, existing HPAA network infrastructure is based on unique autonomous systems, which has resulted in multiple, parallel and separate networks with limited interconnectivity supporting different functions. This created increased complexity in integrating various applications and resulted higher costs in the technology life cycle total ownership. To date, the concept of consolidating HPAA into a converged IP network over standard Ethernet has not yet been explored. This research aims to explore and develop the HPAA Process Control Systems (PCS) in a Converged Internet Protocol (CIP) using experimental and simulated networks case studies. Results from experimental and simulation work showed encouraging outcomes and provided a good argument for supporting the co-existence of HPAA and non-HPAA applications taking into consideration timeliness and reliability requirements. This was achieved by invoking priority based scheduling with the highest priority being awarded to PCS among other supported services such as voice, multimedia streams and other applications. HPAA can benefit from utilizing CIP over Ethernet by reducing the number of interdependent HPAA PCS networks to a single uniform and standard network. In addition, this integrated infrastructure offers a platform for additional support services such as multimedia streaming, voice, and data. This network-based model manifests itself to be integrated with remote control system platform capabilities at the end user's desktop independent of space and time resulting in the concept of plant virtualization.

DEDICATION

This thesis is dedicated to my loving and patient wife and my wonderful kids whom they bear up years of me not being around during weekends, vacations, special events. I can say now… yes, we will do something together in the weekend! Moreover, I would like to dedicate this to my mother who always prayed for me and in loving memory to my beloved father, may God bless his soul.

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LIST OF ABBREVIATIONS USED

BE	Best Effort
BPS	Bit Per Second
CAN	Controller Area Network
CIP	Converged Internet Protocol
CNT	Controller
CCTV	Closed Circuit Television
CPU	Central Process Unit
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DCS	Distributed Control System
ERP	Enterprise Resources Planning
ESD	Emergency Shutdown Systems
FTP	File Transfer
Gbps	Gigabit per second
HMI	Human Machine Interface
HPAA	Hydrocarbons, which include oil and gas, Process Automation Applications
I/O	Input/Output
IEC	International Engineering Consortium
IED	Intelligent Equipment Devices
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPTel	Internet Protocol Telephony
ISA	International Society of Automation
ITU	International Telecommunication Union
Kbps	Kilobit per second
LAN	Local Area Network
MAC	Medium Access Control
MAX	Maximum
Mbps	Megabit per second
MIN	Minimum
MS	Millisecond
MSC	Master Controller
PLC	Programmable Logic Controller
PCS	Process Control Systems
PCSVC	PCS Virtual Center
P2P	Peer-to-Peer
PERA	Purdue Enterprise Reference Architecture
SCADA	Supervisory Control and Data Acquisition
SERCOS	SErial Realtime COmmunications System
SNMP	Simple Network Management Protocol
SR	Safety-Related
TCP	Transmission Control Protocol

TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
QoAC	Quality of Application Connection (QoAC)
QoS	Quality of Service
QoC	Quality of Control
VOIP	Voice over Internet Protocol
WAN	Wide Area Network

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PUBLICATION

Several papers out of this research were published, accepted for publication or under review. This includes the following papers:

- **S. Almadi,** R. EL-Haddadeh, M. Jahromi, "Comparative Analysis of Simulated Converged IP Local Area Network for Hydrocarbon Process Automation Applications," International Journal of Simulation Systems, Science and Technology, IJSSST: Vol. 11, No. 6 *(Journal Paper Under Review)*
- **S. Almadi**, R. EL-Haddadeh, M. Jahromi, "Process Automation Converged Best Effort IP Network Model for Hydrocarbon Automation Applications," Networking and Electronics Commerce Journal, Springer, 2011 *(Journal Paper Under Review)*
- **S. Almadi,** R. EL-Haddadeh, S. Walaie, "Wireless Backhaul Link Converged IP Network For Hydrocarbon Process Automation Applications," The 2011 International Conference on Telecommunication Systems Management, ICTSM2011:Springer, Prague, Czech Republic, May 26-28, 2011*(Conference Paper Accepted)*
- **S. Almadi,** R. EL-Haddadeh, M. Jahromi, "Design Requirements for Best Effort Wide Area IP Network for Petrochemical Applications," International Conference on Information and Industrial Electronics, IEEE R10, Chengdu, China. January 14-15, 2011
- **S. Almadi**, R. EL-Haddadeh, F. Askandrani, M. Jahromi, "Intelligent Field Converged IP Network for Semi-Real Hydrocarbon Process Automation Applications (HPAA) Case Study," IEEE International Energy Conference, Manama, Bahrain, December 18-22, 2010
- **S. Almadi,** R. EL-Haddadeh, M. Jahromi, "Critical Requirements for Converged IP network for Hydrocarbon Process Automation Application," IEEE 4th European Modeling Symposium on Mathematical Modeling and Computer Simulation, Pisa, Italy, November 17-19, 2010

- **S. Almadi**, R. EL-Haddadeh, M. Jahromi,S. AL-Walaie,“Process Automation Converged Best Effort IP Network for Hydrocarbon Automation Applications,” Networking and Electronic Commerce Research Conference, Riva del Garda, Italy, October 7-10, 2010
- **S. Almadi**, R. El-Haddadeh, and M. Jahromi, “Converged IP Network for Hydrocarbon Process Automation Applications,” IEEE Computer Society Second International Conference on Computational Intelligence, Modeling and Simulation, Bali, Indonesia, September 28-30, 2010
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- S. Al-Walaie, **S.Almadi,** A. Al-Omair, M. Al-Qahtani, “Wireless Technology for Industrial Applications-Opportunities and Challenges,”Saudi Telecommunications Committee, Riyadh, KSA, January 18-20, 2010.
- **S. Almadi,** R. EL-Haddadeh, M. Jahromi “Simple Network Management Protocol Co-existence with Hydrocarbon Process Automation Communication Real-time Network,” European and Mediterranean Conference on Information Systems, Izmir, Turkey, June 13-14, 2009
- T. Al Dhubaib, **S. Almadi,** M. Shenqiti, and A. MansourS,“I-Field Data Acquisition and Delivery Infrastructure: Case Study,” Intelligent Energy Conference and Exhibition, Amsterdam, Netherlands, February 25-27, 2008
- S. Al-Walaie, **S. Almadi**,S. Alshammari “Industrial Wireless Technology for Oil Fields Connectivity - Wireless I-Field”, Intelligent Energy Conference and Exhibition, Amsterdam, Netherlands, February 25-27, 2008

CHAPTER 1 INTRODUCTION

1.1 OVERVIEW

With the advancement in networking and systems, Hydrocarbons Process Automation Applications (HPAA's) oil and gas fields and process plants, have evolved. Conventionally, dedicated and standalone networks with limited interconnectivity were designed and implemented to support each plant's process automation segment or cell within an oil and gas Process Control System (PCS). Moreover, stringent network design guidelines were adopted overtime to guarantee traffic separation, information security, and application timeline requirements. In addition, PCS were confined to a specific segment, or cell, with minimal collaborative computing (Control Logic Loops) with adjacent cells and this has resulted in multiplicity of PCS systems within a given plant and/or field. Reliable real-time communication networking provides the foundation for supporting the different HPAA PCS local and remote control and data acquisition capabilities. This practice requires high initial cost, and complexity, due to different wiring, variety of network node components, and operational support requirements over the plant's life cycle. Moreover, the parallel network and system implementation environment results in vertical independent silos. The latter make intelligence data integration, due to the complexity of interfaces and integration cost, a mundane task and challenging objective.

In the early stages, HPAA network nodes presented simple interfaces and interconnected with limited low speed network backbone, utilizing proprietary solutions and protocols. This had led to increasing the complexity and functionality of implemented infrastructure in supporting multiple arrays of functions. However, with the advancement in sensor and instrumentation, network technologies, computing systems, and standard interfaces such as Ethernet, additional embedded intelligence has now extended into the lower layers of the HPAA PCS infrastructure. This offers the opportunity to provide additional performance data on the oil and gas reservoir discovery, recovery and delivery processes.

Most importantly, Internet Protocol (IP) can easily be supported on the Ethernet networking platform, locally, and in wide area domain. This creates a great opportunity to provide a network model for unifying the different HPAA applications. An advanced implementation for distributed PCS architecture supporting a multitude of functionalities in a local Hydrocarbon process plant, wide area networked operation can be realized. These HPPA applications have timeliness requirements that span from the sub-millisecond (ms) to over 200 seconds so IP Quality of Service can be instrumental in providing the needed data transmission rate priority and scalability. Uniform local and wide area network with predefined quality of service for each application will result in consistent and predicable transport performance. This is an essential requirement for an operation that is distributed and requires control logic loops. Those are sometimes extended from the well head, through a pipeline network, spanning a wide area network. Moreover, the use of IP over Ethernet can be further maximized to carry other support services besides HPAA's such as voice, media streaming, and large file data transfer. This leads to a new concept in PCS system automation domain; the concept of HPAA PCS Converge Internet Protocol Network (HPAA CIP).

HPAA CIP brings with it many advantages such as network consolidation, application integration, and increased HPAA process data profiling. In addition, such a platform leverages itself to easily connect people, process, and technology contributing in optimizing the HPAA operation. This can be materialized by voice, video, and HPAA PCS on the same network infrastructure in the form of remote monitoring and control, collaborative engineering, and plant virtualization feature capabilities.

1.2 PROCESS CONTROL SYSTEM

Currently, almost all new instrumentation systems are based on microprocessor technology. This technology ranges from small single loop digital controllers to sophisticated and powerful multiprocessor distributed control systems in support of a safe and cost effective operating environment similar to an automotive environment. In this case, several embedded systems are implemented to provide safe and reliable driving experience. HPAA's supported by different PCS's are no different. Computers provide more sophisticated operator interface and display capabilities which can be used to monitor process variables, process calculated variables, send set points or control commands, and generate reports and historical data trends. Most importantly, computers are typically interfaced within the instrumentations to provide the logic algorithms for advanced control applications and optimization routines which are not available in the instrumentation components. There are three different PCS process categories: process monitoring, continuous process control and discrete process control [2], [3] and [4]. Communication networks provide the medium to interconnect the different PCS layers. Strictly speaking, time delay, jitter, packet loss, and network stability are the essential requirements for supporting these layers.

Advances in the field of information technology (IT), PCS controller Central Processing Unit, and sensor interface have opened up yet more possibilities for HPAA PCS from a design and deployment perspective [4] and [5]. This includes the use of standard Personal Computer (PC) and communication networks in the industrial environment which enables the use of ordinary, off-the-shelf products to do the job of custom-built computing and network elements that are part of a Distributed Control System (DCS), Programmable Logic Control (PLC), or Supervisory Control and Data Acquisition (SCADA) systems. Computer based control systems offer users the flexibility, speed, and scalability that proprietary vendors may not have satisfied in the past. The distinction between the different PCS systems may become blurred as they begin to adopt each others' functionality and add similar features to satisfy the end user demands and earn additional market share [3], [5], and [6] in the future. HPAA CIP network model will be a pioneer in the journey of reaching an integrated end-to-end HPAA operation.

1.3 CONVERGED INTERNET PROTOCOL NETWORK

Utilizing standard Ethernet over Converged Internet Protocol (CIP) networks for Hydrocarbon Process Automation Applications (HPAA) provides an opportunity for an optimal network consolidation. This can be achieved through minimizing the number of interdependent networks and, most importantly, offering a platform for additional support services such as multimedia streaming, voice, and data. Timeliness and reliability are the fundamental requirements for such a network as the main goal remains communication between the HPAA PCS's sensors, controllers, and actuators. This also includes a congestion free, accurate, high-integrity, and prioritization network. As a result Quality of Service (QoS) features are necessary to provide plant network control data in a consistent manner. Ethernet as a transport network has evolved from the initial IEEE 802.3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) [7] standard which had inherent randomness arbitration to the latest Ethernet switching technology. The Ethernet technology divides collision domains into simple point to point network connections between the network elements. Hence, collision is no longer occurring and the need for random back-off algorithm is eliminated. In addition, switch Ethernet technology provides traffic classes as part of the prioritization MAC-Frames as specified in, IEEE 802.1p [8]. The first-come first-serve treats all packets in the same priority so there is no distinction between the different applications packets. A higher speed application acquires more space in the buffer and consume more than its fair share of bandwidth (i.e., an impeded weight factors mechanism directly proportional to the application speed. This model is called a Best Effort (BE) QoS network model. QoS for CIP over Ethernet utilizing priority based scheduling, Differentiated Services (DiffServ) [9] and Best Effort with predetermined thresholds, Integrated Services (IntServ) [10], can be adopted in a form that will ensure the intended HPAA PCS are in compliance with their performance criteria.

1.4 PROBLEM STATEMENT AND MOTIVATION

Hydrocarbon Process Automation Applications are used in industrial plants that operate under conditions that — if not controlled — could become dangerous for people, assets and the environment. Process control systems that support the necessary functions to achieve and maintain a safe steady state HPAA operation are referred to as Safety-Related (SR) systems. These systems are composed of sensors, actuators, and logic solvers, and Enterprise Resource Planning (ERP) linked together by communication networking channels. Reliable networking plays a key role in supporting such a system infrastructure. The existing HPAA network conventional designs consist of multiple and disparate networks with limited interconnectivity. Support services such as voice and media streaming are utilized and are also supported by independent networks.

The aim of this research is to explore and develop the HPAA PCS in a Converged Internet Protocol (HPAA CIP) network model. The CIP network will be investigated in both a Local Area Network (LAN) and Wide Area Network (WAN) environments utilizing Gigabit Ethernet (IEEE 802.3z)[1]. Simulation and empirical data will be used in the comprehensive evaluation of the performance for this network. The primary focus will be on defining the feasible network solution conforming to HPAA applications and networks' delay, jitter, packet delivery, and application stability. Moreover, support services, such as voice and media streaming (video) utilizing the same CIP network, will be an integral part of this research. So, the key objectives of this research can be defined as follows:

- Investigate the use of Internet Protocol (IP) over standard Gigabit Ethernet protocol in support of HPAA and non-HPPA Applications.
- Identify an optimum network model to regulate network resources in compliance to both HPAA and non-HPAA application characterization in this Converged IP (CIP) Network.
- Explore, develop, examine, and verify HPAA CIP network model supporting PCS applications and other media applications such as voice, video streaming, and large file transfer.
- Define network elements, attributes, and engineering network design to be reflected in a simulated network model.
- Simulate the HPAA CIP network model and obtain results.
- Develop prototype implementation for results verification.
- Conduct gap analysis by benchmarking simulated network and prototype testing.
- Formulate results and optimal guidelines for HPAA CIP network model.

As a step forward for identifying HPAA CIP network model that support HPAA and non-HPAA applications concurrently, a conceptual network model is proposed in Figure 1.1.

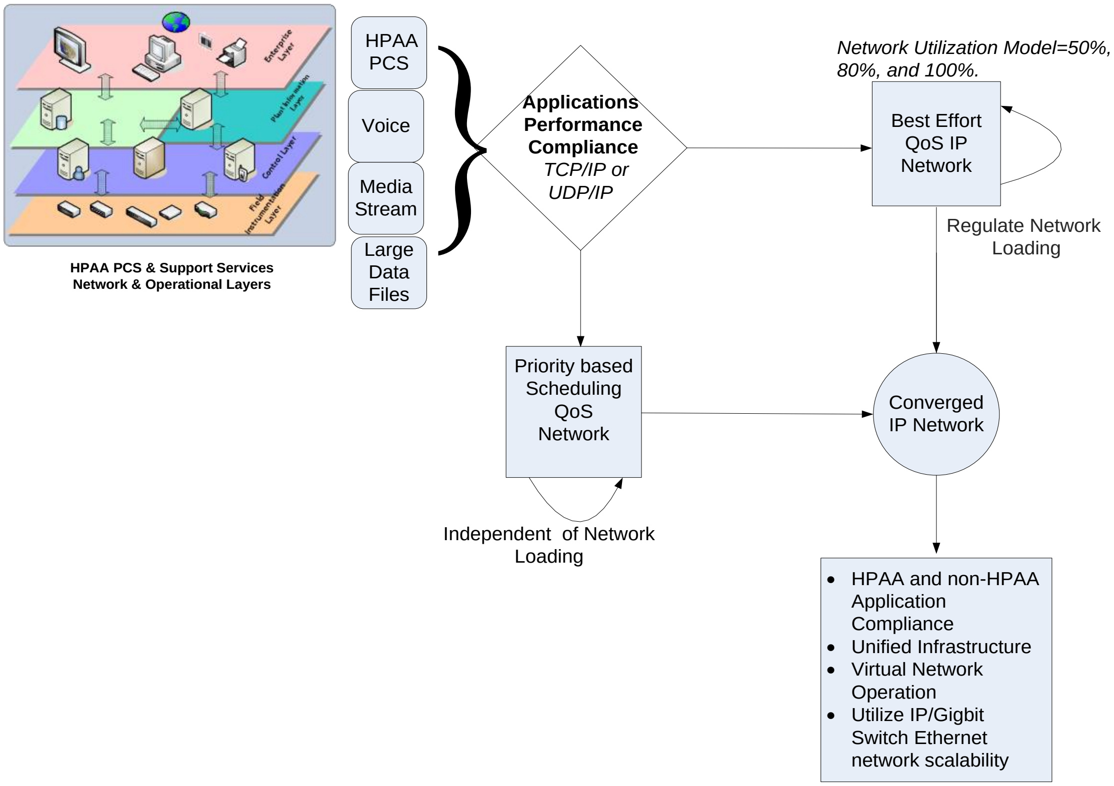


Figure 1.1 Converged IP Network Model for HPAA PCS

HPAA CIP in this research is considered the vehicle for extending system intelligence, data exchanges, and optimizing operation without jeopardizing the strict safety level requirements in local and remote HPAA PCS systems. Moreover, feasible network solution for LAN and WAN supporting this concept will be defined. HPAA can benefit from a converged IP network by minimizing network components and wiring; and provide more integrated applications to the end user's desktop. Moreover, this model provides seamless HPAA PCS LAN/WAN performance to support remote control and plant’s virtual operation environment. The proposed HPAA CIP network model should reduce the number of HPAA PCS networks from at least five (5) to a one (1) uniform and standard network model. In a typical oil and gas HPAA operation there are at least five different networks. This includes, but not limited to, Distributed Control System (DCS), and Emergency Shut-Down (ESD) systems, Supervisory Control and Data Acquisition

(SCADA) system, Media streaming, and Voice. There may be also, in some cases, multiple applications belonging to HPAA support process control functions. An example is Vibration Monitoring System, Corrosion Monitoring System, Substations where each application has its own network and unique performance guidelines.

To the best of our knowledge, no network model or implementations for CIP in an HPAA operating environment have been considered. In addition, no study thus far provides analysis for the use of TCP/IP or UDP/IP protocol for HPAA in a CIP network model. Therefore, the main contribution from this research is to examine and define the requirements of adopting CIP network utilizing Best Effort and Priority based Scheduling QoS. Simulation, empirical data, and comparative analysis for dedicated IP network and the proposed CIP network were used to identify areas of improvements and optimum network.

1.5 NETWORK MODELS

In this effort, the research approach is based on the development of HPAA PCS Controller in LAN and WAN networks utilizing standard Ethernet and IP protocol networking elements. This research will be based on both simulation and experimental real-time network models set up. The empirical data collected from the experimental model will be used then to validate the simulation model that re-enforced the CIP network model as a feasible solution. Comparative analysis between simulation and empirical results are used to deduce new findings and establish the form for the CIP network model. Message size, traffic mix, application behaviour, and traffic loading were utilized to explore the impacts and identify guidelines for CIP network model.

Due to the lack of previous research in the HPAA applications networking area, the models adopted for this research are based on previous work which will be obtained from academic, standard organizations, and industry best practices. The collected data will be then translated into information to identify and define potential gaps in the areas of networking, PCS Controller performance behaviour, and traffic mix impacts on both IP network and PCS application layers. The primary focus is the LAN and WAN networks supporting HPAA applications and their characteristics. It is important here to point out that operating systems and application software architecture supporting the PCS application function are not part of this research. In addition, similar industries will be examined, (such as substation automation distribution systems) to identify parallelisms and differences due to the lack of previous work in the area of HPAA. Figure 1.2 illustrates the research conceptual model which was used throughout the research cycle. Again, this model is primarily driven by a lack of previous work specifically in Hydrocarbon Process Automation Applications (HPAA) networking.

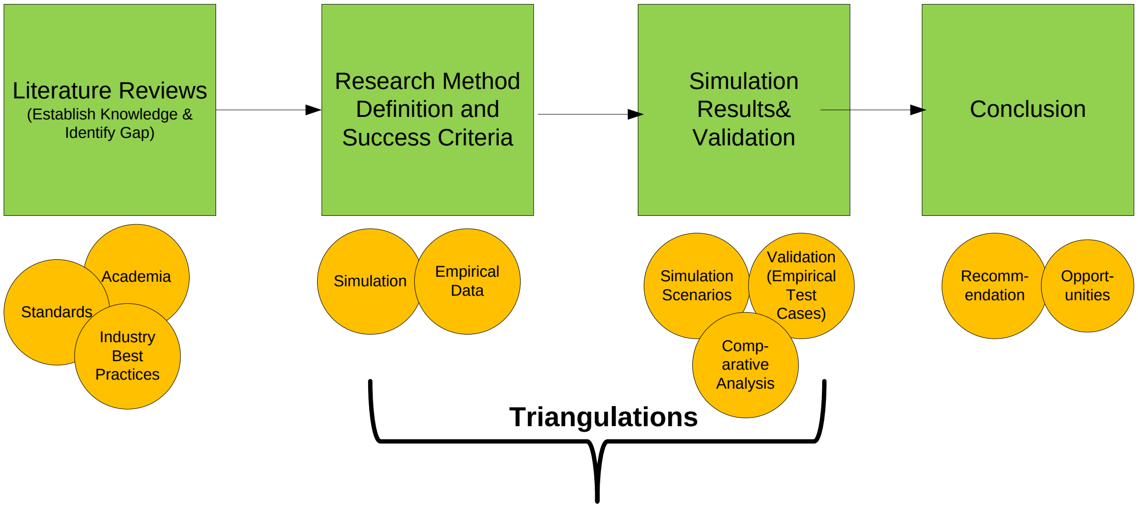


Figure 1.2 Conceptual Research Model and Stages

The simulation is based on utilizing OPNET network modelling tool. The empirical data is based on test case scenarios for LAN as well as WAN networks that resemble an HPAA PCS environment. Finally, this CIP network model addresses the concept of utilizing backbone fiber optic links based on Gigabit Ethernet standard protocol (IEEE 802.3z). This is also, includes exploratory evaluation for wireless (IEEE 802.11g) as a backhaul link to remote "spur" sites that are part of WAN.

1.6 THESIS ORGANIZATION

This research is structured into seven chapters. Chapter 2 presents the literature review findings that include HPAA PCS application requirements, identifying gaps in existing network and technology implementations, and derive network and HPAA PCS assumptions that were used in the network, controller, and converged IP simulation models. Moreover, the CIP network model identifies and classifies time delay compliance for HPAA, IP Telephony, and media streaming.

Chapter 3 describes the research design applied in this thesis. The research method is based on triangulation: utilizing simulation, experimentally derived data, and a comparative analytical synthesis leveraging the two. The first approach is simulation utilizing the OPNET tool. The aim of this research method is to define the HPAA PCS performance in converged IP network based on two network Quality of Service settings: Best Effort and Priority Based Scheduling in LAN and WAN networks. The experimental case study is based on two sub-cases: one is addressing Process Control System (PCS) in Local Area Network (LAN) while the second is PCS in Wide Area Network (WAN) with network parameters that are similar to the simulation network model.

Chapter 4 provides results for the two experimental case studies in support of this research. The primary objective of these case studies is to obtain empirical data that can be utilized in optimizing the simulation model as well as validating the simulation results reflected in Chapter 5. Furthermore, CIP network model performance parameters are examined and results are used in the comparative analysis with the simulation results and the outcomes are presented in Chapter 6.

Chapter 5 presents the simulation results for HPAA PCS application in LAN and WAN network models based on the research design detailed in Chapter 3. Three simulated scenarios are part of this effort. These scenarios include dedicated, converged IP with BE QoS, and converge IP with Priority based Scheduling QoS. The primary objective is to explore the application and network performance behaviours for the HPAA PCS Controllers under different network utilization models; baseline traffic load, 50%, 80%, and 100%. Moreover, support services such as IP telephony and media streaming performance are also investigated.

Chapter 6 discusses the results of the simulation and experimental case studies, and provides comparative analyses for the applicable scenarios. In addition, it cross examines simulation results with empirical data to validate and deduce new results. Relationships are identified and presented based on the comparative analyses which can be more descriptive of the feasible CIP network model.

Finally, Chapter 7 summarizes the research, presents main contributions, and shares opportunities for future prospects.

CHAPTER 2 LITERATURE REVIEW

2.1 OVERVIEW

Networking technologies have evolved over the past decades with different protocols, architectures, and services. This provided different options in connecting the process automation elements to the enterprise applications. Many researchers have explored process automation networks connecting the instrumentations, logic solvers and actuators and plant information system layers. Moreover, research was expended in the operation and management layers. This chapter provides literature review for previous completed research relating to process automation network evolution, HPAA application characterization, HPAA Controller behavior, and the related Quality of Service (QoS) methods.

2.2 HYDROCARBON PROCESS AUTOMATION APPLICATIONS NETWORK

The Hydrocarbon operation consists of oil and or gas reservoir with oil and gas wells, water injection wells that are strategically drilled in a predefined Hydrocarbon reservoir areas. The oil and gas wells are connected with a pipeline network to an aggregation facility that contain collection tanks, boilers, furnaces, oil and gas separators, pumps, etc. This operation produces stabilized oil and gas that is funneled to a refinery or terminal for shipping and or for end user distributions. Each oil and gas process segment from the subsurface stage (i.e., reservoir), upstream stage of delivering and processing the crude at the processing facility, and downstream which includes refining and distribution has its own HPAA PCS network to control the required operating infrastructure. This infrastructure includes field surface and subsurface instrumentation, pipeline network, steams heat exchange systems, boilers, vessels, hydrocrackers, stabilizers, etc. The primary focus of these systems is seamless oil, gas, and their products' derivatives production with minimum operation interruption and a safe shutdown when required. Safe operation involves safety of plant personnel and of the community surrounding the plant as well as plant operation without severe damage to asset. Safety as defined in [11] is the "freedom from danger" or "as an acceptably low risk that a system will injure workers, destroy the plant, or function in some other socially, economically, or legally unacceptable way." So, how do the existing PCS systems networking achieve this objective?

The key answer to the above questions starts with understanding the function of HPAA PCS networking. These systems are typically used to provide stable and safe operation of oil and gas process plants and infrastructure. Local control logic, cascaded, and multi-variable loops are exchanged between controllers and a master controller; utilizing a fault tolerant local network within process plant [2]. PCS are designed to protect plant equipment and plant personnel, community, the environment from potential adverse effects caused by unexpected emergencies, such as fires, explosions, and hydrocarbon or toxic gas leaks. Hence, process variables such pressure, temperature, liquid and gas states, etc., are very vital to successful and stable oil and gas production operation. The data exchanges between the PCS’s are even more important to ensure layers of protection and safety are implemented at the oil and gas upstream (oil field), pipelines, and downstream (refining, distribution) product flow[11],[12]. This leads to the underlying network infrastructure necessary for this operating environment-Real time network. Hence, real-time communications networks play a crucial role in HPAA PCS. They are the key enabler for the successful overall functionality of extended application intelligence and distributed control systems. Reliable real-time communication provides the foundation for supporting peer-to-peer control systems, local and remote plant operation capabilities, and tools to enhance operation productivity and minimize overall costs as discussed in [12].

As discussed in [5], [6], [12], [13] and [14], the benefits and the importance of a real-time network has direct contribution to a steady state and stable operation for the local process automation system environment. In this regard, the real-time network benefits can be further maximized when used in a wide area network. Multiple operational plants can be managed from a common command and control center or different control centers that are geographically dispersed; providing back up support for each other when needed.

As a result, a distributed autonomous command and control center is formed [12]. This concept can be extensively and effectively used in managing local plant process automation (i.e., within the factory or plant operation field) for different plants apart from each other. However, this concept is not applied in petrochemical and hydrocarbon (oil and gas) producing operating environments. These different industries typically have dedicated autonomous system with a stand alone, local, and real-time network, dedicated controllers, and operation to manage a designated process. These networks are typically connected to management systems located within the operating facility and are seldom connected to each other. Today's process automation system implementations are mostly proprietary system, different network protocol solutions, dedicated networks, and vendor-specific architecture, Figure 2.1. This includes hardware, software, protocols, and the physical network infrastructure [1], [3], [4], [5], and [6]. The PCS is connected to corporate layer (Enterprise Resource Planning systems (ERP). The ERP layer is typically supported by standard IP over Ethernet network contrary to the PCS layer.

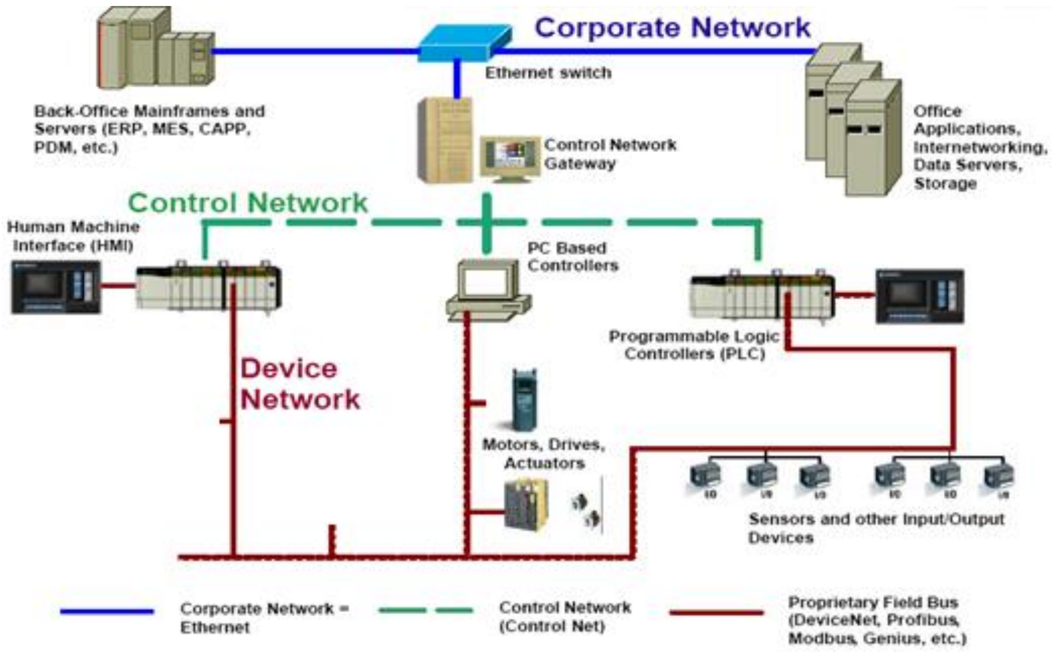


Figure 2.1 Process Control Network & Enterprise Hydrocarbon Network Model Architecture

2.3 NETWORK ARCHITECTURE FOR HYDROCARBON PROCESS AUTOMATION APPLICATIONS

The HPAA network architecture also has evolved over the past many years with network technology development from a service and feature functionality but maintained a layered network design approach. Three different key layers' components are inter-networked to form a generic process control system operation. The lowest layer is the instrumentation that is directly engaged in the both sensing and transmitting process performance data and activating mechanical process settings [15]. Data is acquired on a cyclic basis or utilizing preset thresholds. Examples of these types of data are alarm events, controller interlocking program events, batch reports, and control device programs events. A data communication network is used to connect different instrumentation layers to their designated controllers, forming a process loop as part of the Control Layer. Multiple controllers are typically connected to the master nodes that are used for data acquisition, modeling, and Human Machine Interfaces (HMI) access decisions.

As discussed in [16] and [17], the key criteria for selection and designing of local distributed control network system; where the primary key features are transmission time, reliability, safety operation in hazardous area, and maximum number of supported devices. The authors highlighted that the control network system selection needs individual consideration of the operation and the controlled environment [16]. For example, the number of controlled devices in a factory plant as compared to an oil and gas operation is much less. Factory plant is typically confined within space and operation while gas and oil operation span over large space area from upstream (oil and gas wells, oil and gas separation plants, etc.) and downstream (refineries, distribution, loading, etc.). Number of controller and devices in a gas and oil refinery sometime are even more with higher level of complexity. The authors discussed the network supporting two different environments and their primary focus was on the use of narrow-band communication; low speed links for field bus protocol. However, the selection criteria (i.e., transmission time, reliability, safety operation in hazardous area) discussed by the authors can also be considered for high-speed network (i.e., Ethernet technology); which is the basis for this research.

The legacy process control network architecture is based on layered approach that would provide the appropriate separation between the process instruments interfaces and the system controller [3], [15]. Examining [2], [5], and [6], each system controller is designed for preset process functions. Multiple controllers for the same process, supporting different functions, are connected to a high-speed server and are used to manage different process segments. The high speed centralized server, sometimes called multi-variable controller or master controller, communicates to all the field controllers. Controllers are also designed and deployed based on distributed local intelligence and typically contained within the plant process operation. Each controller supports the full control (control loops) locally. With networked controllers' environment, process decisions and control functions can be distributed among controllers. Cascade control loops are exchanged between different controllers providing an end-to-end stable and safe operating environment. Massive message and traffic mix is exchanged in support of these different components of the process control network. The traffic mix even increases with electronic data exchanges with Enterprise Resource Planning system [13].

In fact to determine the desired outcomes of each layer on the communication network, the layer can be subdivided into a smaller layer to study their behavior and determine their profile. In [18], the authors went further and discussed the need to have the instrument layer as two layers data exchanges in a distributed control environment. The lower layer is based on continuous scan cycle for all of the different process variables. While, the higher layer is based on discrete event triggered or report by exception. These two layers, together, are forming a distributed control sensor network providing a design for robust controllers. This approach can be a fit for multi-dimensional process automation environments such as aviation, motion control and or virtualization, but not for oil and gas system. Traditionally, the two layer controller functions in oil and gas environment are collapsed into one layer; where the controller is sending both continuous scan and discrete event triggered messages. In fact, controllers can also support broadcast type messages; specifically when there is a process upset.

In this research, the controllers will support all three types of messages. The breakdown for the traffic mix of these different message types will be part of this research. The complexity with the messaging at the lower layer is the high frequency of message exchange and timeliness requirements. But, the message size is small in number of bytes [17], [18], and [19].

Traffic mix is even at greater complexity for higher layers; especially when we have PCS along with support services such as voice, video and large file data transfer traffic on the same network. The major shifts in business environments (for example: business to business, aviation, security, etc.) have resulted in Ethernet being the most widespread communication technology in electronic data processing systems. Further, vendors and standard bodies have invested extensive resources to ensure Ethernet can keep up with the continued “quality of service” demanded by end users and their applications. Hence, IP over Ethernet has become the standard protocol that offers the platform for the PCS diverse traffic mix that we will need to address in this research. As a result, the goal of reaching the network convergence for PCS is becoming within reach due to the latest technology advancement in the instrumentation, and controller domains. Ethernet enabled devices is now extending its reach down to the local process controller level. This leads to an open system interface and lower operational cost, Ethernet leads to a seamless infrastructure that stretches, with the help of network filters and secures access, from the office to the controller and or sensor, Figure 2.2[1], [3],[4],[5],[6], and [12].

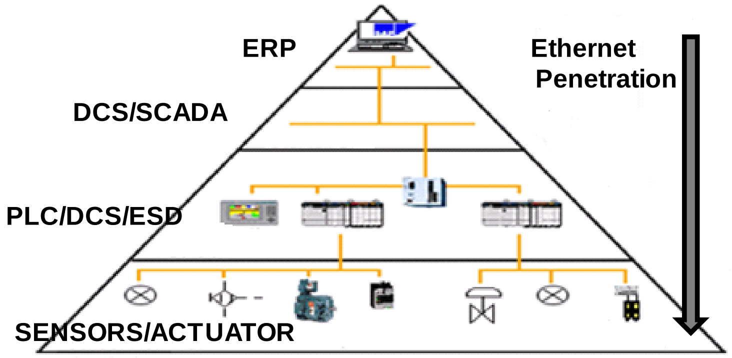


Figure 2.2 Ethernet-Extended over Separate/Multiple Layers

In [20], [21], and [22] among other authors have discussed means of overcoming Ethernet un-deterministic inherent behavior. Solutions were discussed such as impeded middleware layer or firmware by altering the protocol format between the service layer and the data link layer; thus bypassing the TCP/UDP layer of the IP Protocol. An example is Fixed Time Slots, Tokens, producer/consumer, or master/slave concepts resulting in an improved real-time communication. These concepts work very well in local area network and result in Ethernet vendor specific solutions (i.e., proprietary). The dilemma is when sending these real time messages in a wide area network, the real-time messaging will be part of the TCP/UDP layer bay load i.e., standard protocol format which leads in having TCP/UDP packet flow features overshadowing the altered LAN protocol. Also, in [20], [21], and [22] suggested the concept of suppressing the collisions, reduce their numbers and resolve collisions in a deterministic manner as an alternative to altering the Ethernet IP middleware.

Suppressing collisions can be met by utilizing Ethernet switch technology, standard protocols (e.g., IEEE 802.1p, IEEE 802.3x, etc.), and with high-speed Ethernet switches (Gigabit Ethernet) at the process and control systems layer. This allows seamless integration, Figure 2.3, into higher layers data acquisition and control systems and enterprise applications. This capability can be adopted and implemented independent of space and time. Controllers linked via wide area Gigabit Ethernet network can be several hundred kilometers away from each other, exchanging process messaging and command control, but functioning as one autonomous virtual distributed process control system [12], [20]. It must be noted suppressed collision domain architecture can improve the quality of data exchange but does not imply a real time deterministic architecture; since it is very challenging to avoid network delay imposed by switching, buffering, protocols, and transmission. This research will consider these elements as part of the different simulation scenarios and analysis.

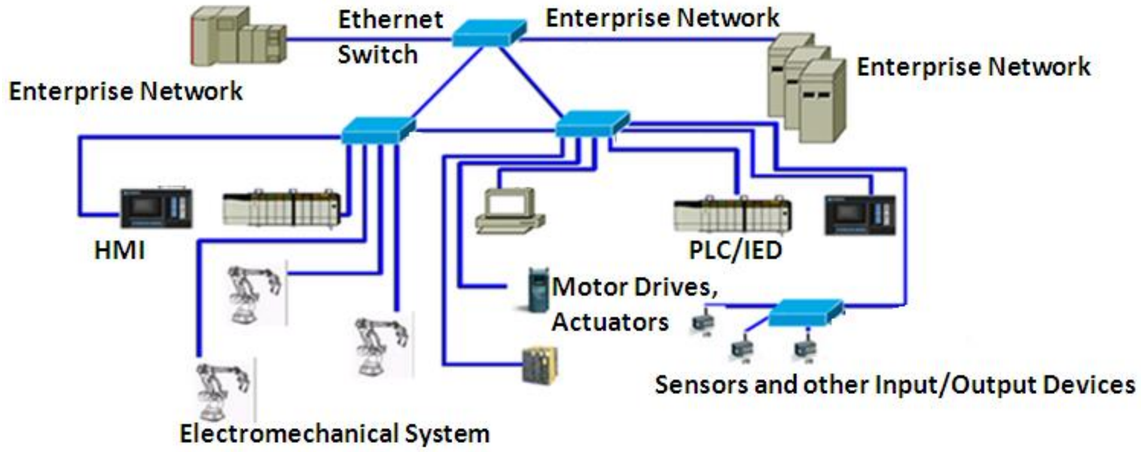


Figure 2.3 Integrated Network – IP over Ethernet

There are major challenges in adopting the standard Ethernet into the hydrocarbon process control system domain in a wide area network environment [20], [21], and [22]. These challenges discussed in [20], [23], and [24] and can be summarized into the Network deterministic nature, Quality of Service network requirements (i.e., delay, jitter, packet loss, congestion, etc.), Optimal network design configuration and performance, Reliability of the network and failure. In this research, these challenges will be examined in relation to hydrocarbon's process automation applications.

2.4 HYDROCARBON PROCESS AUTOMATION APPLICATIONS AND CONVERGED IP NETWORKS

Real time network for HPAA has evolved over the past many years. The level of complexity and expected performance has increased as a result of development in computing infrastructure and software applications. This has enabled extended application intelligence and distributed control systems from the oil and gas wells to the refinery production plant and even to the end product distribution systems. Reliable real-time communication provides the foundation for supporting PCS application systems, local and remote plant operation capabilities, and tools to enhance operational productivity [12]. Hence, dedicated and standalone networks were designed and implemented to support each process automation segment within an oil and gas plant over time to meet the reliabilities and protocol propriety limitations of PCS systems and their network interfaces.

The network is composed of three different layers connecting instrumentation and device level to the control, and then to management information level. Their level of complexity and expected performance has increased as a result of development in computing infrastructure and software applications. Moreover, technology and standard Ethernet network protocol enhancements are providing the necessary platform to overcome the current PCS network limitations [12].The technology development as discussed in [23] and [25] highlights the evolution in the different PCS layers, Figure 2.4. The instruments are becoming an intelligent node (i.e., microprocessor-based communication enabled devices) and their adoptions at the lowest layer of process automation instrumentation and control in the manufacturing field has risen. As a result, instruments and sensors have evolved from nomadic and analog environment to the digital and more intelligent PCS element. The instrument is providing vital performance data for the end-to-end PCS system and is able to make some independent intelligent decision locally. Hence, the traffic being generated by the instrument has increased and, most importantly, networked-instrumentation system solution is now more feasible.

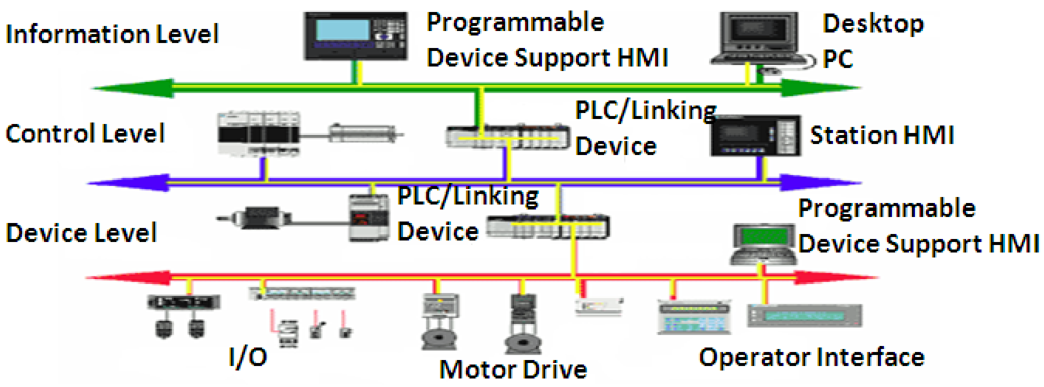


Figure 2.4 Process Control Layers [27]

The different PCS HPAA applications are conventionally supported by a unique network that comprises a series of logical and physical network layers that represent the building blocks to the end-to-end network design, Figure 2.5, as discussed in [3], [15], and [26]among others. The different interfaces between the separate PCS systems may dictate a propriety type interface to perform preset functionalities. These functionalities are either HMI or Peer-to-Peer (P2P) driven.

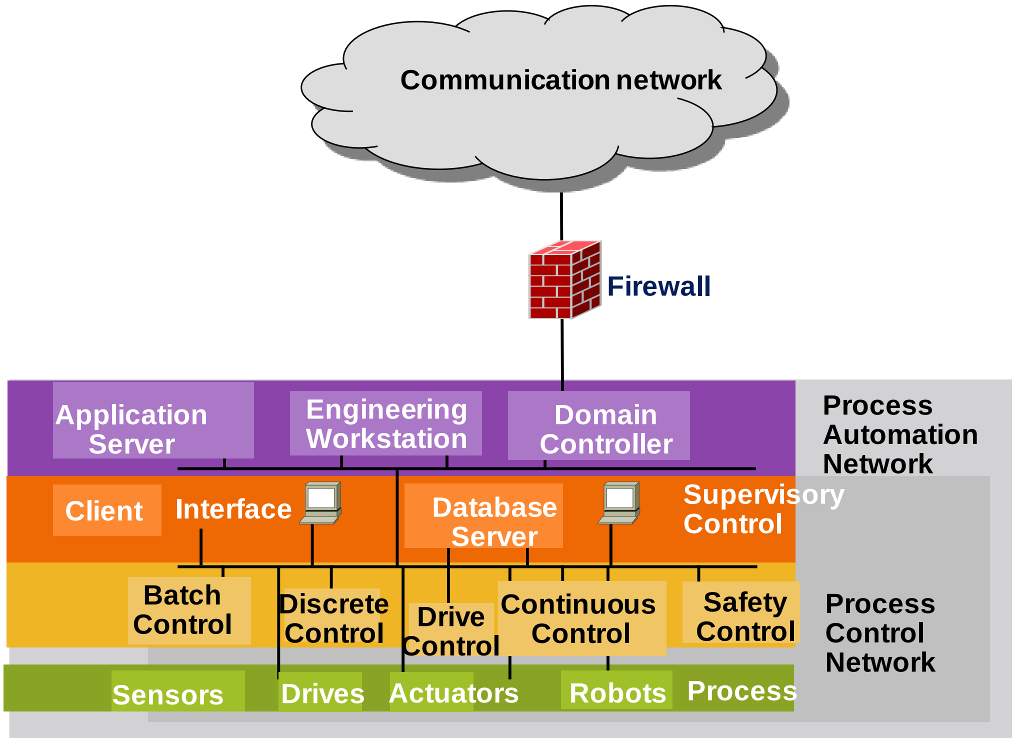


Figure 2.5 Independent Parallel Process Control Systems

Boyer [3] provided an overview of the new developed systems and referencing different applications to specific networking solution. Each layer is connected by unique network to provide the needed data exchange (cyclic and acyclic) and more over interface to the above layer (s) according to the PCS control strategies (local vs. networked control). In [28], discussed the processing time and focused on the networking delay by studying different technologies. The primary finding is PCS elements (instruments and controllers) are utilizing high speed Central Processing Unit (CPU) so the inherent delay within the PCS systems is becoming less of a concern. The intra-node processing time up to the application layers can range from 500 ms to 800 ms. This include the time that takes to receive the process variable, run the impacted logic loop, and send back the appropriate decision message. Of course message arrival randomness is governed by the application configuration [2], [4]. Hence, the primary concern is now being shifted from the PCS elements to the network.PCS system elements intelligence is now becoming a key variable in the network connectivity design and model. In [29], author's theorized network based control system behavior as it is no longer only where controller is governing the network design; rather the controller design itself has to be robust to handle possible network deficiencies. Hence, a coupling relationship is now found between the PCS system elements and the network that defines the expected performance for the HPAA application time delay, integrity (packet loss, jitter) and efficiency (i.e., supporting multiple services).

As discussed in Brooks [27] among others, several Ethernet protocols for process control; where most require alteration to the IEEE 802.3 Layer 2 and or IP layers. Any type of alterations typically results in incompatibility with standards based network solutions. Several attempts were made at enhancing the network for PCS system. In [30], discussed the various industrial networks types which includes CAN (Controller Area Network), SERCOS (SErialRealtimeCOmmunications System), and Lonworks and their technical design techniques in fulfilling the process application requirements. Feature capabilities such as speed, node configuration, data link layer arbitration, and physical layer-cable type among others were used to compare these different networks. One of the key capabilities that relates to this research effort is speed; e.g., Lonwork at 1.25Mb/s. The authors believe speed is not critical factor due to arbitration and limited number of devices connected per a network segment [30]. While this may be true for such a limited segmented network design, speed is one of the most important parameters of this research as it provides the platform to carry different traffic mix such as PCS, voice, multimedia and still conform to the time delay boundaries of the application. In [31], the authors discussed EtherCat, EtherNet/IP, and Modbus TCP among other and the primary highlight of their research is the special implementation modification at the data link layer and CPU design supporting the TCP/UDP/IP protocol. The author highlighted the continuous implementations of TCP/UDP/IP protocol layers to serve the real time requirements of the process application. The primary aim is to administrate the interface between the automated system, and the TCP/UDP/IP protocol. In some cases, the hardware is being developed with unique implementations of TCP/IP that reduces the processing time of the CPU. This has resulted in a special stack that was developed to allow IP communication in sensor networks [18], [19].

By contrast, another track in real-time Ethernet based systems implements special proprietary protocols, optimized stacks or both. Modbus TCP [32], Ethernet Powerlink [33], Ethernet for Control Automation Technology (EtherCAT) [34], and PROFINET Isochronous Real-Time (IRT) [35] are an example of such implementations. These systems implement dual stack: a deterministic transmission control layer on top of Ethernet for controlling access to the network. The second is standard TCP/IP services. The key advantage is deterministic Ethernet services regarding latency and jitter. However, one drawback is that lower bandwidth is available. In addition, these implementation mostly depend on dedicated hardware, which might result in their being solutions that are less than cost-effective and more difficult to maintain [36]. In this research, we are not considering such an implementation as the primary focus is standard Ethernet protocol implementation. The research hypothesis is the IEEE 802.3 Ethernet standards protocol; full duplex speed, high-speed (Gigabit Ethernet per second), and the utilization Internet Protocol (IP) Quality of Service will lend itself to be a protocol for real time process automation network. It was apparent from tapping into the different data sources mentioned in Section 2.0; there are trends in addressing, in general, the process automation industry over time. This includes addressing the instrumentation, control, and information layers and the PCS network interconnecting these layers. The primary focus is improving the network time delay and jitter performance by either evolving each of the PCS layers into an open standard interfaces such as Ethernet, higher speed interface, and more embedded intelligence in each of the layers in question.

There was no research that was found in the area of CIP networking in either LAN or WAN network model that supports the three different HPAA network layers. Of the literature that was found relating to WAN networks, the primary focus was on the electrical substation domain and with a limited perspective on remote monitoring. Three key areas were uncovered by reviewing previous research. These are: 1) Process Controller Behavior, 2) Peer-to-Peer Communication, and 3) Networking Cross Traffic: Delay and Reliability. These different areas are essential elements impacting the formulation of CIP network model.

2.4.1 Process Controller Behavior

In this research, Process Controller behavior was studied due to its dynamic impact on the network. Understanding the behavior of the process Controller (CNT) will help in exploring the feasibility of utilizing CIP network for PCS system. Moreover, this will also help in the research method, simulation and experimental case study, parameters definition and validation. CNT's are considered the first layer of traffic aggregation that connects the instruments and actuators to either a Master Controller (MSC) or to another CNT. The instruments are connected to the actual HPAA petrochemical process (pumping, boiling, cooling, condensation, separation, stabilization, pipelines flow, etc.). The captured process variables (pressure temperature, level, speed, rate, density, variable frequency, viscosity voltage, etc.) by the instruments are based on a predefined cycle or thresholds. Messages captured by the CNT are then filtered into a logic solver and computing instructions are then communicated to an actuator. Messages may also be sent to a MSC or another peering CNT [2], [4].

In general, messages among the different PCS system elements (instrument, controllers, and higher order logic solver) are typically governed by the controller processing time, network delay time, and wait time. This relation was discussed in detailed by [28] and can be presented by equation (1).

$$T_d = I_t+W_t+F_t \qquad (1)$$

Where: T_d *= Time Delay;* I_t*=pre-process time;* W_t*= Wait time, and* F_t*= Post-Process time.*

and

$$W_t = NP_t + M_t+\lambda \qquad (2)$$

Where: NP_t *= Network Protocol,* M_t *= Message Type Connection,* λ *= Network traffic Load*

The processing time in equation (1) is defined by two different segments at two different time points. These are: pre-process which is time allocated at the initiating Controller and post-process as the time allocated at the receiving Controller. The process time is typically constant since it is predominately governed by the controller CPU. On the other hand, the wait time can be variable since it includes three different key components: Network Protocol, message control type, and overall network time delay caused by traffic load and network nodal design as defined in equation (2).

The wait time can be influenced by the type of process control messages. There are typically cyclic messages based on predefined scan cycle and report by exception (event triggered) based on preset thresholds; resulting sometimes in broadcast messages and traffic burst [3], [5]. In a steady state operation, cyclic messages are the predominant message type by the controller and small percentage of the messages are considered event triggered. These messages are driven by process variables and governed by the process control loops and network health [14], [26].

Process controller has now evolved from process bus and Local Area Network (LAN) technologies such as Token ring, Profibus, Modbus, LonWorks, to standard Ethernet utilizing TCP/IP protocols (i.e., Modbus, DNP, Profibus) [28].The traffic behavior is determined by tracing it from message initiating to the outgoing port's sending a frame during the switching operation. The outgoing port may have a queue depth depending on the traffic mix. The worst case switching delay can be estimated based on the maximum Ethernet frame size (1518 bytes or 12144 bits) utilizing 100 Mbps would translate to 122 µ seconds [9], [20].This delay is followed by controller message (assuming 1024 bytes) resulting in 82 µ seconds. So, the total network processing time for 100 Mbps Ethernet switch can be approximated to 326 µ. The PCS application running on the controller may have a composite processing time close to 800 ms. This will include the network process time and application running time as defined by [3], [4], and [28] among others.

Additionally, message size and scan rates are key parameters that impact the Controller behavior as well as the overall network delay. In [18], the authors discussed the need to have the instrument layer as two layers data exchanges in a distributed control environment. The lower layer is based on continuous scan cycle for all of the different process variables. While, the higher layer is based on discrete event triggered or report by exception. These two layers, together, are forming a distributed control sensor network providing a design for robust controllers. This model can easily be correlated to multi-dimensional process automation environments such as aviation, motion control and or virtualization, but not for oil and gas system [4], [37]. Traditionally, the two layer controller functions in oil and gas environment are collapsed into one layer; where the controller is sending both continuous scan and discrete event triggered messages since its function is based on two dimensions, or a maximum of 3 dimensions, as compared with other industries that were mentioned earlier [2].

Another important behavior is the controller ability to support broadcast type messages; specifically when there is a process upset. These messages can be small in size but they can be massive resulting in a burst in network loading. The complexity with the messaging at the lower layer is the high frequency of message exchange and timeliness requirements. But, the message size is small in number of bytes as depicted in Figure 2.6 [3], [21]. Traffic mix can be even at greater complexity for higher layers; especially when we have distributed control system traffic running along with support services such as voice, video and large file data transfer traffic on the same network [21], [38]. The messaging between the controllers to upper layers increases in size as well as in the delay timelines requirements. In this research, the controllers will support all three types of messages [39]. This will be handled by assuming a continuous request/response per second. The message size at 1024 bytes is considered large since typically the message size is in order of 64 bytes to 576 bytes, [3], [15], [16], [18] and [39].

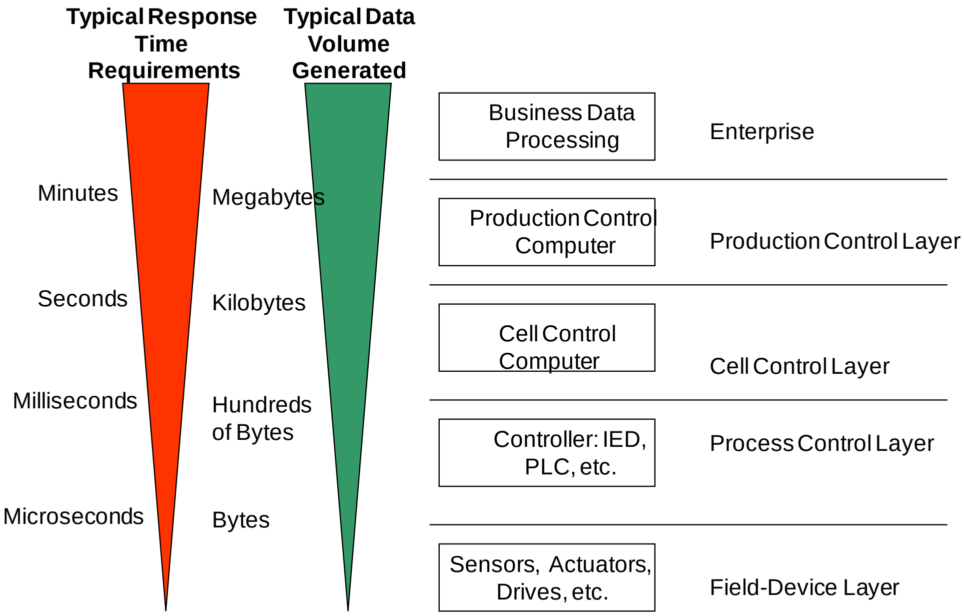


Figure 2.6 Hierarchy of Information Flows in Manufacturing Applications

Another key finding in exploring the Controller behavior as theorized by [29], is network based control system not only where controller is governing the network design; rather the controller design itself has to be robust to handle possible network deficiencies. While this approach provides a robust and resilient system implementation, optimizing the controller attributes (message types, mix, and arrival rate) could mitigate the need to invest in the controller design robustness and relay on the network to compensate for controllers' limitations [39]. Therefore, as part of this research it is necessary to investigate the controllers' behavior based on a case study to formulate common controller attributes that can be used in the needed network simulation for the intended CIP network.

2.4.2 Peer-to-Peer Communication

Currently, most oil and gas operating companies recognize the value of merging networking infrastructure within the plant and a across their different fields of process automation environment [3], [4], [5], and [40]. The networking infrastructure may support not only data acquisition and delivery requirements but could be used for remote control, operation virtualization, and collaboration centers. Most important, PCS control loops could be supported without dependencies on the application to compensate for possible network time delay [3] and [39]. Such an environment requires real-time Peer-to-Peer (P2P) communication providing higher level of process integration functions, control, and distributed protection. As a result, dedicated control centers, fragmented communication infrastructure, and segmented small islands of automation functions will be eliminated thus reducing infrastructure cost and increasing overall operational efficiency. Besides PCS applications, communication support services such video, voice; large file transfer can be supported upon developing the optimum network model of a CIP network connecting different sites locally and globally.

While time delay is a crucial part to a successful PCS, network reliability and integrity has an equal weight in these regards [3]. High speed Peer-to-Peer (P2P) communications are used to replace low speed, dedicated hardwired control signal exchanges. This capability is extended from managing steady state process functions to safety protections and emergency shutdown systems. These different functions are critical and must be reliable [39].In [30] and [39], a technology brief of industrial networks was provided and highlighted the different local and wide area networking options. The paper did not provide specifics on the characterization of these different options from an application perspective but highlighted key features such as speed, communication protocol methods, and their physical characteristic (fiber, wireless, etc.). The key challenge when using a WAN network is WAN may expand over many small networks that are interconnected without a uniform Quality of Service design criteria. This condition may create variance in network availability and timelines especially due to the heterogeneous nature of the WAN infrastructure [9], [10]. However, new trends in establishing homogenous networks, such as Giga Ethernet, are transforming wide area network to be an optimal communication platform for PCS applications [12], [20], [22].

In [4], the author highlighted the importance of standardization in promoting interoperability between peer-to-peer process automation nodes and in this case the Intelligent Equipment Devices (IEDs) as part of electrical substation automation. Further, he emphasized the importance of Local Area Network (LAN) segmentations (virtual LANs) to keep network message processing to an appropriate minimum and reduces the results of network failure or cyber attacks. While he theorized the traffic types to be beyond a single PCS application, he also envisioned the IED LAN to support concurrent PCS applications, multiple protocols such as Modbus TCP, Data Network Protocol (DNP) over IP, and moreover support services such web access, email service, telephone and media application, etc. The only drawback in this effort is it was focused on local substation implementation and the author did not provide the approach on how all of these services will be supported. The answer to this will be part of this research effort outlined in the subsequent chapters. Moreover, both LAN and WAN conceptual models will be examined in these chapters.

P2P communicating over a CIP network will utilize Ethernet switches that are with advanced features that are critical for real time control and process automation. These features are standard based (e.g., IEEE 802.3x full duplex, IEEE 802.1 priority queuing, and IEEE 802.1e VLAN, etc.).And, as outlined in [1], by making use of the attributes, traffic class prioritization and dynamic multicast filtering as specified by IEEE 802.1p, it is possible to prioritize mission-critical data with noncritical data and also provide the mechanism for efficient multicasting in an Ethernet network mode via layer 2 protocol, resulting in better network delay performance. Total network delay, T_d, for a network with N number of switches can be defined as Frame transmission time in addition to the actual switching delay [27], [39]. So, for a network with N number of switches the T_d is defined as follows:

$$T_d\,(N) = (Frame\ Trans.Time + Intra\ Switch.Time)\ \mathrm{X}\ N \qquad (3)$$

While time delay is a crucial part to a successful process automation operation, network reliability and integrity has an equal weight in this regard. High speed P2P communication channels are used to replace low speed, dedicated hardwired control signal exchanges. This capability is extended from managing steady state process functions to safety protections and emergency shutdown systems [3], [4], [39]. These different functions are very critical and must be highly reliable. In [42], the authors highlighted the importance of network time delay in power grid distribution systems in particular at the substation as part of a key function: load shedding. The load shedding is a scheme that is triggered within 10 milliseconds from generator circuit breakers status changes. In the Ethernet based control for load shedding case, Ethernet shall meet the timely requirements for substations automation. This is defined in the order of as low as 4 milliseconds to support fast functions such as tripping; within Local Area Network [23], [27], and [39]. This is comparable to the Emergency Shut Systems installed at Gas well head to prevent H_2S (lethal gas) from causing environmental and human casualty impacts [2], [4], and [40]. In this research, we will examine the wide area based control and protection functions if they can benefit from extending the local operation to remote sites by enabling certain control functions and utilizing a high-speed network.

Wide Area Network supporting distributed real time process automation for oil and gas field’s plant operation will be exposed to different traffic mix [3], [4], [43] and [44]. Real time process automation traffic itself has different dynamics and the underlining network requirements are zero packet loss rate and predictable delay [44], [45].Control loop stability is directly impacted by missing or delayed process variable values [2]. Hence, special network characterization shall be predefined for desired network quality of service. This becomes a daunting mission when real time process traffic is mixed with other services such as voice, video streaming, internet, FTP, email, etc. In [40], the authors experimented cross traffic impact on real time traffic for Proportional Integrator Controller (PI) loop and they concluded that bursty cross-traffic has adverse effect on the stability of the distributed process control even when the average utilization is low; in reference to equation (3) driven by nature of Ethernet serialization, buffering, and transmission. The experiment was confined to an Ethernet network setup based on 10Mbps and 100Mbps. In addition, this effort did not consider combining other real-time traffic, for example, voice to identify relationship impacts between the distributed process automation traffic and other real time applications.

In [38], the author completed comparative analysis for the different communication medium and the appropriate associated application in the process automation domain. Fiber optics medium is considered the most reliable transmission medium connecting different process automation fields to a centralized control center. This communication medium typically has a higher cost for trenching and securing right-of way. On the other hand, Wireless was discussed as the most cost effective communication medium but it has its inherent signal quality issues, bandwidth capacity inverse relation with distance, and frequency licensing regulation restrictions as demonstrated by [46] for a dedicated PCS application case study. Satellite, coaxial, and power line carriers were discussed as well. These options have their limitation in bandwidth, distance, response time delay, and cost. The authors suggested the hybrid solution where fiber is connecting the main backbone process automation nodes and wireless is used as a last mile reach for those facilities that are spread out on the edge. Hence, this design criterion minimizes infrastructure cost while providing the needed bandwidth and reliability for the highly concentrated process automation nodes. In this research, the wide area network transmission considers fiber optics. Wireless connection, as a point-to-point backhaul link, to a remote site will be explored. These different research efforts shed some light on the P2P communication anticipated environment in LAN and WAN network model.

2.4.3 Networking Cross Traffic: Delay & Reliability

The conventional high speed network solution for existing PCS is typically designed and implemented to support all of the controllers, sensors, and subsystem traffic requirements [4] and [39]. The common practice is limited to process automation traffic (i.e., alarm events, controller interlocking program events, and control device programs events, etc.) as the sole user for the network. This strict networking rule is set forth to ensure zero (0%) packet error, zero (0%) packet discarded, and minimum delays during an anticipated packet peak load. Therefore, support type applications such as maintenance, asset management, large file transfers, etc., are not permitted to run concurrently with the PCS applications, on the same network.

The source of time delay and jitter in LAN/WAN networks are typically induced by network traffic and protocol as discussed in 2.4.1. The network traffic, specifically cross network traffic, can cause congestions resulting in unnecessary delay and jitter. Cross network traffic can be simulated on a common controller attributes to depict the network behavior for P2P communication. In [29], the authors concluded that delay, jitter, and packet loss impact the process automation traffic and control loop directly. The authors were able to provide means such as activating Quality of Service to alleviate the impacts of delay. However, the study did not address multi-traffic streams over the same IP channel. Given Ethernet has evolved from 100Mbps to 1000Mbps since the authors completed their research work, this research does consider both multi-process automation traffic stream and other support applications on the same IP channel. Moreover, the WAN HPAA PCS will be explored. As discussed in [47], the cross traffic also impacted by the application nature. Some applications are designed based on unconfirmed request/response messaging while others are dependent on the confirmation as depicted in Figure 2.7.

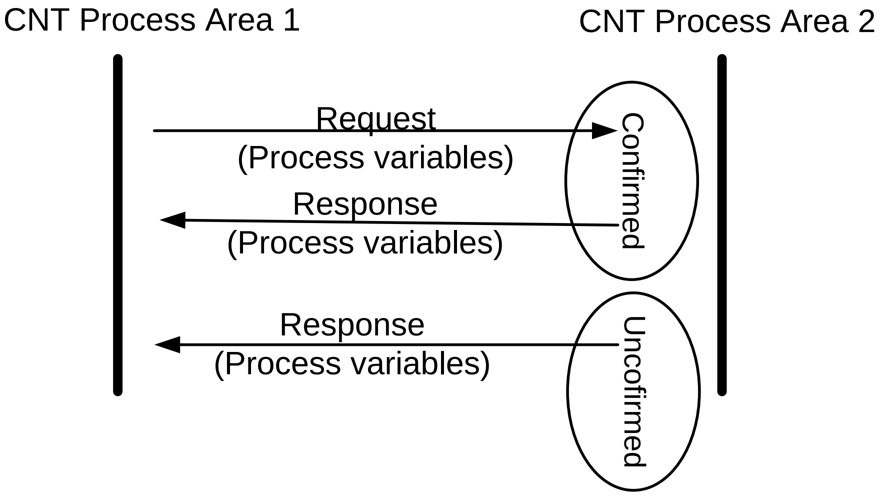


Figure 2.7 PCS Controller Messages Flow Format

In this research, both the end-to-end delay and the response delay will be examined. Table 2.1 depicts the different general process automation types and acceptable time relay requirements based on industrial survey as described in [36] and [29] that will be consider as part of this research.

Table 2.1 Summary General Real-Time Delay Requirements for Industrial Applications

Automation System Type	**Architecture Design**	**Response time**
Enterprise Level Networking	Top Level. Between conventional computers	100 ms – 200 ms
Field Bus Level Networking	Middle level, networks with a compromise between versatility and performance	40 ms – 200 ms
Device Bus Level Networking	Bottom level, high performance used to control I/O	10 ms – 100 ms

Detailed literature review for PCS HPAA timeliness requirements uncovered a difference in time delay, as depicted in Table 2.2. One key observation is there appear to be a wide range of delay requirements for the HPPA [2], [3], [43], [44], [45], [47] and [49].

Table 2.2 HPAA Application Characterization

HPAA Application	**Process Variable**	**Process Loop**	**Response Time Delay (s)**
Power Load shedding	Voltage	Fast	0.01
Rotating equipment over speed	Speed	Fast	0.04
Wellhead Shutdown	Pressure	Fast	0.5
Rotating Equipment Vibration Safety Case	Vibration	Fast	1
Lube/Seal Oil Pressure Safety Case	Pressure	Fast	2
Rotating Equipment Bearing/Casing	Temperature	Moderate	10
Liquid Pipelines Pressure	Pressure	Moderate	10>
Lube Oil Level Safety	Level	Slow	120>
Drum level Safety	Level	Slow	200>

The range in timeliness can be defined in the range of $40ms < T_d < 200s$ for HPAA from the table above. The primary focus of this research will be on the time delay at the lower bound as it will represent the most stringent requirement for the CIP network. Also, there are other sensitive support applications that will be considered in the CIP network such as voice and media streaming.

As for voice application in CIP networks, it requires compression such as in the case of G.711. This is typically results in a network delay in the order of 150ms to 200 ms [24], [49], and [50]. This delay can be broken into transmission (encoding, compression and packetization delay), transmission and network queuing delay, and receiver (buffering, decompression, and depacketization,). The allocated delay at the transmitter is estimated at 25ms, the receiver 45 ms, and the network is between (80 ms to 130 ms) as discussed in [51], [52]. Similarly, Media streaming, Closed Circuit Television, based on MPEG-4 [51] is another has an end-to-end delay ranges from 250ms to 2000ms depending on the available bandwidth. In 1 Gbps Ethernet network, the network delay is estimated at 200ms or lower.

Also, another key parameter is jitter, variation in time delay. These different applications will have an impact on the CIP network model architecture. The architecture will need to be flexible and accommodate the timeliness (delay, jitter), and integrity (acceptable packet loss and error).In [53], the authors examined three basic network architectures, with different iterations, that are commonly implemented within electrical substation controller model; utilizing Ethernet switches. The basic architectures that were considered in their research are Star, Ring, and Cascaded network topologies. Each design of these basic architectures, or combination, resulted in different performance and cost outcomes. Star network topology has resulted in the highest degree of time delay as compared to ring topology with highest network recovery capability. The bus network is more prone to delay due to the aggregate cascaded switches between source and sink nodes. Furthermore, network reliability is exposed due to a node or link failure. The study outlines Ethernet network capability compliance requirements for process automation in Local Area Network substations. Additional network compliance elements such as throughput, best effort vs. QoS based network, and traffic mix shall be considered when addressing the wide area network for such an application.

As described by[54] and [55], the most common mechanism for keeping tabs on Ethernet based network health is Simple Network Management Protocol (SNMP). A monitoring program (agent) is embedded within each device, and that gathers information on its network activity. The collected information is in the form of messages called Protocol Data Units (PDU) and is stored in a database called a Management Information Base (MIB). Centralized server, network management station(s), with a monitoring application are used by the administrator (or an automated or scheduled process) for polling all or some of the network nodes, requesting information which was collected. In [55], the authors outlined the fundamental SNMP capabilities. SNMP can also be used by the network administrator to reconfigure specific devices and automatically notify the network management station if certain predefined conditions, or events, occur. These alerts are called traps.SNMP is a highly complex protocol that can be difficult to implement. Also, SNMP is not very efficient. It relays unnecessary information, such as the version number, which is included in every message and other overhead packets. Hence, it increases network bandwidth utilization as discussed in [56].Previous work on assessing SNMP impacts was focused on communication networks for public and enterprise users. In [19], the authors addressed the Sprint IP backbone network focusing on the characterization of traffic congestion by analyzing link utilization at various times. The study was able to identify traffic bursts, their duration, and drivers. However, packet or byte loss was not illustrated in this study.

Packet loss investigated in [57].This relates to delay across network components (router, firewall, switches) where the primary focus is packet loss during delay. In addition, the effort in [58] assessed and analyzed packet loss on web traffic and its download time. The authors in these two different efforts were able to ascertain a direct relationship between packet loss and web page download time. An improved packet loss performance was observed with the increase of both link speed and network component backplane capacity.

In [3], [27], and [59] provided an overview of the new developed systems which include a multitude of operational functionality that span massive performance data acquisitions, control, embedded command, peer to peer communication, and Human-Machine Interfaces. As a result of network nodes and intelligent steady evolution and standardization, the amount of information that must be exchanged over the network has also increased for configuration and operational purposes. It was highlighted Ethernet based interfaces for the intelligent nodes and Ethernet high-speed network nodes provided a homogenous platform that is operable with different systems, and enabled massive performance and profiling data access for the end user. Packet loss, delay, and jitter were not observed in these different research efforts as the networks that were explored were based on dedicated LAN. Also, the HPAA PCS load was kept at minimal. Moreover, the authors did not explore Ethernet in a converged IP network mode nor considered WAN network for supporting HPAA control and non-control traffic.

2.4.4 Standards and Industry Best Practices Perspective

Various resources in information and communication technologies are maintained through industry standards. This includes International Electro-technical Commission (IEC) [44], International Society of Automation (ISA) [60], Purdue Enterprise Reference Architecture (PERA) [61], and Applied Research Center (ARC) Advisory Group [13] which primarily focused on the industry trends and best practices. These different organizations strive to provide reliable, secure, and efficient design. In general, their design approach is based on 4R's of system design, specifically: Response; Reliability; Repairability; and Resolution as it was expensively discussed in ISA 99 [40] and IEC 61508 [60]. The design approach is out of this research scope but the key finding is none of these organizations explored CIP network for process control and non-control network.

The Institute of Electrical and Electronics Engineers (IEEE) [1] and Internet Engineering Task Force (IETF) [62] provide standard and design strategies to deliver traffic routing and transmission with high quality. There are several protocols in the IEEE and IETF suites that can help in this regard. However, these capabilities were not mapped into actual cases specific to Hydrocarbon Process Automation Applications (HPAA). The standard and industry trends best practices relating to PCS network can be summarized into five major themes and they are outlined as follows:

1. Process Control System Communication Network Security: Historically, process control systems (PCS) have been essentially proprietary and isolated. Over the past decade and with the rapid advances in Information Technology, these systems have become more open and powerful. PCS systems are increasingly moving toward standard technologies and communications protocols. Hence, there is an increase in the level of vulnerability and security that have resulted in having firewalls, Demilitarize Zone (DMZ) to become an integral part of the network design and architecture for PCS systems.

2. Network and Communication System Attacks: Network and communication system shall adopt a plan, design and implement a system that ensures a high level of separation or implement extensive firewall/ DMZ setups to prevent unauthorized access to the control network. This theme is partially contrary to this research's intended objectives of creating a CIP network model that can support both HPAA PCS and non-HPAA applications.

3. Cyber Security: System and network attack analysis has shown that the current threats are coming from outside hackers trying to break into systems, just for the sake of doing it or for malicious intent. Numerous incident reports show electrical power plants shutting down or experience temporary loss of control. There have been cases of nuclear power generation stations also experiencing

such issues. This over emphasizes the need for designing secure systems and keeping them updated to minimize the security vulnerability.

4. Control System Operation and Availability: The primary requirement for the plant control system is to stay operational and in control. Systems must be designed and implement with that point in mind.

5. Communication Infrastructure Weaknesses: Primary concerns fall into two main categories; communication system redundancy (hardware, fiber, copper, etc.), and communication systems operational control. As with any critical communication connection, all possible single points of failure must be eliminated by providing infrastructure redundancy and or alternate paths to ensure operational status.

2.4.5 Process Automation Industrial Networks

There are various kinds of industrial networks in the field of automation. This research focuses on the use of standard Ethernet IEEE 802.3 protocol [1]. However, it is worth going briefly into the other type of industrial Ethernet networks to provide a rationale on utilizing standard Ethernet solution for this research.

2.4.5.1 Industrial Ethernet Network

Industrial network is a network for communication between devices or facilities. In [30], the authors discussed the various industrial networks and technologies such as CAN (Controller Area Network), SERCOS (SERCOS (SErialRealtimeCOmmunications System), and Lonworks. Feature capabilities such as speed, node configuration, data link layer arbitration, and physical–layer cable type among others were used to compare these different networks. One of the key capability that relates to this research effort is speed; e.g., Lonwork at 1.25 Mb/s. The authors believe speed is not critical factor due to arbitration and limited number of devices connected per a network segment. While this may be true for such a limited segmented network design, speed is one of the most important parameters of this research as it provides the platform to carry different traffic mix such as HPAA PCS, voice, multimedia and still required to conform to the time delay boundaries of each application.

In [31], discussed EtherCat, EtherNet/IP, Modbus TCP and the primary highlight of this effort is the special implementation at the data link layer and CPU in the TCP/UDP/IP protocol. The authors highlighted the need for continuous implementations of TCP/UDP/IP protocol layers to serve the real time requirements of the process applications as they are added or changed. The primary aim of these modifications is to administer the interface between the PCS and the TCP/UDP/IP protocol stack. In some cases, the hardware is being developed with unique implementations of TCP/IP to reduce the processing time requirements on the CPU as discussed in [38]. Moreover, this has resulted in a special stack that was developed such as the µIP stack to allow IP communication in sensor networks as in [63].

By contrast, another track in real-time Ethernet based systems implements special proprietary protocols, optimized stacks or both. Ethernet Powerlink [33], Ethernet for Control Automation Technology (EtherCAT) [34], and PROFINET Isochronous Real-Time (IRT) [35] are an example of such implementations. These systems implement dual stack: a deterministic transmission control layer on top of Ethernet for controlling access to the network. The second is standard TCP/IP services. The key advantage is deterministic Ethernet services regarding latency and jitter. However, one drawback is that lower bandwidth is available. In addition, these implementation mostly depend on dedicated hardware, which might result in their being solutions that are less than cost-effective and more difficult to maintain [23].

In this research, industrial Ethernet network protocols implementation will not be considered. The primary focus in this research is standard Ethernet implementation that is based on IEEE 802.3 Ethernet standards protocol; full duplex links, high-speed (Gbps) and the utilization of Internet Protocol Quality of Service to meet HPAA real time process automation network requirements.

2.4.5.2 HPAA IP Network Quality of Service

IP Quality of Service (QoS) [62] is one of the major networking requirements, especially when considering mission critical application such as PCS HPAA. The challenge in IP QoS is to ensure each application is networked within the application performance tolerance [19] and [21]. The main QoS parameters that must conform to HPAA application are latency; message delay or response time, and jitter; deviation of the latency from an ideal value [31], [9]. Moreover, QoS performance measures are sensitive to other factors that include bandwidth, packet drop rate, traffic behavior burstiness, etc.

IP over Ethernet QoS can be supported by two approaches. The first one is based on providing ample bandwidth and or minimizing number of application traffic running on the network and know as Best Effort (BE) QoS. The second is based on Priority based Scheduling switching capability QoS.

As discussed in [9], [10], and [64], BE QoS network strategy is based on maintaining a balance of high speed links vs. medium to low link utilization. Moreover, BE handles different applications by allocating bandwidth based on a weighted average of their traffic size. So, an application with large traffic demand will acquire more bandwidth than a lower one as shown in Figure 2.8.

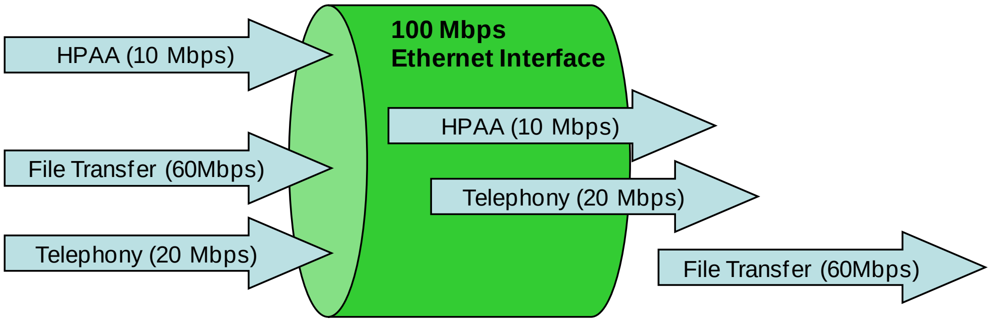


Figure 2.8 IP over Ethernet Best Effort Data Transfer

BE QoS different than Priority based Scheduling QoS. In the later, each application is assigned a unique priority indicator that governs how the application is treated throughout the network as shown in Table 2.3 [1]. Voice is given highest service priority then followed by video and then other critical applications. While this priority format works very well for Enterprise applications, this model does not serve HPAA PCS systems. Hence, in this research, we will adopt a modified version as shown in Table 2.4 to address the gap in needed network priority level relating to HPAA.

Table 2.3 IEEE 802.1p Recommended Standard Priority for Service Types

Standard IEEE 802.1P	
Priority Level	**Traffic Type**
1 (Lowest)	Background
0	Best Effort
2	Excellent Effort
3	Critical Applications
4	Video
5	Voice
6	Internetwork Control
7 (Highest)	Network Control

The modified implementation of IEEE802.1p as shown in Table 2.4 should address assigning a higher priority for the HPAA PCS application without altering the protocol layers. This is very important as this step ensures the adaptability of standard Ethernet for HPAA PCS systems.

Table 2.4 IEEE 802.1p Adopted Standard Priority for Service Types

Modified Implementation for Standard IEEE 802.1P	
Priority Level	**Traffic Type**
1 (Lowest)	Background
0	Best Effort
2	Excellent Effort
3	Video
4	Voice
5	HPPA PCS
6	Internetwork Control
7 (Highest)	Network Control

As a result of implementing the HPAA PCS in the form defined in Table 2.4, the HPAA PCS applications will be processed faster than the other lower priority applications as shown in Figure 2.9.

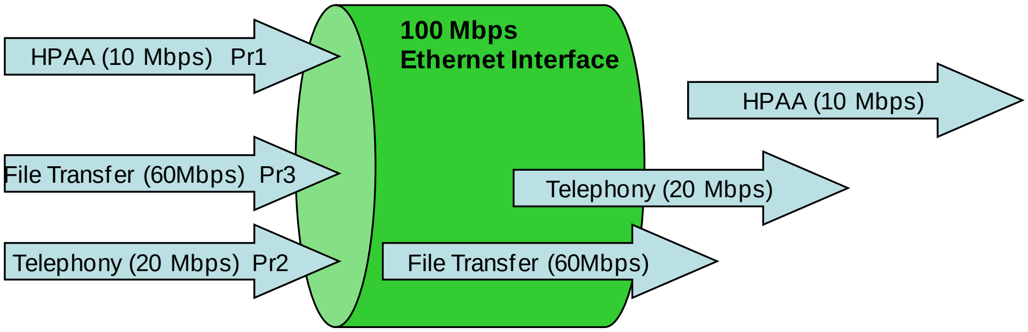


Figure 2.9 IP over Ethernet Priority Based Scheduling Data Transfer

In this research, QoS will be utilized in the simulation network model, development of the PCS Controller node, and HPAA application's parameters. Both Best Effort utilizing high speed links and Priority based Scheduling QoS parameters will be considered. The target CIP network model is depicted in Figure 2.9.

2.5 SUMMARY

As discussed in the earlier sections of this chapter, HPAA PCS networking has evolved over the past many years. The common practice is to utilize a dedicated and standalone network for each process automation segment within an oil and gas facility (plant, refinery, pipeline, etc). Application integration has been hampered by the different layers, interfaces, and silos. The development in processing power and standard interfaces at the controller, instrumentation, and network layers creates an opportunity to assess the potential for utilizing standard Ethernet network as communication channel for end-to-end LAN/WAN HPAA PCS in a CIP network model.

The conventional HPAA process Controller (CNT) and network nodes offered simple interfaces and limited data scanning capabilities, and minimal embedded intelligences as compared with the latest development trends. So, understanding the evolved behavior of the process Controller (CNT) will help in exploring the feasibility of utilizing CIP network for PCS system. In this research, simulation and empirical test validation that will be covered in subsequent chapters are designed based on this premise and understanding.

First, the CNT process time is typically constant since it is predominately governed by the controller CPU. Therefore, the network delay is independent of the CNT process time and mainly impacted by the CNT wait time (i.e., Request/Response time period). The wait time can be variable since it depends on the nature of the CNT messaging (Cyclic and Acyclic) and network protocol. The one (1) second cyclic time allocated for the CNT request and response messages should account for most of the CNT peak frequent traffic. Traffic that is captured below the one second is considered chatter and of no residual value to the HPAA PCS. Moreover, traffic above one second period may result in missing important performance data that may occur during the second. This finding is discussed further in Chapter 3, research design.

In addition, Process controller has now evolved from process bus and local area network (LAN) technologies such as Token ring, Profibus, Modbus, LonWorks, to standard Ethernet utilizing TCP/IP to carry these process control protocols. So, network delay is impacted by the outgoing port queue depth depending on the traffic mix. Moreover, message size and scan rates are key parameters impacting the overall network delay.

The CNT message relationship is transforming from the conventional Master/Slave to Peer-to-Peer (P2P) relationships. This change in role playing requires uniform network resources to support traffic distribution throughout the whole network. It is no longer where controllers send their traffic based on a predefined time slot to a master controller. Controllers can establish multiple sessions with a centralized master controller and with other controllers depending on the PCS logic and process flow.

The network links connecting the CNT’s can be digital transmission, optical fiber, and or wireless. The review has shown fiber optics links are the most ideal network connectivity in the industrial domain. This is due to its resiliency against electromagnetic interference, connecting long haul links, and providing necessary bandwidth.

Wide Area Network based on Gigabit Switch Ethernet, (IEEE 802.3z) [1], is a great opportunity to provide required network connectivity between different PCS systems. The Ethernet technology is fast, reliable, and provides the necessary bandwidth. Wireless network connectivity for dispersed and/or remote sites present an alternative option as discussed [3], [5], and [46]. In this effort, the authors discussed the cost effectiveness of wireless as compared to trenching and securing right-of way. Moreover, the authors highlighted wireless inherent signal quality issues, bandwidth capacity inverse relation with distance, and frequency licensing regulation restrictions.

The variance in timeliness can be defined in the range of 40ms <Td< 200s for HPAA from the HPAA application survey that was completed in Table 2.2. Performance of this application as part of LAN and WAN network cross traffic will be mainly impacted by available bandwidth, QoS settings, application specific traffic behavior. Bursty cross traffic has an adverse effect on the stability of the distributed process control even when the average utilization is low. This was confirmed by experiment on 10/100/1000Mbps Ethernet network types. So, this creates a major challenge while we try to explore the CIP for both HPAA and non-HPAA applications.

The standards (IEEE, ISA, and IEC) and their comparative analysis show no reference to converge IP network for PCS in general and HPAA in specific. These different standards highlight the reliability, availability, and timeliness required for PCS in general. Industrial networking utilizing Ethernet may be adopted based on altering the data link layer or IP layers. Thus, is considered unfavorable proposal due to the solution being proprietary making integration complex and at a higher cost for support. However, utilizing standard Ethernet for PCS in general is now emerging in a form of dedicated network. The proposition of utilizing converged IP network was not considered for PCS or HPAA PCS. So, introducing this concept is considered a pioneer approach. Moreover, utilizing IP over Ethernet network for PCS application in an integrated form utilizing Wide Area Network is also considered a new concept. The application characterization for both HPAA and non-HPAA were identified and will be part of both the simulation and the empirical study. Moreover, QoS will be examined for both LAN and WAN.

QoS is a large field to consider, so the primary focus will be on both Best Effort utilizing high speed links and Priority based Scheduling based on IP over Ethernet.

In this research, the target CIP network model shall be supported by an algorithm that will facilitate connecting both HPAA and non-HPAA locally and in geographically dispersed operation. This would lead to a network model that support HPAA PCS plant virtualization. The network model is discussed in detailed in Chapter 3.

CHAPTER 3 RESEARCH DESIGN

3.1 OVERVIEW

This chapter discusses the research design adopted for this research. The research design is based on utilizing simulation, experimental derived data, and provides a comparative analysis between the two. The simulation is based on utilizing OPNET network modeling tool for HPAA PCS LAN/WAN network models; where different network scenarios and traffic configurations are examined. Two different network models will be simulated: Dedicated HPAA PCS, Converged IP (CIP) HPAA PCS. The simulated CIP network models will be exposed to traffic loading of 50%, 80%, and 100%. On the other hand, the experimental work will be collecting empirical data based on test case scenarios for LAN/WAN networks that represent an HPAA PCS environment similar to the simulated network model.

The aim of this research design is to define the HPAA PCS performance in a converged IP network based on two network Quality of Service settings (QoS): Best Effort and Priority Based Scheduling. This CIP network model addresses the concept of utilizing backbone fiber optic links based on Gigabit Ethernet (IEEE 802.3z) as well as wireless point to point link (IEEE 802.11) to remote spur sites that are part of WAN.

3.2 RESEARCH TECHNIQUES FOR IP COMMUNICATION

In the last five to seven years, extensive amount of work has been completed on assessing the Ethernet technology for industrial automation application. There are three basic techniques for evaluating the performance of such networks: Analytical technique modeling, Simulation, Empirical measurements data [65]. These techniques have been applied, with varying degrees of success, to achieve different performance evaluation objectives [65].Analytical technique modeling for evaluating the real-time performance of communication networks have predominantly supported by Network Calculus theory; in particular, this theory has been used for ATM networks [66] in the Internet community, and more recently, for assessing the real-time properties of Ethernet in the context of industrial domain [47], [67], and [68]. Network Calculus was first introduced by Cruz in the seminal papers [69] and [70], and describes a theory for obtaining delay bounds and buffer requirements. Analytical modeling is considered to be the alternative to simulations that will generate the fastest results, but its limitations become evident as the system or protocol to be evaluated becomes larger or more complex. To construct solvable models, in general, a set of simplifications and make assumptions are combined during the process. This might lead to unrealistic outcomes [68], [69], and [70].

By contrast, simulation as an evaluation method is well understood and has been discussed comprehensively in the literature [65]. Simulations may incorporate more details and require fewer assumptions, and should consequently generate more realistic results for larger and complex systems. Hence, when assessing the performance of communication networks, simulation should be one of the chosen evaluation techniques. However, it should be noted that there is a possibility of designer error, with the consequence that the problematic operational scenarios might not be generated during simulations [21], [65].

Experimental (Empirical) measurement data is powerful technique for evaluating performance of industrial IP communication. It has demonstrated its ability to identify and validate network performance models for both LAN and WAN networks [19]. Experimental measurement is less flexible than simulation when the model in question needs to be redefined or augmented [69] and [70]. The configuration requires disciplined effort to ensure consistent and uniform attributes across the different network elements as discussed in [71]. Hence, the need for specialized software tools becomes more in demand as the network model increases in size [71].

This research is based on the use of both simulation and experimental research techniques. The empirical data collected from the experimental model will be used then to validate, the simulation model that re-enforced the CIP network model as a feasible solution. Comparative analysis between simulation and empirical results are used to deduce new findings and establish the form for the CIP network model.

The strategy is to conduct initial experimental tests to define parameters that are used in the simulation model. Simulation is then conducted for LAN and WAN HPAA PCS networks followed by experimental testing to validate simulation results and establish relationship between both simulation and experimental results. Finally, comparative analysis between simulation and experimental results will be used to identify the optimized model for CIP network. The test cases for both simulation and experimental are centered on examining three LAN/WAN network models: Dedicated network, CIP network with Best Effort and CIP network with Priority based scheduling QoS settings. The network models are exposed to network loading of 50%, 80%, and 100% to identify HPAA PCS, voice, and media streaming performance. The 50%, 80%, and 100% network utilization thresholds were selected to identify a relationship between the overhead capacity and the network loading that would lead to optimize traffic mix and network resources.

3.3 EXPERIMENTAL CASE STUDY

The empirical data case study is based on two scenarios. One scenario is to establish network performance in LAN and the second is focused on WAN network. The first scenario is used to examine non-HPAA application (i.e., Simple Network Management Protocol-SNMP) and large file transfer co-existence with HPAA on a LAN PCS network. The second empirical case study is HPAA and non-HPAA in converged WAN IP network.

3.3.1 HPAA & Non-HPAA Co-Existence in Local Area Networks (LANs)

Hydrocarbon Process Automation Applications (HPAA) utilizes real-time network connecting process instrumentations, controllers, and real-time logic control applications. Conventional practice is to dedicate a real-time network for process automation applications and prevent other applications from utilizing the same infrastructure. An important non-HPAA application that can help optimize, improve network performance, and provide rapid response time in network diagnostics and mitigation is Simple Network Management Protocol (SNMP). The impacts of activating this non-HPAA protocol with the real-time HPAA utilizing high speed Ethernet network design will be examined in this case study. Moreover, network loading by activating large file transfer will be used to assess the performance of network at high utilization. Empirical data for an implemented Hydrocarbon process automation system will be used to illustrate the interdependency of application performance, traffic mix, and potential areas of improvements. The sub section that follows covers the network connectivity, test tools, and test cases approach.

3.3.1.1 Network Connectivity

The network for the first case study is composed of primary and backup switch Ethernet network running concurrently. The switches are based on Cisco Gigabit Ethernet technology. This is to ensure ample bandwidth capacity exist so to secure HPAA application is not impacted. The network is used to connect process controllers, Human Machine Interfaces, and field instruments. Digital performance data is collected by the field instruments and sent to the process automation controllers. The controllers evaluate the collected data and based on an embedded logic control loop, decisions are either made and executed back to the instrument or sent to the master control station for further automated analysis and decision tree making. The outcomes are sent back to the impacted controllers and instruments based on predefined cycles or on demand.

The network topology is based on fully redundant Gigabit Ethernet network; star/tree architecture. Several branches (domains) utilizing Layer 2 Gigabit Ethernet switches are connected to one redundant Layer 3 switch. Each domain (branch) has several switches with a maximum of nine (9), but in reality can be more than 9 switches as this is governed by the process control type, coverage area, and number of controllers served by each domain, Figure 3.1. The Gigabit Ethernet network is configured based on best effort (i.e., QoS features were not activated). The network is exclusively dedicated to HPAA applications. Hence, there is no Web, FTP, or multimedia traffic. A total of 65 PCS controllers and close 10,000 input and out instrumentation, Table 3.1, were utilizing this network.

The bandwidth utilization, CPU utilization, and packet error rate are key indicators used to assess the impacts of running live SNMP traffic within a process automation network. In addition, these parameters will be utilized to measure the performance of the network when traffic load is increased by a traffic generator to a certain threshold. The target is to keep the Gigabit Ethernet Network at 50% utilizations (500 Mbps overhead capacity) to absorb traffic bursts.

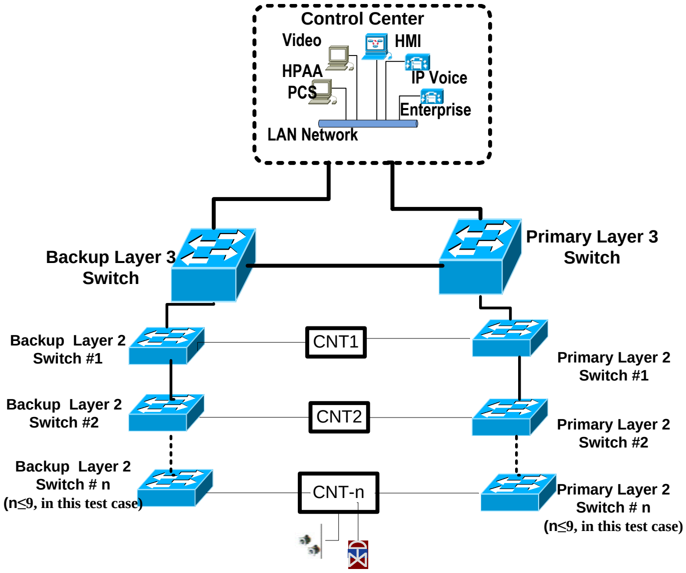
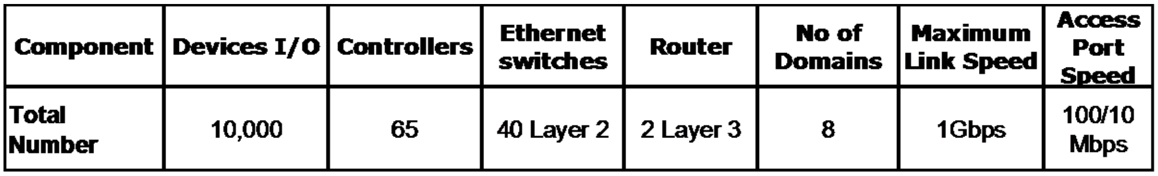


Figure 3.1 Network Architecture for One (1) Domain

Table 3.1 Traffic Source Profile



Component	Devices I/O	Controllers	Ethernet switches	Router	No of Domains	Maximum Link Speed	Access Port Speed
Total Number	10,000	65	40 Layer 2	2 Layer 3	8	1Gbps	100/10 Mbps

Traffic monitoring system is based on SNMP utilizing Cisco Works as defined in Cisco (1992-2008) since the switches that part of the test network are Cisco [71]. SNMP agent is used to collect performance data (packet loss, utilization, etc.) from the Layer 2 switches and the Layer 3 switch. Collected SNMP data is sent to a master station and in this scenario, IPref Traffic generator tool, as defined in IPerf (2008) [72], was used to inject traffic (TCP and UDP) at key points in the network topology. The tool is based on a client-server environment and has the ability to generate a traffic load and measure performance concurrently. SNMP maximum message size is 1,500 bytes with a minimum of 484 bytes. In [56], the authors discussed how to perform large-scale SNMP traffic measurements and traces to develop a better understanding of how SNMP is used in production networks. The research illustrates SNMP traces that include GetBulk requests containing larger response messages. Although most, if not all, GetBulk response sizes could be observed, no response message was larger than roughly 1400 bytes. This implies no fragmentation and confirms a minor SNMP traffic load was added to the production network. SNMP's request and response polling cycle directly govern the traffic addition. Poll cycle of 30 seconds is adequate for acquiring performance data in most implementations. In our study case, the polling cycle is a bit more granular: every 5 seconds.

The traffic collection methodology in our study case is based on SNMP agents running in all the different switches (Layer 2 and Layer 3). We decided to monitor the largest domain (nine Layer 2 switches daisy chained to a Layer 3 switch). The first Layer 2 switch connected to the Layer 3 switch has the aggregate traffic of all the subtending switches sending traffic to the Layer 3 switch, where the Controller Host Server is connected. The Layer 3 switch is connected to all the different domains. Hence, monitoring this switch provides performance data on each domain’s trunk connected to the Layer 3 switch, and overall switch performance.

3.3.1.2 Test Cases

Several systematic test cases were conducted to illustrate impacts on the process automation network while SNMP agents are on a predetermined network performance; polling cycle of 5 seconds. The primary focus during all of these different test cases is to monitor the densest domain as mentioned in Section 3 (i.e., 9 Layer 2 switches daisy chained to the Layer 3 switch). The busiest switch is anticipated to be the Layer 3 switch connecting all the domains to the Controller Host Server. Trunk utilization, CPU, packet discarded and packet errors were the key indicators for overall performance of the process automation network and SNMP. In addition, HPAA performance, including delay and accessibility to the instrumentation and controllers, comprised the second set of data validating the impacts.

Test Case 1: Steady State Operation of PCS and SNMP Traffic

The first test case is based on HPAA PCS running in a steady state operation and then SNMP is activated. All different instrumentations, controllers and host servers were collecting data, validating their integrity; running logic loops and decisions are made back to other upstream and or downstream controller to regulate the actual process. The primary focus will be on the Layer 3 and Layer 2 switches in question to analyze the performance of their CPU and memory utilization. Moreover, the HPAA PCS traffic performance will be monitored. The expectation is upon activating SNMP traffic along with HPAA steady state operation, an increase in the CPU and memory utilization shall be observed. Moreover, HPAA PCS application performance shall not be impacted.

Test Case 2: Steady State Operation Test Case with Alarm Flooding

The second test case is based on PCS network running in a steady state operation, SNMP is active (i.e., Test Case 1) and invoking massive alarms by a sudden multi-controller failure. The intent is to examine and identify peak HPAA traffic burst and broadcast. The expectation is HPAA PCS traffic will be impacted. Packet lost shall be observed due to traffic peakedness.

Test Case 3: Superimpose Steady State Operation with Traffic Injector

The third test case is based on process automation network running in a steady state operation; SNMP is active (i.e., Test Case 1) and utilizing traffic generator tool, as defined in IPerf (2008). This traffic generator tool is used to inject traffic (TCP and UDP) traffic at selected points in the network topology. The tool is based on client server environment so multi-client (traffic injection source) can be utilized to send traffic to a server connected to the densest domain. The traffic loading increased from 0 to 30% then to 50%, and 80%. The expectation is HPAA PCS traffic will be impacted. Packet lost may be observed due to traffic peakedness and shall be higher than Test Case 2.

Test Case 4: Network Delay During Varying Traffic Loading

The fourth test case is based on varying the traffic load systematically from steady state operation to 50% then to 80% and finally to 100%. The traffic injection source was at the farthest switch and controller in the domain. The traffic sink was placed at the Layer 3 switch supporting the Master controller. While the test is progressing, selected functions such as changing set point, and controlling a valve position were initiated. The focus of this test is on the network delay as well as HPAA PCS application impacts.

3.3.2 Hydrocarbon Process Automation Application Converged IP Wide Area Networks (WANs)

The second case study addresses a high speed Gigabit per second (Gbps) Ethernet, WAN for HPAA PCS applications in a CIP network environment. Empirical data for an implemented Hydrocarbon process automation system will be used to illustrate the interdependency of PCS application performance, traffic mix, network loading, and network recovery. The self healing Gbps ring network topology capabilities are examined. The case study design includes ring network topology, network elements, HPAA PCS applications, and support services such as IP Telephony and Video Streaming. Consistencies in these different elements play a key role in the case study analysis and results.

3.3.2.1 Network Connectivity

There are three different network configuration topologies utilized in Ethernet implementation which include bus, star, and ring. Combination of these configurations can make up hybrid implementations to meet different design criteria. Each topology provides different performance and disadvantage. This case study is based on a ring topology, Figure 3.2, as it is a common network implementation approach [9] and [10]. The network is based on two layered rings; multiple Access Rings connected to one Backbone Ring. All the switches, within one ring, are connected with each other via a single high speed fiber link. Access and backbone rings are 1 Gbps and 10 Gbps accordingly. This configuration provides ample bandwidth, self healing recovery, and cost effectiveness in fiber link and ports requirements. However, data need to circulate the ring for the switch that is farthest from the primary terminating switch, thus resulting in additional delay that shall be considered when defining the HPAA PCS application expected performance (delay, jitter). This additional delay though is very small, 12 µs for 1 Gbps switch and 1.2 µs for 10 Gbps.

The Gigabit Ethernet network is configured based on two scenarios: Best Effort and Priority based Scheduling. The priority based scheduling is on assigning highest priority to HPAA PCS application, followed by voice, and then video. The bandwidth utilization, delay, jitters, packet loss, and network recovery are key indicators used to assess the impacts of running both video streaming and voice with HPAA PCS application. The target is to stress test the Gigabit Ethernet network at 50%, 80%, and 100% utilizations.

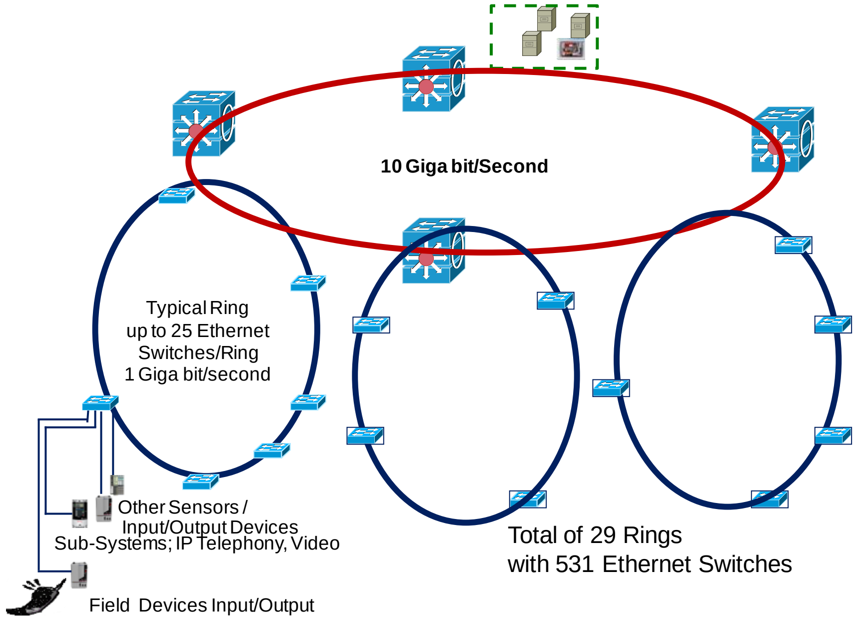


Figure 3.2 Test Case # 2 Network Topology

The network switches are based on standard IEEE Ethernet protocols [7]. This included IEEE 820.3, Ethernet, IEEE 802.3x, Full-Duplex operation, IEEE 802.1 P, Priority Queuing, IEEE 8021 Q Virtual LAN (VLAN) capabilities and IEEE 802.1W Rapid Spanning Tree**.**In addition, a data concentrator connected to each access switch collects real time data from different instrumentation and sensors (pressure, temperature, flow, etc.). The data concentrator also has the capability to control (start/shutdown, adjust flow, etc.). IP telephony is installed at each of the access switches for voice applications.

Some of the access switches are also serving process control subsystems such as subsurface Permanent Downhole Systems (PDHS), Electric Submersible Pump (ESP), and Multiphase Flow Meters (MFM) capturing data and providing other support functionalities that make an intelligent field. Closed Circuits Television Video streaming cameras are utilized at some of the access switches for monitoring. Each application is supported by its dedicated host located at Centralized Control Room (CCR).

Digital performance data is collected by the field instruments and sent to the process automation controllers. The controllers evaluate the collected data and based on an embedded logic control loop, decisions are either made and executed back to the instrument or sent to the master control station at the CCR for further automated analysis and decision tree making. The outcomes are sent back to the impacted controllers and their subtending instruments.

3.3.2.2 Test Case Tools

Traffic for different applications and performance data for each network component was captured by a centralized Simple Network Management Systems (SNMPc 7.1), which has the advantage of pulling together large numbers of remote users and multiple events[71]. To generate the data source and traffic mix, the software tool IPref 2008 was used. This tool increased the network traffic load, utilizing its feature capabilities of client servers and ability to support both UDP and TCP traffic types. The LAN Fault Timing Analyzer (FTA) software measurement, GarrettCom™ [73] — due to its capability of multi-thread sessions in milliseconds — was used to measure fault recovery times in self-healing Ethernet networks. Delay was measured by the automatic PING command.

All the test cases had consistent settings for both the tools and the network elements to enable performance benchmark. These incorporated test cases are developed to examine the WAN CIP network performance. These test cases were developed and executed in consistent manner.

3.3.2.3 Experimental Test Cases

Test Case 1: Steady State Operation

The very first step was to identify the baseline traffic for PCS, multimedia (video and voice) traffic for the access rings and backbone rings. Moreover, application performance such as increasing poll cycle, remote control and startup operation were tested. Maximum allowable video traffic by the server was also activated. Video functions of Pan Zoom Tilt (PZT) were also activated. The expectation is to have minimum traffic load on the Gbps network. Moreover, all the intended tested functionality shall pass the test since there is no traffic burstiness under normal traffic load.

Test Case 2: Traffic Load Stress Testing by Superimposing Steady State Traffic Load with UDP & TCP Traffic Injector

This test case is based on process automation network running in a steady state operation, multimedia traffic is in progress (i.e., Test Case 1) and utilizing traffic generator tool, as defined in IPerf (2008). The traffic generator tool is used in two scenarios where one is based on injecting TCP traffic and the second is UDP at selected points in the network topology. A total of two computers with 1 Gbps Ethernet interfaces forming client/server relation were used to generate the anticipated traffic load, with close to 1 Gbps at the access. For backbone, ten computers with 1 Gbps Ethernet interface were used to load the backbone ring.

Test Case 3: Networking Cross Traffic Jitter

The source of jitter in a wide area network is typically induced by network traffic and protocol. The network traffic, specifically cross network traffic, can cause congestions resulting in unnecessary delay and jitter. Two parameters were focused on during this test: overall network and an application specific delay and jitter. The overall network jitter was determined by identification of the standard deviation for the overall network delay. In this test case, we make use of Test Case 2, increase traffic load for access and backbone rings and monitor the jitter. The jitter is reported by the performance networking tool and is shown as a function of time driven by the experienced traffic loading.

Test Case 4:Network Reliability & Application Performance

In this test case, both link/node failures were tested for both access and backbone rings. The primary focus was on link recovery time and Quality of Application Connection (QoAC). The QoAC is a measure of time the application completely loses the network connection with the field process instrumentation due to the ring recovery (i.e., network re-convergence) process. The observed time delay is a function of the number of switches and routing protocol that was selected. In this case, Open Shortest Path Forwarding protocol is used as a common Link-State algorithm implementation in a wide area network [9] and [10].The expectation is there will be some time delay before the HPAA PCS is revived in the backup link.

3.3.3 IP Telephony & Media Streaming Application Performance IN Co-Existence With HPAA PCS

IP telephony and media streaming (closed-circuit television) performance are examined in a converged IP network where network also supporting HPAA PCS applications. IP telephony and media streaming are supported by a dedicated server. IP Telephony uses UDP/IP protocol, and this test case involves all the IP phones, 500 phones, which are served concurrently. The voice call is based on ITU G.711 compression standard; 64 kbps voice channel as defined in [49].

In the other hand, media streaming uses TCP/IP protocol and the maximum number of concurrent cameras that can be pulled simultaneously is nine cameras. The media streaming is based on MPEG 4 standards [51]. The key performance indicators to track, in this test case, are delay and jitter. The expectation is there will be some time delay and jitter encountered, in the IP telephony and media streaming, upon loading the network.

3.4 NETWORK SIMULATION-OPNET

As discussed in [22], [65], and [74], the limitations of analytical modeling become more apparent as the network under evaluation grows larger and more complex. Model simplifications and assumptions are used to establish solvable analytical models. This might lead to unrealistic results in estimating latency, jitter, and traffic mix behavior that are too pessimistic. Hence, simulations were used for analyzing the HPAA PCS controller converged IP network [65] and [75]. Network simulation provided the needed flexibility for addressing network complexity, variable data sources and sinks, and different traffic flow types. This method aids in assessing the PCS controller behavior and determining the optimal hydrocarbon process automation communication real-time converged network. OPNET [76] is selected to support the intended simulation objectives and define the factors impacting the real time network in this research.

In this research, two primary questions will be addressed. These questions are: can HPAA PCS Controller application co-exist with other services utilizing shared standard Ethernet network based on Best Effort Converged IP network? How does Quality of Service impact such an operational network environment when network loading is increase from dedicated network to 50%, 80% and 100% loading? Time delay, jitter packet delivery, and HPAA application performance dependency on the network will be examined as part of answering these questions. Moreover, support services such as IP telephony and CCTV application performance conformance will be an integral part of this effort. The outcome of this effort shall lead to identify the most optimal network model for PCS Converged IP network in both LAN and WAN network implementations.

3.4.1 Driver for utilizing OPNET

OPNET [76] is network simulation and analysis application software tool used to build different virtual networks and simulated 'what if?' network scenarios. It provides flexibility and reduces cost in building virtual networks; prior to invoking changes in a real-time production network. Most important, the tool supports different network topologies, protocols, and communication nodes configuration. The key advantages of OPNET, besides simulating a network environment, are its capabilities for supporting comparative analysis by running different 'what if' scenarios and comparing the outcomes [76] and [77].

OPNET simulation has a tracking record of usage in both academia and industry. It has flexible and easy to use Graphical User Interface that enables user-built network components. Moreover, the tool has a rich library of nodes, links, end devices, and protocols that can be selected and netted to form the topology of choice that is easy to understand and depict the intended simulated network [76] and [77].OPNET can simulate different communication channel substrates and represent the network into a visual map for users to further study and assess. The simulation tool produces tables, graphics, and a lot of statistics that enable users to assess the impacts and produce usable results. One very important aspect of this tool is the ability to build one’s own network node, links, and traffic source and sink properties, create custom applications to present the behaviour of non supported applications. These capabilities were used in this research in building a Process Automation Controller in OPNET and the Process Control System (PCS) Custom Application.

3.4.2 Process Control System (PCS) Controller Behavior Simulation

The HPAA PCS Controller behavior is designed and developed based on:

1. TCP/IP was elected for the HPAA PCS Controller Application since it provides higher level of reliability than a UDP without comprising the anticipated tolerable network delay requirements as defined previously in Table3.1. Moreover, standards (Modbus, DNP3, and FF) for PCS protocols are mainly based on TCP. The UPD/IP as a real time protocol is able to meet the time requirements, but the end controller and network must be high-performance [21] CPU otherwise the anticipated controller behavior and application will be poor.
2. The PCS controller application was allotted 800 ms processing time within the Controller CPU.
3. The HPAA PCS will co-exist with non-HPAA non-critical traffic.
4. The criterion for success:
    - End-to-end network response time of better than 1 ms; jitter in the order of 0.001 ms Table 2.2.
    - End-to-end PCS controller response time of better than 40 ms, Table 2.2.
    - The simulation environment and associated modeling of the controller and support services are defined in sufficient details to allow full reflection of the complex setup or the different “what if scenario”
    - IP telephony response time below 150 ms; network delay below 80 ms
    - Media streaming response time below 250 ms, network delay below 200 ms.

3.4.3 Application Characterization

As a preliminary to discussion, the HPAA PCS Controller behavior is governed by the nature of the industrial device traffic pattern. Normally, it consists of periodic data with temporal constraints, typically, sampling data being subscribed by controller nodes. The second type is aperiodic data and message (e.g., a controller sending trip commands to actuators) is considered time-critical [2], [3], and [23]. In addition, there might be other aperiodic data sources, such as file transfer, that result in a “bursty” traffic pattern on automation networks [3] and [23]. One of the key characteristics of PCS controller behavior is response time (acceptable time delay). Hydrocarbon Process Automation Applications (HPAA) and support services endure different time delay requirements. Hence, a survey of the most critical application was completed. These application spans from the energy electrical sources (power) feeding the HPAA process, rotating equipment (compressor and pumps), liquid and gas pipelines pressure, furnace temperature, petrochemical gas and oil separation vessels, drum level safety systems, and more. These applications’ delay behavior was identified during the literature review phase of this research and was reflected previously in Table 2.2. In this research, we are defining the time delay requirements into four categories as defined in Table 3.2.

Table 3.2 HPAA Time Delay Applications Categorization

Timeliness Tolerance	**Time Delay Band**
Highly Demanded	$D \leq 50$ ms
Moderately Demanded	50 ms $< D < 500$ ms
Low Demanded	500 ms $\leq D < 1000$ ms
Very Low Demanded	$D \geq 1000$ ms

3.4.4 OPNET Simulation Set Up

The network element attributes were configured based on the following criteria. These criteria were developed based on literature review and research objectives.

3.4.4.1 General

1. PCS Controllers were simulated using predefined “Ethernet Advanced Server” object. This is to discount for any delay in the processing server and most importantly to generate discrete events that the server resources (i.e., CPU, Random Access Memory) can support. An important configuration parameter is the IP processing rate as this has direct impact on the application to application response time. This parameter is set to a default value of 500,000 packets per second. The CPU speed is 333 MHz.
2. The network elements are connected via error-free point to point communication links.
3. Most of the simulated application layers in OPNET emphasize the client-server or request-response relationship.
4. The simulated traffic arrival rate is based on the maximum constant uniform distribution rate to subject the network and applications to a maximum traffic load that the network can process. As a result, traffic peakedness and bursts were addressed by 100% traffic utilization network model.
5. Default profile setting for support services (i.e., IP telephony, Video streaming, and FTP traffic injection) were utilized with the exception of the following parameters:
    a. Video stream frame size was altered to mimic MPEG4 with an average of 1,000 Bytes/second video streaming (i.e., 8 Mbps).
    b. IP telephony IP Strict priority were moved from default value 7, highest, down to 6 as the only application that was in 7th priority was the PCS controller.

c. Video streaming IP strict priority was moved to a higher priority from Best Effort to priority 6th. The intent is to provide high quality for the support services in a converged IP network but not on the expense of the PCS controller performance.
d. Finally, traffic injection, File Transfer Protocol, was given the lowest priority since the primary goal of this service is to load the backbone network. However, the FTP application was modeled based on discrete events traffic rather than background traffic to expose the network to the maximum effective network loading in the different what if scenarios.

3.4.4.2 Local Area Network Simulation Environment

The primary focus of the PCS simulation is to analyze the PCS application behavior in a Local Area Network based on a uniform PCS Controller network with predefined boundaries. Moreover, support services such as voice and video streaming were considered.
In the simulation model, the following assumptions were made:

1. Simulation is conducted based on allocating 100 Mbps Local Area Network from the 1000 Mbps (Giga Ethernet network). A 100% Giga Ethernet links will require more traffic resources and calculations that the simulation tool cannot support effectively from a CPU and memory resources perspective. This is based on the findings that we were able to reach in the simulation phase of this research. We tried to simulate 1 Gbps switches and trunks since OPNET is a discrete event simulator and loading the links with real traffic forces OPNET to generate very large number of packets that has resulted in generating very high number of events that consumed the available memory which resulted in simulator time-outs (crashes). So, another alternative was considered is use background traffic that will make OPENT account for this delay analytically without generating the real packets. This solution has two problems; the first is calculated delay and jitter is

approximated and more importantly the background traffic has no effect on the QoS scheduling algorithm since these packets are not created.

2. The network is defined as a two different domains exchanging different traffic mix, Figure 3.1, since the maximum PCS control message inter-domain hops is one (1) domain [39]. In reality, there may be several domains but two domains were selected to optimize simulation time and simulator CPU limitation.
3. There are 10 switches in each domain. A domain can be greater than 10 switches, however, each domain was selected with 10 switches to simplify the network design and optimize the simulation time.
4. Each PCS controller is connected to one switch.
5. The PCS controller is communicating to the MSC and to their designated peer(s), if any.
6. The MSC is communicating to all subtending controllers in both domains concurrently.
7. Simulation is conducted for a network based on two scenarios, Figure 3.2 and Figure 3.3. These are: dedicated network and the second is shared converged IP network with Priority based Scheduling QoS and Best Effort QoS.

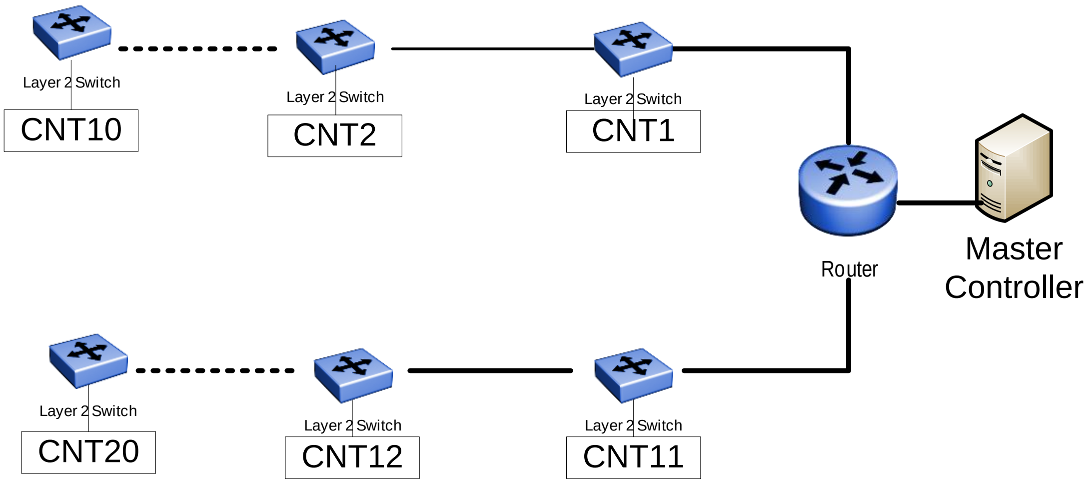


Figure 3.3 Dedicated Process Control Network Simulation Model for Two Domains

8. PCS P2P was established more than the controller but the focus is the farthest from the MSC (i.e., Controller 10 and Controller 20).
9. Voice and video services were simulated where voice given higher priority than video but lower priority than PCS. The injected traffic for loading the network, FTP, was given the lowest priority.
10. The second simulation scenario (i.e., Best Effort) is conducted based on Best Effort application and network performance settings.
11. Injected traffic was increased systematically with a 50%, 80% and 100% utilization to indentify the performance relationships between the traffic load and the PCS and other support applications.

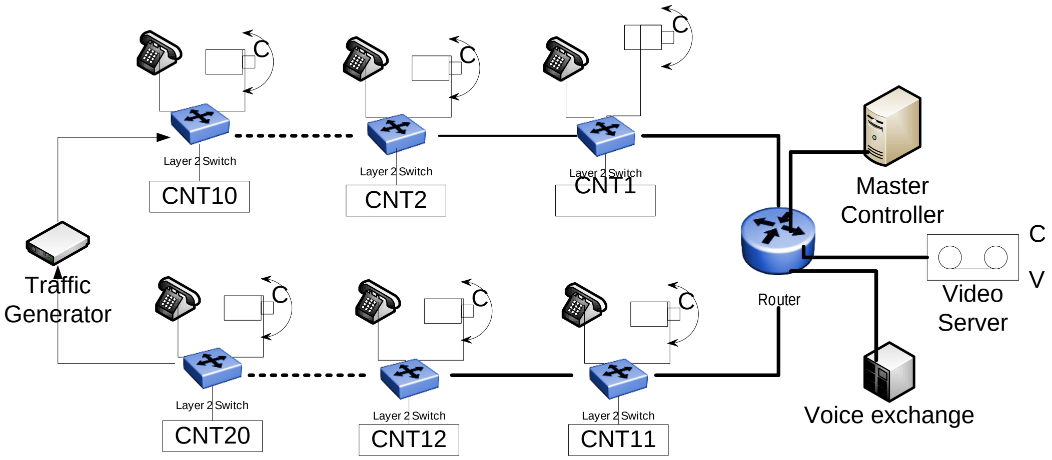


Figure 3.4 Converged IP Process Control Network Simulation Model for Two Domains

12. A cross traffic time delay industrial survey was used to correlate the simulation outcomes to actual application requirements. The survey completed based on [2], [3], [4], [29], and [36]and was summarized in Table 2.2.

    - The message size for the Request (Req) is defined as 1024 bytes and Response (Res) as 1024 bytes. [IEEE802.3]

- The processing speed of network nodes is very fast and the processing delay can be neglected. This is a valid assumption because today's network entities have high backplane CPU capacities in the order of 100 Gbps or higher.
- However, the controller processing wait time was defined to be 800 milliseconds. Hence, a total of 1.6 seconds are allocated for a request/response processing time and the difference in the round trip delay is contributed by the network. Figure 3.5 depicted the data flow time allocation for a 10 second cycle. The first 2 second time allocation is repeated for the remaining requests (Req)/Responses (Resp).

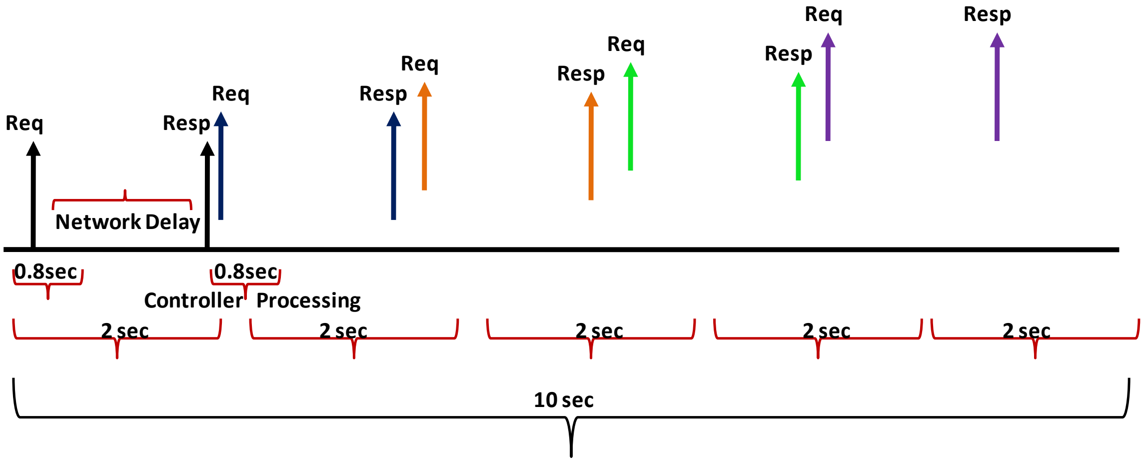


Figure 3.5 Application Request/Response Time Allocation for a Cycle of 10 Seconds

- The Master controller (MC) is controlling each of the subtending controllers based on an application that runs continuously with a cycle poll of 1 second as defined in Table 3.3. The MC in table 3.3 signify the Master Controller and CNTn where n= 1, 2, 3, 10 defines the physical relation to MC; where 1 is nearest to MC; 10 is farthest from MC.
- Selected controllers were designated with a function of P2P control based on an application that runs continuously with a cycle poll of 1 second as defined in table 3.3 (i.e., CNT10 has P2P relationship to CNT20).

Table 3.3 Controller Peering Relationship

Master Controller	**MC (Master Controller)**	**MC (Master Controller)**	**CNT1**	**CNT2**	**CNT2**	**CNT6**	**CNT10**
Remote Controller	CNT1 thru CNT10	CNT11 thru CNT20	CNT2	CNT3	CNT6	CNT10	CNT20
Relationship	1st Domain	2nd Domain	P2P	P2P	P2P	P2P	P2P

3.4.4.3 Wide Area Network Simulation Environment

Similar to the Local Area Network Simulation environment Section 4.2.3.3, time delay, jitter, packet error are key performance indicators that tracked in the different simulated scenario in a Wide Area Network (WAN). In the simulation model, the following assumptions were made:

- Simulation assumptions listed in Section 4.2.3.2, Local Area Network, were maintained in what is known Process Control System Area (PCS) defined in five different locations: PCS Area 1, PCS Area 2, PCS Area 3 (Defined as PCS Virtual Center), PCS Area 4, and PCS Area 5, Figure 3.6.

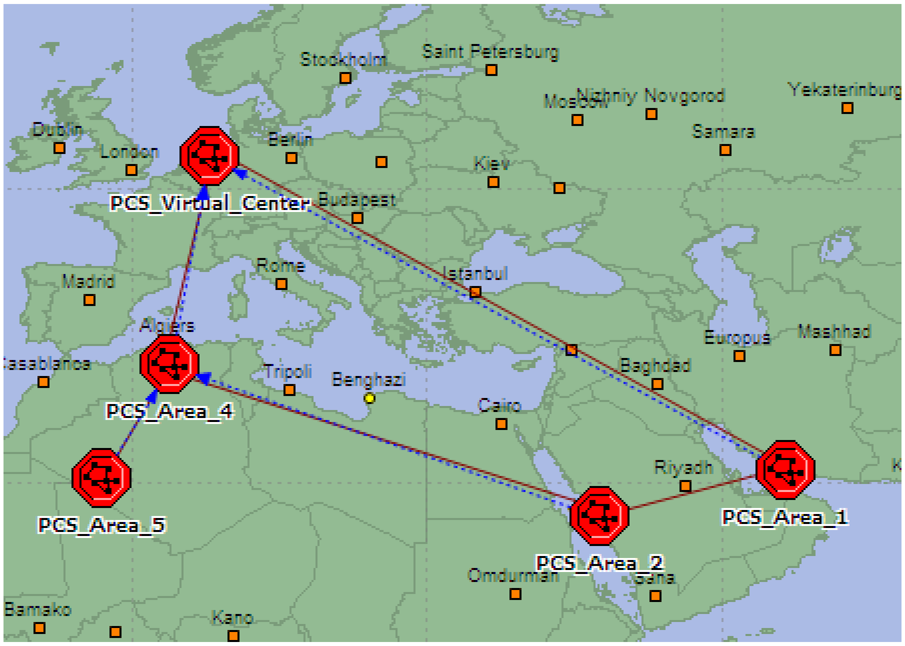


Figure 3.6 HPAA PCS Wide Area Network

- The LAN network was reduced to one switch with one controller along with support services (Video Streaming, IP telephony) to minimize the simulation impact on the simulator CPU and memory as the primary target is to assess the performance of these elements in a WAN.

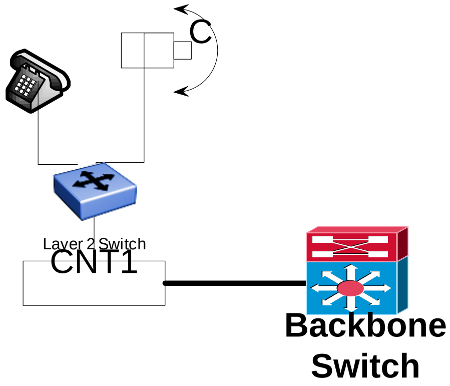


Figure 3.7 HPAA PCS Backbone Node-LAN Network

- The backbone network is based on high speed 1 Gbps Ethernet links connecting PCS Area 1, PCS Area 2, PCS Area 3 (PCS Virtual Center), and PCS Area 4.

PCS Area 5 is a spur; remote facility connected to the backbone network node in PCS Area 4, with a wireless wifi (IEEE) point-to-point link at a speed of 54 Mbps [7] and [46].

- 100% actual service traffic on a Giga Ethernet links will require more traffic resource input and calculations that the simulation tool cannot support effectively. Hence, OPNET Traffic Flow demand feature function to establish IP traffic flow injection was used in all test cases. The traffic flow is based on discrete traffic and assigned with the lowest Type of Service class (l) to consume 90% of the available bandwidth.
- The network typically supports several PCS domain areas. However, the traffic load simulation will be limited to PCS Area 1, PCS Area 2, PCS Virtual Center, and PCS Area 5, Table 3.4.
- PCS Area 4 has a backbone node and is only considered as a transitional node (i.e., there is no access traffic for PCS or support services)

Table 3.4 Traffic Source per PCS Area

PCS Area	PCS Traffic	IP Telephony	Video Steaming	PCS P2P
PCS Area 1	CNT 10	IP Tel-1; IP Tel 1-12	CCTV1	MC/CNT10; CNT10/CNT20; CNT10/CNT6
PCS Area 2	CNT20	IP Tel-5	CCTV5	MC/CNT20, CNT10/CNT20;
PCS Area 3 (PCS Virtual Center)	Master Controller (MC)	IP Tel_1-1; IP Tel_1-5; IP Tel_1-10	CCTV_Serv_1; CCTV_Serv_5; CCTV_Serv_10	MC/CNT10, MC/CNT20,
PCS Area 4	None	None	None	None
PCS Area 5	CNT6	IP Tel -10, IP Tel-12	CCTV10	CNT6/CNT10

- The simulation will cover three different simulated scenarios: Dedicated, Best Effort, and QoS enabled Wide Area Networks.
    a. Dedicated network is supporting only HPAA PCS.
    b. Best Effort is where HPAA PCS competes with other application on

utilizing the available bandwidth.

c. Priority based scheduling by assigning Controller highest priority, IP telephony and video streaming were assigned next accordingly.

d. The BE and Priority based Scheduling will be exposed to a network traffic loading of 50%, 80% and 100%.

e. The intended CIP network model for WAN is shown in Figure 3.8 but can be in different network topologies (Ring, Star, Cascaded, or Hybrid network topologies) and this depends on the scale of the implementation as discussed in Chapter 2.

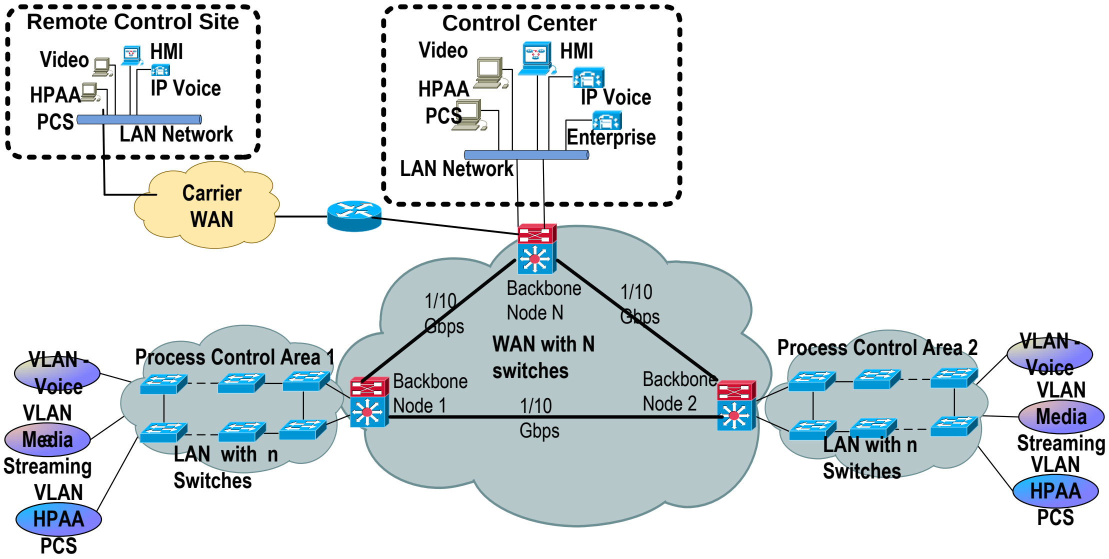


Figure 3.8 CIP Conceptual Network Design

3.3 SUMMARY

In this research, the research design was developed based on triangulation utilizing experimental, simulation, and comparative analysis between the two research methods. The comparative analysis for the simulated scenarios and experimental test cases provides additional findings. In addition, experimental data will be used for validation. Experimental includes two scenarios, HPAA & non-HPAA application co-existence on a PCS LAN. The second is converged IP for HPAA and non-HPAA applications along with support services such as IP telephony and media streaming utilizing WAN network.

OPNET network simulation and analysis application software tool was selected since it has been proven an effective research tool in both academic and industry. It provides flexibility in building virtual networks; supports different network topologies, protocols, and communication nodes configuration. Moreover, the tool has comparative analysis and correlation function when running different 'what if' scenarios to compare and validate outcomes. The OPNET simulation scenarios and experimental test cases assumptions and requirements are defined in this chapter to facilitate the actual model implementation and configuration. The primary focus is on the application and the network performance parameters. This includes delay, jitter, packet delivery, and stability for the CIP network models. The simulation and experimental case study scenarios are configured based on dedicated network, CIP network with BE QoS, and CIP network model with Priority based Scheduling QoS. Each network model will be exposed to a traffic network loading of 50%, 80%, and 100%.

The experimental test cases designed in this chapter will implemented in the next chapter, Chapter 4. The results of the experimental test cases are used to build the initial network models for simulation and to further examine the CIP network model. Moreover, the results are used to validate simulation assumptions and as well in establishing links between simulation and experiment that will define the CIP network form.

In Chapter 5, the simulation test case scenarios are implemented in the OPNET tool. The simulation will be as defined in the research design as outlined in this chapter.

The simulation test case scenarios results are presented in this chapter as well. The results will be used for comparative analysis and to also help in defining the network loading impacts on the proposed CIP network models.

CHAPTER 4 HPAA Converged IP Networks: EXPERIMENTAL CASE STUDY

4.1 OVERVIEW

Converged Internet Protocol (IP) network utilizing standard Ethernet for HPAA, as discussed in detail in Chapter 2, provides an opportunity for network consolidation by minimizing the number of interdependent networks and, most importantly, offering a platform for additional support services such as multimedia streaming, voice, and data. Timeliness and reliability are the fundamental requirements for such a network as the primary goal remains communication between the process control systems. The concept of using a converged IP network for HPAA and non-HPAA was not explored utilizing experimental case study. The performance and characteristics of such a network are not examined. This chapter provides results for two experimental case studies in support of this research. The primary objective of this experimental case study is to obtain the necessary empirical data that will enable to assess measure and evaluate the impact of running HPAA applications over converged IP networks. Two experimental case study scenarios were defined in the research design in Chapter 3. These are: HPAA and non-HPAA co-existence in HPAA LAN network and HPAA, non-HPAA, and support services in converged IP WAN network. The network were designed based on enabling BE and Priority based Scheduling QoS.

An important aspect that was kept in mind during the experimental test case studies design and collected results is to conform to the actual application behavior and delay requirements. Moreover, areas for optimizing the network such as minimizing number of switching nodes and simplifying the network links connectivity, where applicable, were taken into consideration and throughout the implementation of these two case study scenarios.

4.2 EXPERIMENTAL CASE STUDY #1: HPAA AND NON-HPAA CO-EXISTENCE LAN NETWORK

Test cases were designed and conducted to illustrate the impacts of mixing HPAA applications with non-HPAA applications on high speed Gbps as described in Chapter 3. SNMP was selected to be the non-HPAA application due to its cyclic nature, ability to create concurrent broadcast download to the HPAA PCS controllers, and provide network performance reporting. In addition, large file data transfer was used to drive the network loading from steady state operation to 100%.The primary focus during all of these different test cases is to monitor the densest HPAA PCS network domain and report on both network and application performance.

4.2.1 Test Case One: Steady State Operation of HPAA and non-HPAA (SNMP) Traffic

The very first experimental test case was to activate non-HPAA (SNMP) traffic while HPAA applications are running in steady state operation to identify the traffic increment impacts. The objective of this test case is to explore the network performance (Layer 3 and Layer 2 switches) and analyze links utilization and the performance of the switches CPU and memory utilization. Moreover, the HPAA PCS traffic performance was to be monitored. The expectation is upon activating SNMP traffic along with HPAA steady state operation, an increase in the CPU and memory utilization shall be observed. Moreover, HPAA PCS application performance shall also be observed. However, it is expected to have the impact at minimum since the network elements (switches and links) are based on Gbps speed.

Figure 4.1 depicts the actual bandwidth utilization vs. time for the backbone switch (Layer 3 Gbps) Ethernet trunk connecting to the densest domain. The utilization peaked at 1% (10 Mbps) most of the time. This low utilization validates the fact SNMP traffic has negligible additional traffic load impacts during steady state operation when utilizing high-speed, Gbps, links.

Time (Minutes)	0	12	16	20	24
Utilization (% of Gbps)	0.50%	1.00%	1.00%	0.70%	0.80%
Effective Bandwidth Used	5Mbps	10Mbps	10Mbps	7Mbps	8Mbps

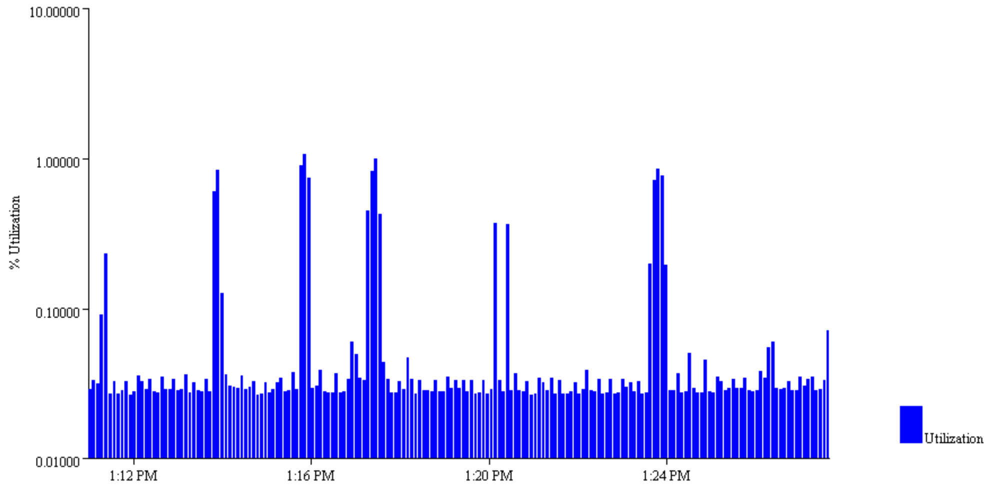
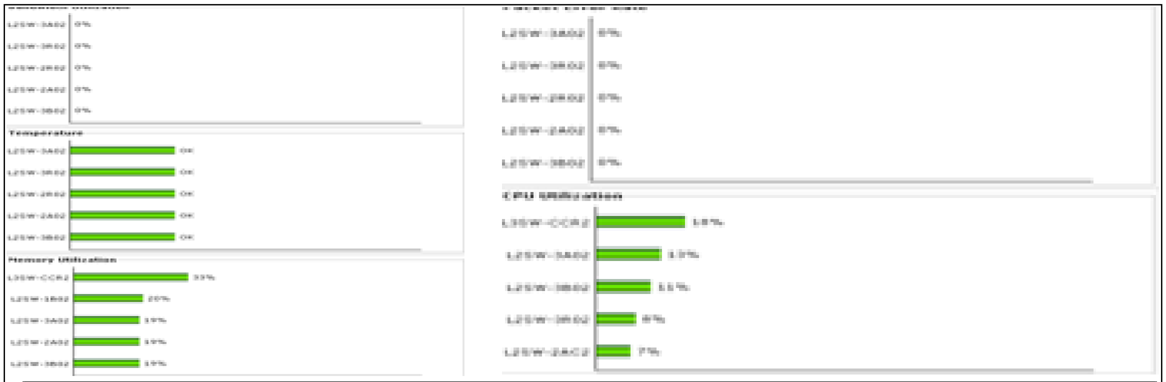


Figure 4.1 Layer 3 Bandwidth Utilization — HPAA and non-HPAA

To confirm the minimal impacts of SNMP on the network resources, both Layer 2 and Layer 3 switches in question were investigated further by analyzing the performance of their CPU and memory utilization during steady state operation. It was found that both switches had a modest CPU and memory utilization, less than 50% and with an increase of close to 4%.

The packet error was also tracked during the steady state test case and was to be at 0%. Figure 4.2 depicts these outcomes.



Switch	Memory Utilization	CPU Utilization
Layer 3 (Backbone)	33%	18%
Layer 2 (Access)	20%	13%

Figure 4.2 Memory; CPU Utilization, Packet Errors Performance

4.2.2 Test Case Two: Steady State Operation Test Case with Alarm Flooding

The second test case objectives are to explore HPAA performance under a traffic spike that is triggered momentary but in a repetitive format. So, the traffic load that was in Test Case 1 was kept the same and sudden massive alarms generated from HPAA PCS controllers to the master controller were invoked. The intent is to examine and identify peak HPAA traffic burst and broadcast. The expectation is HPAA PCS traffic will be impacted. Packet lost shall be observed due to traffic peakedness under BE QoS settings. However, with Priority based Scheduling, the packet lost for HPAA shall be zero. While it was not possible to physically have all controllers failed at the same exact time point, a systematic shutdown for the controllers was implemented rapidly to examine the cumulative impacts of alarm flooding on the network. The composite impact of massive alarms, normal traffic load, and SNMP application was depicted in Figure 4.3.

The test outcome shows bandwidth has peaked from 10 Mbps to 12 Mbps (1% to 1.2% bandwidth utilization). The peak traffic was momentary, during alarm floods, and then subsides to the normal traffic load of 10 Mbps (1%). It was also noted that most of the additional traffic load was unicast and broadcast packets. This is due to the nature of alarms flooding of the HPAA applications, as displayed in Figure 4.4. This test case also shows packet error rate was zero for both BE and Priority based scheduling and there were no discarded packets. This is mainly attributed to the Gbps Ethernet network switches and low network links utilization.

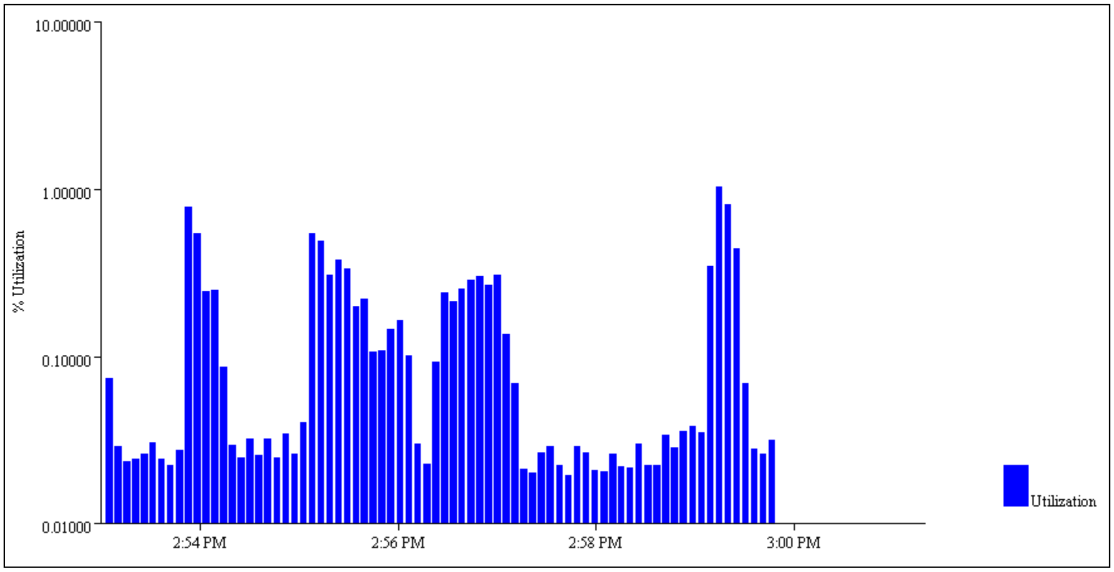


Figure 4.3 Massive Alarm Flooding — 1.2% Peak Utilization

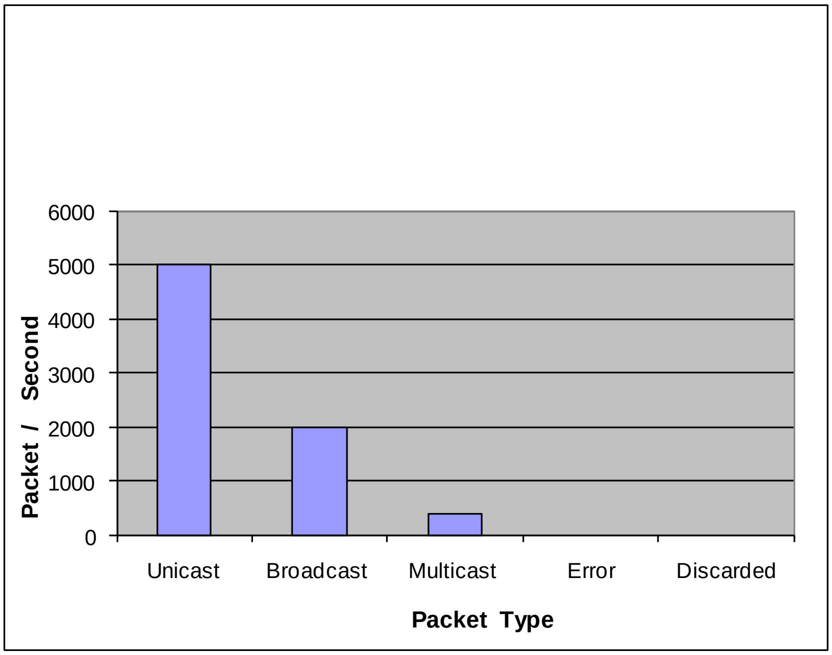


Figure 4.4 Packet Type: Packet Transmission by Service Type

4.2.3 Test Case 3: Superimpose Steady State Operation with Traffic Injector Test Case

This test case objective is to explore the HPAA PCS application in a converged IP network with a steady state high traffic load. Both BE and Priority based Scheduling QoS impacts were examined in this test case. The expectation is HPAA PCS traffic performance will be impacted from delay and packet delivery perspectives. Traffic injector, source and sink, was installed in the network to systematically increase the traffic load on the backbone links. The traffic loading increased from 0 to 30% then to 50%, and up to 100%. TCP and UDP message type performance was tracked to assess the application performance. Systematically, the traffic injection progressed from 30% to 100% network loading as shown in Figure 4.5.

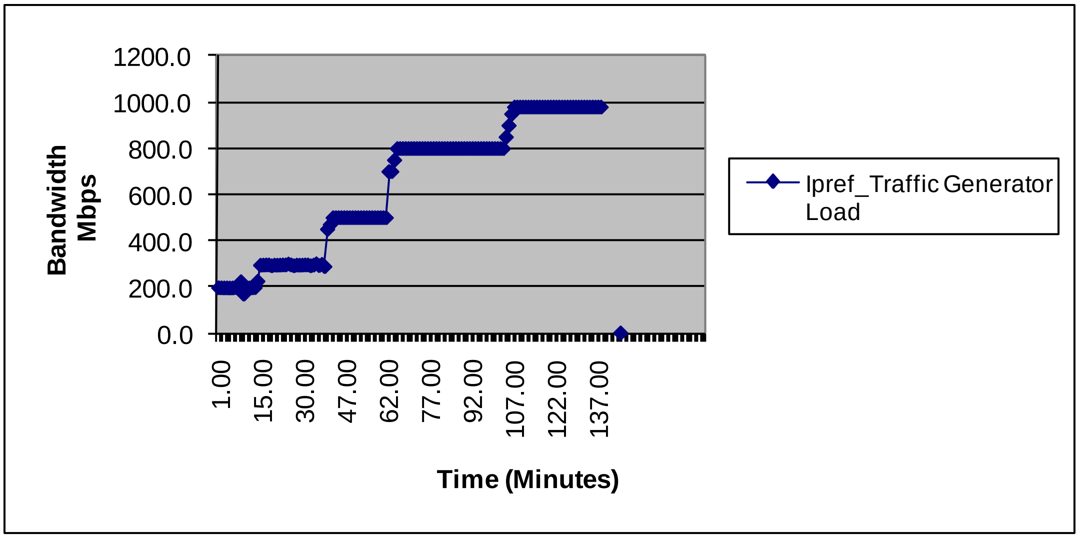


Figure 4.5 Traffic Injector IPref: 300-1000 Mbps

HPAA traffic was randomly mixed with the traffic generator large file transfer. Peakdness traffic with a cyclic behavior was observed and was correlating to the HPAA application. Initially, the total maximum trunk bandwidth utilization was 32% (320 Mbps) as shown in Figure 4.6.The delta between the traffic generator traffic, 300 Mbps, and the total load was 20 Mbps that is mainly attributed to the HPAA traffic.

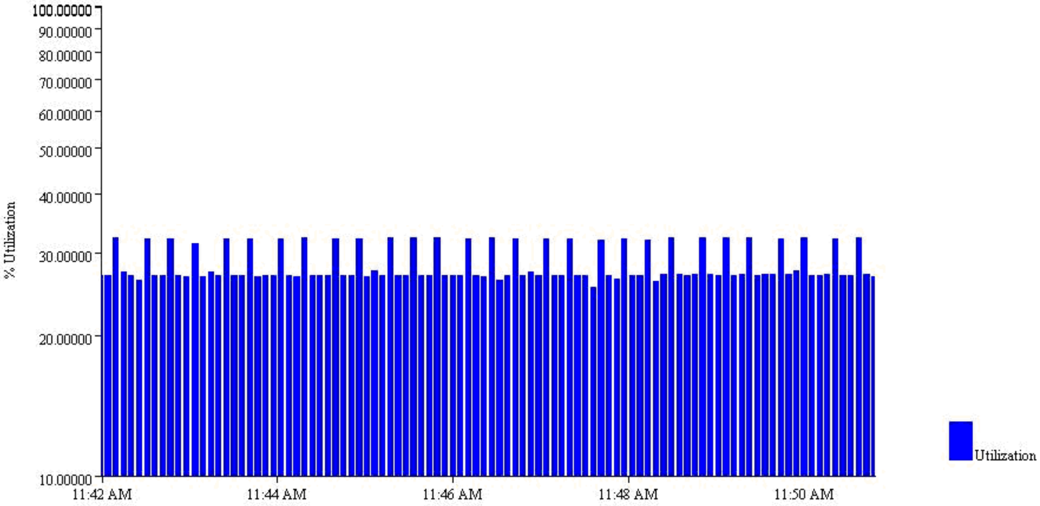


Figure 4.6 Layer 3 Switch, 32% Utilization (320 Mbps)

It must be highlighted both BE and Priority based scheduling traffic load results were similar. So, traffic loss was not observed and this mainly due to the high speed, Gbps, switches and low network utilization (i.e., 32%).Also, the test results show zero packet errors for both the HPAA application and non-HPAA (SNMP) traffic as shown in Figure 4.7.

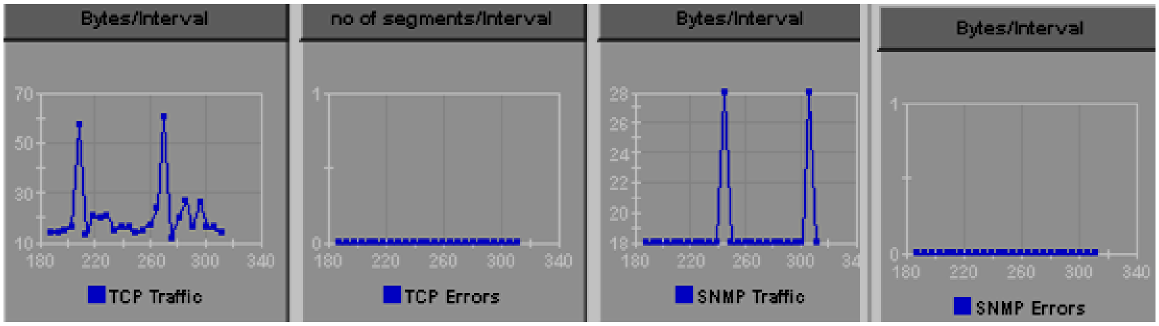
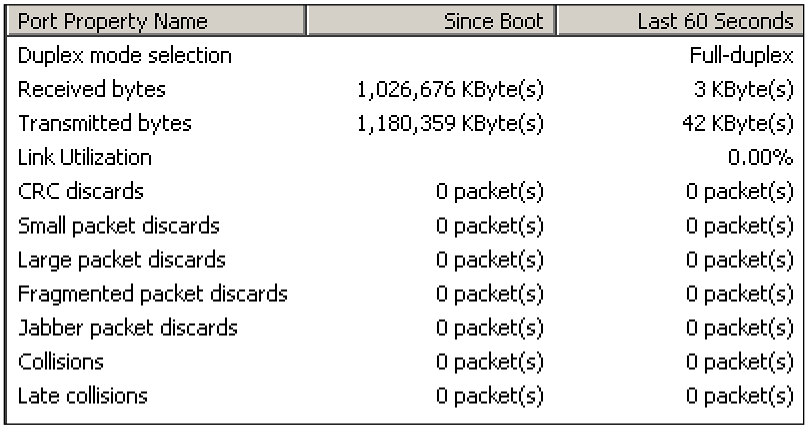


Figure 4.7 Zero Packet Error during Stress Test

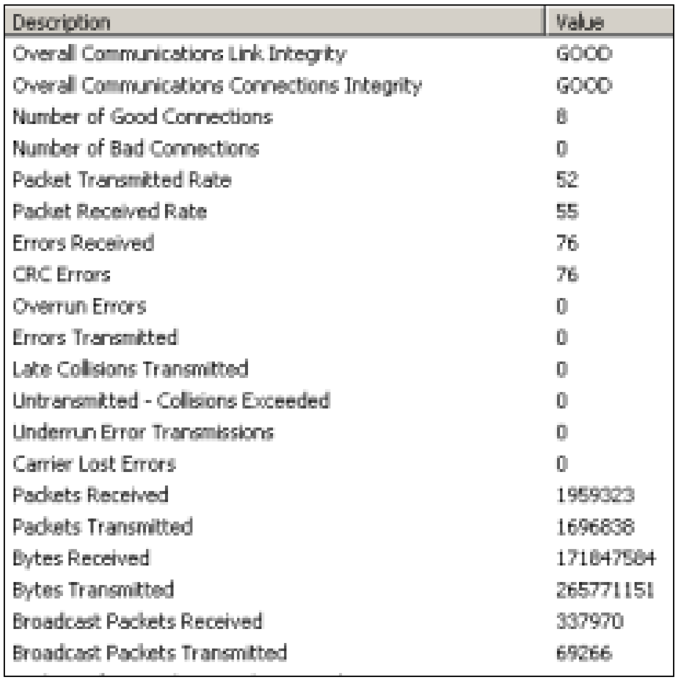
The traffic load was increased to 50% and 80% utilization for both BE and Priority based scheduling. The test results show zero packet error/discarded as per Figure 4.8. The application performance was also monitored during this test case to identify the process variable updates (poll cycle) and sending commands. In this case, the application did not have any performance degradation.



Port Property Name	Since Boot	Last 60 Seconds
Duplex mode selection		Full-duplex
Received bytes	1,026,676 KByte(s)	3 KByte(s)
Transmitted bytes	1,180,359 KByte(s)	42 KByte(s)
Link Utilization		0.00%
CRC discards	0 packet(s)	0 packet(s)
Small packet discards	0 packet(s)	0 packet(s)
Large packet discards	0 packet(s)	0 packet(s)
Fragmented packet discards	0 packet(s)	0 packet(s)
Jabber packet discards	0 packet(s)	0 packet(s)
Collisions	0 packet(s)	0 packet(s)
Late collisions	0 packet(s)	0 packet(s)

Figure 4.8 Network Zero Packet Error/Discarded at 50% and 80% Utilization

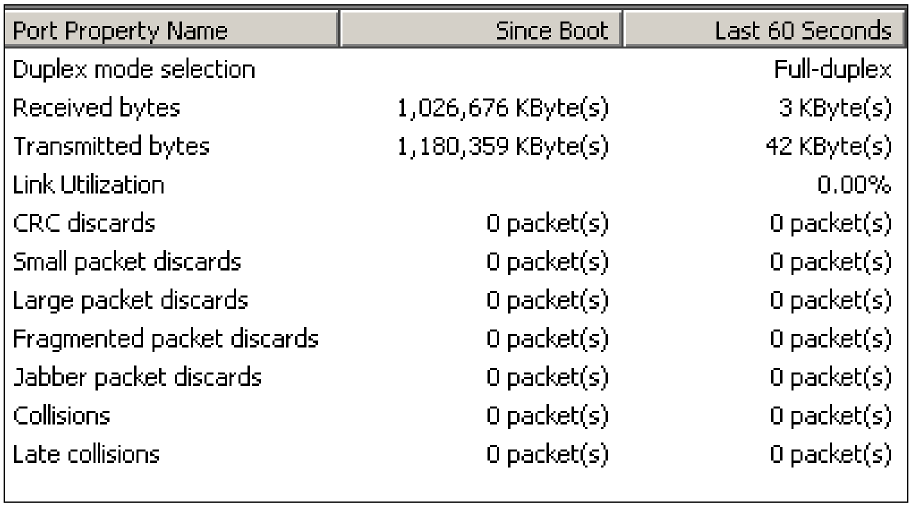
As the traffic load progressed to 100% on BE QoS network's setting, the HPAA application performance was impacted as shown in Figure 4.9. The transmitted and received packets were not equal (13% packet loss). The broadcast messages which sent concurrently and resemble peak application traffic, specific to HPAA alarms, shows significant degradation close to 30% lost.



Description	Value
Overall Communications Link Integrity	GOOD
Overall Communications Connections Integrity	GOOD
Number of Good Connections	8
Number of Bad Connections	0
Packet Transmitted Rate	52
Packet Received Rate	55
Errors Received	76
CRC Errors	76
Overrun Errors	0
Errors Transmitted	0
Late Collisions Transmitted	0
Untransmitted - Collisions Exceeded	0
Underrun Error Transmissions	0
Carrier Lost Errors	0
Packets Received	1959323
Packets Transmitted	1696838
Bytes Received	171847584
Bytes Transmitted	265771151
Broadcast Packets Received	337970
Broadcast Packets Transmitted	69266

Figure 4.9 Application and Network Performance for Best Effort QoS Network at 100% Utilization

The application and network performance with Priority based Scheduling QoS at 100% network loading shows zero impact to HPAA traffic from packet lost and discarded perspective. This attributed to classifying HPAA traffic with the highest priority. However, the file transfer application had packet lost/discarded that ranged from 10 to 20% depending on the randomness of the generated traffic and the HPAA traffic behavior. Figure 4.10 depicts the outcomes.



Port Property Name	Since Boot	Last 60 Seconds
Duplex mode selection		Full-duplex
Received bytes	1,026,676 KByte(s)	3 KByte(s)
Transmitted bytes	1,180,359 KByte(s)	42 KByte(s)
Link Utilization		0.00%
CRC discards	0 packet(s)	0 packet(s)
Small packet discards	0 packet(s)	0 packet(s)
Large packet discards	0 packet(s)	0 packet(s)
Fragmented packet discards	0 packet(s)	0 packet(s)
Jabber packet discards	0 packet(s)	0 packet(s)
Collisions	0 packet(s)	0 packet(s)
Late collisions	0 packet(s)	0 packet(s)

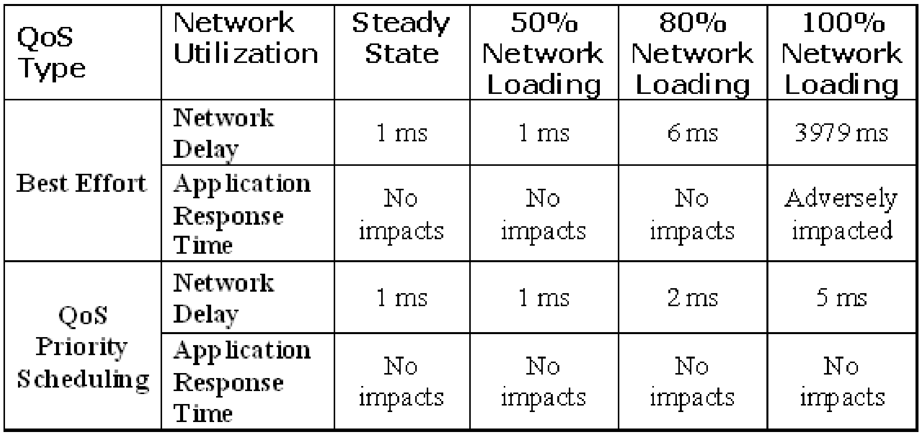
Figure 4.10 Application and Network Performance for Priority based QoS Network at 100% Utilization

4.2.4 Test Case Four: Network Delay for Varying Traffic Loading

The network delay was traced during a varying traffic load increase to 50%, then 80% and finally 100% for both BE and Priority based scheduling QoS network settings. The primary objective is to show the HPAA network delay under a varying traffic load. While the test is progressing, selected functions such as changing set point, and controlling a valve position were initiated. The test case tracked both network delay as well as HPAA PCS application impacts.

Table 4.1 reflects the test outcomes. The HPAA application network delay was exponentially increased from 1ms to close to 40s for BE network setting. Application functions were invoked by sending command and or requesting status updates from the control. The application performance showed no impact at network utilization of 80% or lower. However, an adverse impact was noticed at 100% utilization where the application did not receive response and or the response was delayed in seconds. On the other hand, when Priority based scheduling QoS was enabled; the delay was slightly increased from 1ms to 5ms. This demonstrated the strength of QoS in confirming the network delay to a range that is transparent to the HPAA applications. In addition, it was confirmed HPAA application functions were not impacted regardless of network utilization as shown in Table 4.1

Table 4.1 QoS Network Performance for Network Loading Scenarios



QoS Type	Network Utilization	Steady State	50% Network Loading	80% Network Loading	100% Network Loading
Best Effort	**Network Delay**	1 ms	1 ms	6 ms	3979 ms
	Application Response Time	No impacts	No impacts	No impacts	Adversely impacted
QoS Priority Scheduling	**Network Delay**	1 ms	1 ms	2 ms	5 ms
	Application Response Time	No impacts	No impacts	No impacts	No impacts

4.3 Experimental Case Study #2: HPAA Converged IP WAN Network

The second case study addresses a high speed Gbps Ethernet, WAN for HPAA PCS applications in a CIP network environment. Empirical data for an implemented HPAA PCS system was used to illustrate the interdependency of PCS application performance, traffic mix, network loading, and network recovery with other non-HPAA traffic. BE and Priority based Scheduling QoS was enabled during each test case scenario. The test cases include exploring the CIP network performance in steady state operation, traffic load stress testing, networking cross traffic jitter, and network reliability and application performance. Moreover, the IP Telephony and media streaming application performance and their co-existence with HPAA PCS application were examined.

4.3.1 Test Cases Results

Different test cases were conducted to investigate the impacts on the process automation network supporting both HPAA’s, voice, media streaming; while SNMP agents are active on a predetermined polling cycle of 1 second. The primary focus during all of these different test cases is to understand the network performance under defined traffic load; existing traffic load, 50%, 80%, and 100% network utilization model. The network model is based on two different QoS configurations: BE and Priority based Scheduling. The test case results will be based on the busiest access switch which is anticipated to be the Layer 2 Ethernet IP switch connecting the access ring to the backbone ring. The backbone Layer 3 Ethernet IP switch connecting the different hosts is anticipated to be the busiest switch network-wide since it supports multiple access rings traffic terminating to the different application hosts.

4.3.2 Test Case One: Steady State Operation

In this test case, the traffic load and network delay in steady state operation was identified. The intent is to determine the baseline traffic so to determine the type of traffic loading is required to address the subsequent test cases. Moreover, the performance outcomes for steady state provide a benchmark for the network performance under higher traffic loading. Under normal traffic load, the network and application were running in a converged IP traffic seamlessly since the overall traffic load was less than 10% for both backbone (10Gbps) and access rings (1Gbps) regardless of QoS settings type. Moreover, the maximum delay was 2 ms and there were zero packet losses as shown in Table 4.2. Also, the breakdown for the traffic is HPAA PCS based on TCP, IP Telephony UDP based, and media streaming based on TCP. The SNMP traps are based on TCP (PCS controller configuration file) and UDP (alarms, network performance, etc.).

Table 4.2 Network Performance for Existing Traffic Load

Component	Existing Load	Utilization	Delay	Frame Loss
Access Ring *(BW=1Gbps)*	Minimum	1.20%	1 msec	0%
	Average	3%	1.2 msec	0%
	Maximum	7%	2 msec	0%
Backbone Ring *(BW=10Gbps)*	Minimum	0.80%	1 msec	0%
	Average	1%	1 msec	0%
	Maximum	1%	1 msec	0%

4.3.3 Test Case Two: Traffic Load Stress Testing by Superimposing Steady State Traffic Load with UDP & TCP Traffic Injector

This test case involves stress testing for the network links by exposing both TCP and UDP traffic while still maintaining a steady state operation (i.e., Test Case 1). The intent is to assess the different transport protocols, UDP and TCP, behaviors under traffic loading in CIP network. Moreover, the behavior of HPAA traffic (TCP), Multimedia (TCP) and IP Telephony (UDP) under the increased UDP and TCP traffic loading is examined. In this test case, the results show, UDP traffic had less network delay impact but more packet loss as depicted in Table 4.3. Also, HPAA PCS application encountered delay in the order of 889 milliseconds during the mass, 100% utilization driven by the UDP, traffic injections.

Table 4.3 Network Performance with UDP Traffic Stress Load

Component	Utilization	Average Delay	Average Packet Loss
Access Ring (BW=1Gbps)	7% (Existing Traffic Load)	< 1 ms	0%
	50.00%	≤ 2 ms	0%
	80.00%	2 ms	0%
	94.27%	3 ms	18%
	100%	6 ms	20%
Backbone Ring (BW=10Gbps)	1% (Existing Traffic Load)	< 1 ms	0%
	50%	≤ 1 ms	0%
	80.65%	12 ms	0%
	99.65%	13 ms	20%
	100.00%	14 ms	21%

The second scenario is injecting TCP traffic and sustaining a steady state traffic load for HPAA PCS, non-HPAA, and multimedia (voice and video). The intent is to examine the TCP traffic performance from delay and packet loss perspectives. Results are depicted in Table 4.4 and show TCP traffic experience more network delay but much less than UDP in packet loss. This is due to TCP inherent behavior of confirming before sending the subsequent message. The HPAA PCS application layer is based on TCP and its encountered delay was higher than the network delay but was followed the same behavior. The delay at low network loading was below 15 ms. However, it 100% network loading the application delay was close to 378 ms.

Table 4.4 Network Performance with TCP Traffic Stress Traffic Loading

Component	Network Loading	Average Delay	Average Packet Loss
Access Ring (BW=1Gbps)	7% (Existing Traffic Load)	< 1 ms	0%
	50.00%	2 ms	0%
	80.60%	3 msec	0.00%
	98.30%	5 msec	14%
	100%	7 msec	15%
Backbone Ring (BW=10Gbps)	1% (Existing Traffic Load)	< 1 ms	0%
	50%	≤ 1 ms	0%
	81.65%	12 msec	0%
	99.65%	15 msec	4.10%
	100.00%	17 msec	4.80%

4.3.4 Networking Cross Traffic Jitter

The application and network jitter was examined. The application specific jitter was based on performance data reported by the applications by subjected traffic stream of 40 kbps to a network loading increase from 50% to 100%. The application jitter was between 0.1 ms and 4.4 ms as shown in Figure 4.10 depicts the outcome in a BE network configuration. The jitter was below 1ms for Priority based Scheduling QoS.

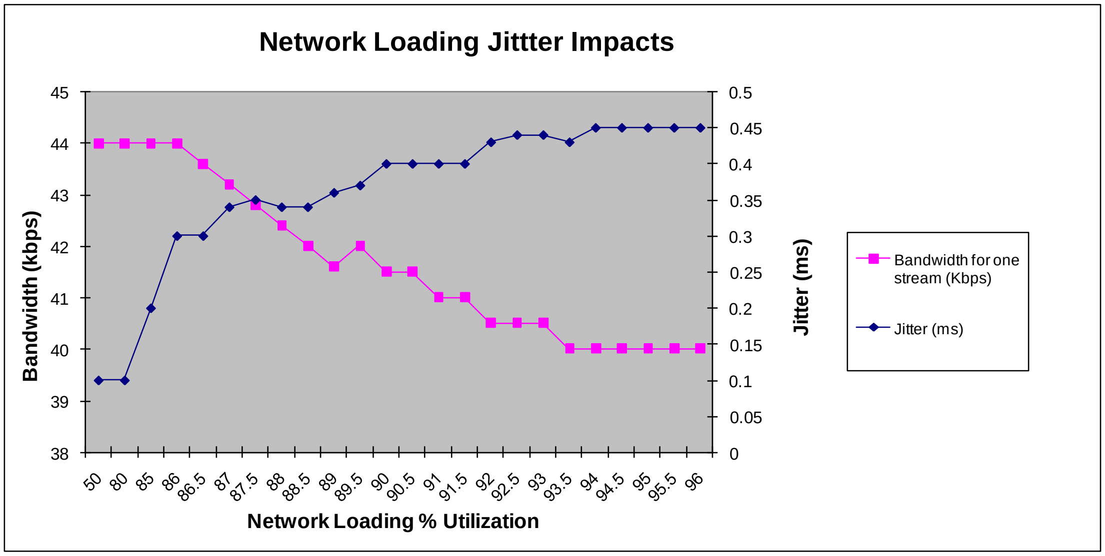


Figure 4.10 Application's UDP Sub-Stream, Network Loading Jitter Impacts BE Network

The cross traffic performance for HPAA application under the two different network loading types, TCP and UDP, is depicted in Table 4.5. As shown, the 50% network utilization model provides the least time delay and followed by the 80%. At 100%, the application performance shows extended delay; in the order of 100's ms. On the other hand, delay during Priority based Scheduling for HPAA application was 2ms at utilization below 80% and then increased to 7ms at 100% utilization.

Table 4.5 HPAA Application Performance with TCP and UDP Traffic Loading Best Effort Network

Network Model	**HPAA Application Delay**	
	UDP Network Loading	**TCP Network Loading**
100% Utilzation	889msec	378msec
80% Utilzation	97msec	93msec
50% Utilzation	90msec	90msec

4.3.5 Network Reliability & Application Performance

In this test case, the application performance, ability to sustain connection, was tested under a network failure. The intent is to identify the tolerable time of network disconnection before the application initiate an application restart. While this totally contingent on the application configuration and process system design, this test case provide an insight on an HPAA PCS application under normal configuration with thresholds (application response delay below 2 s for fast loops) as discussed in Chapter 2. As depicted in Table 4.6 shown below, the maximum recovery time for the network, is 24.85 seconds. Loss of the communication link for such a period drove the application to restart, hence extending the delay time to re-establish connection with the field instruments. This condition results in running the process blindly and impacts Quality of Control (QoC) and considered a major challenge. This challenge is not addressed in this research and is a candidate topic for future research and further study as the primary focus of this effort is CIP for HPAA application.

Table 4.6 Network Recovery Time

Network Component	**Minimum**	**Average**	**Maximum**
Link Recovery	31 msec	69.13 msec	187 msec
Ring Recovery	18760 msec	19.9447 msec	24850 msec

4.3.6 IP Telephony & Media Streaming Application Performance

The IP Telephony and Media streaming delay performance is presented in Tables 4.7, and 4.8, respectively. Two test cases were examined, One test case was based on running the network with BE QoS configuration. The second is where priority based scheduling QoS is enabled and the network loading as increased from 50% to 100%. The intent is to identify support services performance in a CIP HPAA network. IP Telephony test results show a delay that was close to 100ms during steady state and then extended to up to 400 ms with the network loading increase from 50% to 100% in the BE network configuration. However, the delay was consistent between 90 ms to 150 ms in the priority based scheduling QoS settings. It must be highlighted that the IP telephony delay was not fixed to a certain threshold. It was more or less in a range, due to the overall CIP network traffic dynamics, as shown in Table 4.7.

Table 4.7 IP Telephony Delay Performance

QoS Type	**Steady State (10%)**	**50% Network Loading**	**80% Network Loading**	**100% Network Loading**
Best Effort	≤ 100 ms	100 ms ≤ D ≤ 150 ms	100 ms ≤ D ≤ 150 ms	≥ 400 ms
Priority Scheduling	≤ 100 ms	≤ 100 ms	100 ms ≤ D ≤ 150 ms	100 ms ≤ D ≤ 150 ms

Video streaming test case results show the nature of this application delay under a varying network loading. The BE QoS network configuration resulted in a delay that was not tolerable, at 500ms or higher, when network utilization reached 100%. However, when Priority Based Scheduling was activated, the network delay was transparent to the application regardless of network utilization. The maximum delay was at 250 ms.

Table 4.8 Media Steaming (Video) Delay Performance

QoS Type	Steady State (10%)	50% Network Loading	80% Network Loading	100% Network Loading
Best Effort	≤ 200 ms	≤ 200 ms	≤ 200 ms	≥ 500 ms
Priority Scheduling	≤ 200 ms	≤ 200 ms	≤ 200 ms	200 ms ≤ D ≤ 250 ms

4.4 SUMMARY

The results of this research design experimental case studies were presented in this chapter. The primary focus was on the application and network performance which includes delay, jitter, packet lost and application behavior. Quality of service based on Best Effort and Priority based Scheduling were examined under CIP LAN/WAN network traffic loading of 50%, 80%, and 100%. The presented experimental case study results were based on approximation to averages due to the multiple and different tools that were used concurrently to trace the network and application performance. Actual results' snap shots for the test case studies were included where possible. Graph and tables were collected from the various tools that were used, as per the research design defined in Chapter 3.

An important aspect that was kept in mind was the experimental test case studies collected data conformed to the actual application standard requirements. So, the test cases did not include abnormality of the usual operating environment for the HPAA PCS application. The key challenge in the test cases is the ability of maintaining an exact application operation. This challenge stems from the HPAA PCS application dynamics with the control elements (PCS controllers, instruments, and actuator). Hence, the application behavior was approximated to threshold levels that were determined and optimized during the test cases. Areas for optimizing the network such as minimizing number of Ethernet IP switching nodes and simplifying the network links connectivity, where applicable, were considered and implemented and resulted in realistic test outcomes.

The test results show the delay, packet loss/discarded, jitter, and application stability for both network QoS configurations. BE effort and Priority based Scheduling at low network utilization, bellow 50%, shows similar performance; delay was maintained at minimum, zero packet loss, and jitter was transparent to the HPAA and non-HPAA applications. However, as the network loading increase to 80% and 100%, the network performance was drastically degraded. Delay was in the order of 100’s ms, packet lost was close to 20%, and application stability was not consistent at all the time. Support service IP telephony had excessive delay over 400 ms followed by media streaming close to 500 ms.

The QoS Priority based Scheduling where HPAA was assigned the highest priority, shows very positive and consistent performance results for all the different test cases. Moreover, support services such as IP telephony, second in priority and media streaming, third in priority, performance were well within their application tolerance limits. The IP telephony had network delays that ranged from 90ms to 150ms. Media streaming test results was conforming to the media streaming application with a delay that was close to 250 ms.

The test cases provided essential empirical data to be measured against the simulation test case scenarios results in Chapter 5. Moreover, the empirical data provided a baseline for the HPAA PCS system performance and HPAA controller behavior such as cyclic message types-TCP, traffic peakedness driven by alarms, and controller configuration large file transfer, etc. These are crucial elements in the simulation test case scenarios setup as discussed in the research design of Chapter 3 and presented results in Chapter 5. Moreover, the test cases were used to validate the initial simulation configuration parameters, confirming and validating the expanded simulation test case scenarios that are presented in detail in Chapter 5.

CHAPTER 5 SIMULATION RESULTS

5.1 OVERVIEW

Simulation as a research tool for exploring CIP for HPAA and non-HPAA was not explored previously based on the completed review in Chapter 2. In this chapter, the simulation results for CIP LAN and WAN network models supporting HPAA and non-HPAA applications are presented. The simulation test case scenarios are based on the simulation research design, detailed previously in Chapter 3. Three test case scenarios are part of this simulation effort. These test case scenarios include: dedicated (steady state operation), converged IP with BE QoS, and Priority based Scheduling QoS.The primary objective is to explore the application and network performance behaviors for the HPAA PCS Controllers under different network utilization models; baseline steady state traffic load, 50%, 80%, and 100% utilization. Moreover, support services such as IP telephony and media streaming were tracked as part of the simulation test case scenarios to measure their performance and relationship between HPAA and these non-HPAA applications.

Similar to the experimental test case studies in Chapter 3, network simplification which includes Ethernet switch nodes, links, and topology, were addressed in the initial stages of the simulation test case scenarios development to depict a typical HPAA PCS production network. Moreover, the primary focus during all of the different simulation test case scenarios is two application's relationships. These relationships are: HPAA Master Controller (MSC) communicating to subtending Controllers. The second is HPAA Controller in one domain communicating to another Controller in another domain as part of a Peer-to-Peer (P2P) relationship or cross domain traffic similar to the experimental test case scenarios presented in Chapter 4.

As discussed in the research design, Chapter 3, the Master Controller has the functionality to communicate with field controllers and process parallel logic loops, message exchanges, and management of the field controllers (i.e., subtending controllers). On the other hand the subtending controllers have direct communication with instruments and actuators that are directly tapped into the process and also communicating back the MSC Controller. Delay, jitter, TCP packet loss, and TCP re-transmission attempts/timeout are the key parameters that are being tracked in the different simulation test case scenarios.

5.2 DEDICATED HPAA PCS LAN NETWORK

The dedicated IP LAN network supporting HPAA PCS application was simulated. As explained in Chapter 3, research design, the dedicated LAN is based on two different HPAA PCS domains internetworked with an aggregation switch. The HPAA PCS messages were simulated to run based on predefined cycle where one HPAA Controller is communicating to the HPAA Master Controller and also to the HPAA Controller that is part of the opposite domain. The simulation results are presented in this section. This includes network delay, packet delivery performance, jitter, and applications behavior under predefined network loading. The results also show relevant cross relationships between the different network model QoS settings.

5.2.1 Dedicated Network-Master Controller to Subtending Controllers Performance

The Master Controller (MSC) has the functionality of collecting process variables from all the Controllers that are extended over the process control system network. The relationship between the MSC and subtending Controllers CNT*n* where *n= 1, 2, 3,…,10* is based on full duplex client-server; with a predefined cyclic and acyclic updates within 1 second**.**Figure 5.1 depicts HPAA PCS MSC communication performance to all the subtending Controllers. The HPAA PCS Controller performance shows a consistent behavior in a dedicated network. Network delay is directly proportional to the subtending Controller location in the network. The nearest Controller, CNT1, to the

MSC had the lowest HPAA PCS delay at 0.3 ms as compared with the farthest Controller, CNT10, at 1.1 ms. This resembles a 266% increase in delay. Since the network is dedicated, the primary contributor to the increased delay for HPAA CNT10 can be attributed to the number of switches (i.e., 10 switches) in the LAN network.

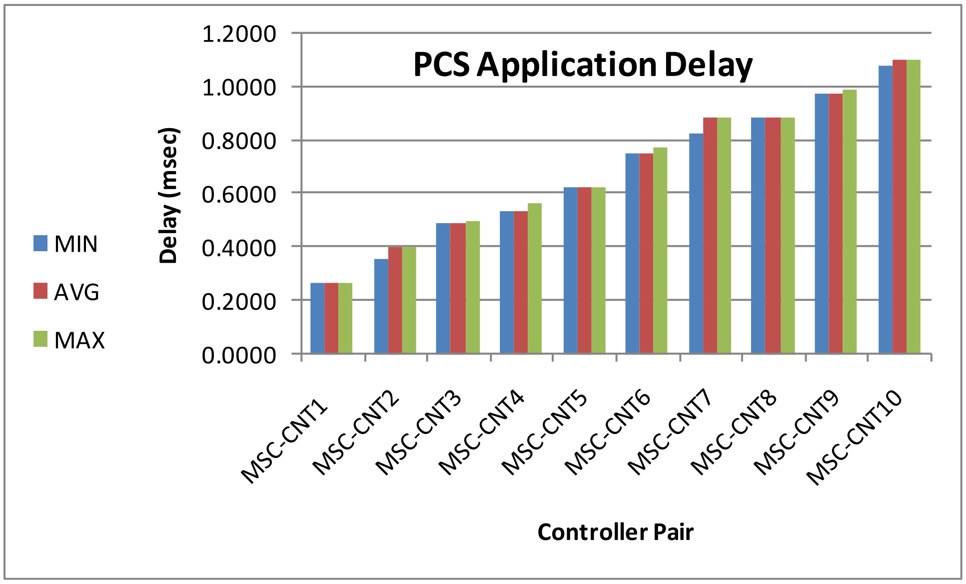


Figure 5.1 Dedicated Network: HPAA PCS Master to Sub-tending Controllers Delay

The maximum network delay encountered in supporting the HPAA PCS application between the MSC and the subtending Controllers was 0.7 ms. The average network delay between two adjacent nodes is estimated at 60 µsec. Figure 5.2 depicts MSC network delay between the MSC and the sub-tending Controllers for one of the simulated domains.

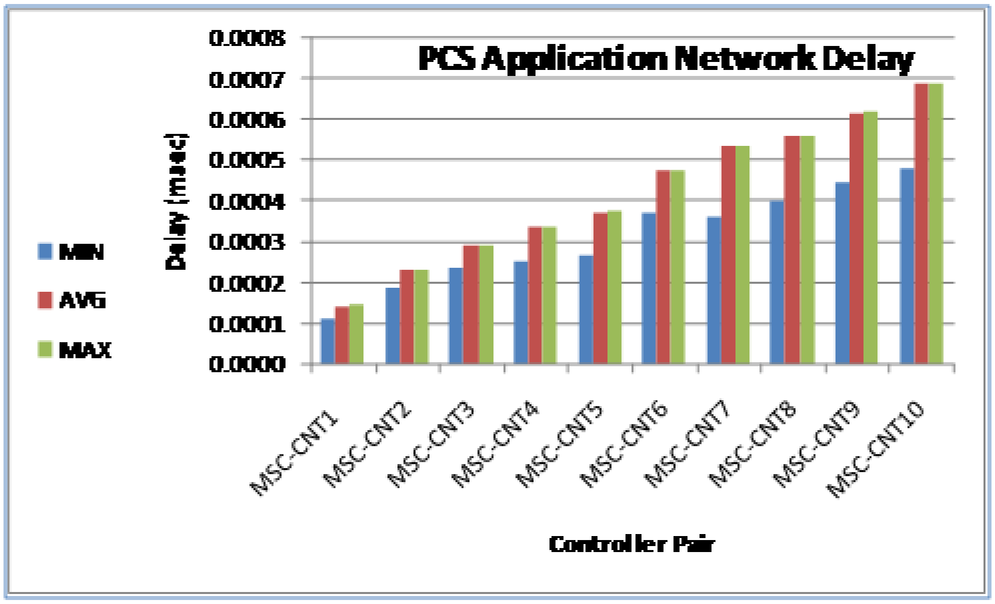


Figure 5.2 Dedicated Network: Network Performance

Typically, a traffic load for PCS application (request/response) is very minimal and far below 5,000 bps. However, the simulated network model defined the PCS traffic load for the Controller to be at 8,000 bits per second. Due to high-speed Ethernet links of 1 Gbps, the IEEE 802.3 [7] and full duplex Ethernet link feature, the simulation results for packet loss ratio per second is zero. Moreover, the packet drop was at zero. Figure 5.3 shows traffic load vs. packet loss for the dedicated network. This demonstrates and reconfirms Ethernet network fitness for connecting PCS Controllers, instruments, and actuators in a dedicated network setting.

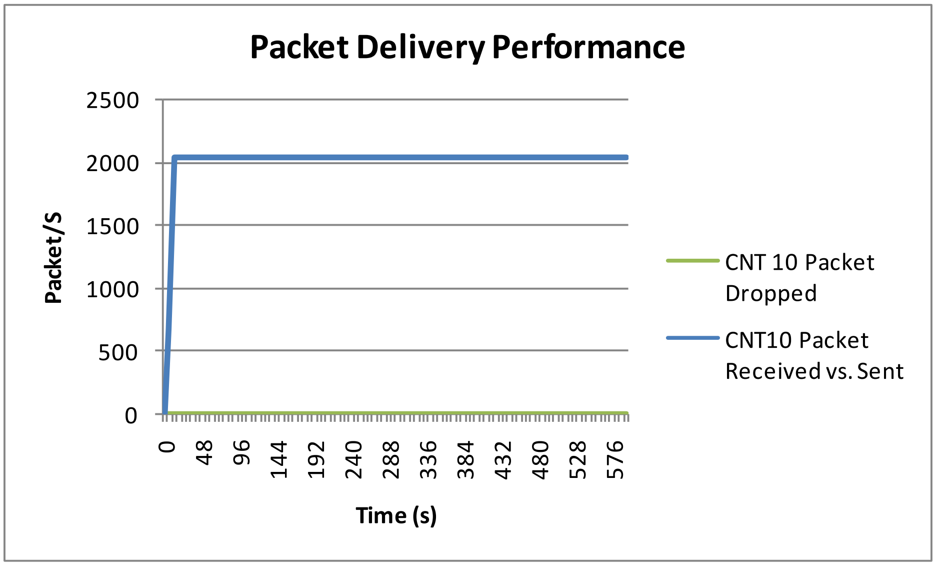


Figure 5.3 Dedicated Network: Packet Performance for the Farthest Controller (CNT10)

The TCP retransmission, which is an indication of the timeliness of a message arrival within the allocated TCP window, is shown in Figure 5.4. The TCP retransmission is within a 1 second which is during the defined Controller request/response cycle.

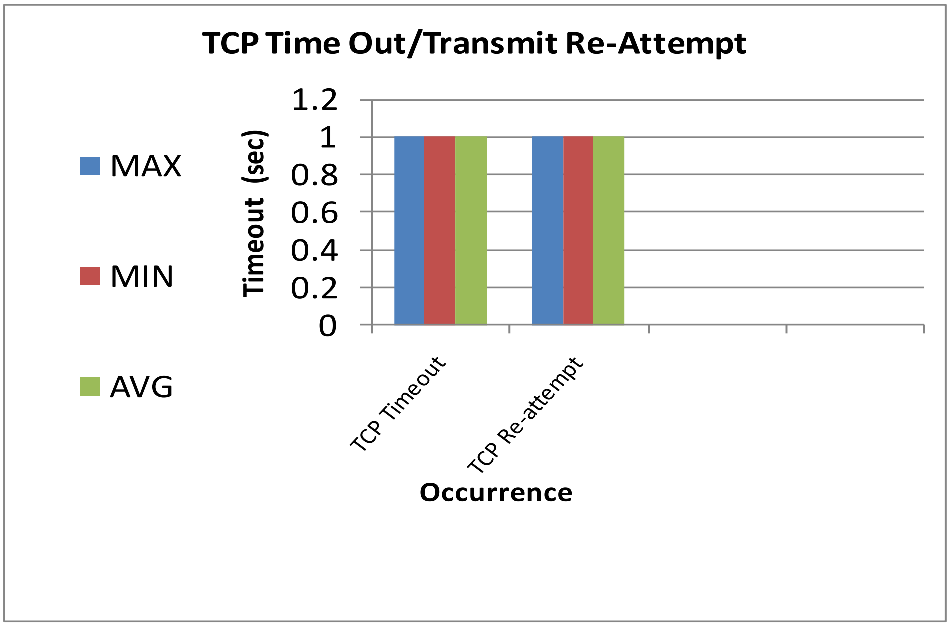


Figure 5.4 Delay vs. TCP Timeout/Retransmission Attempt Window Cycle

5.2.2 Dedicated Network Peer-to-Peer (P2P) Controller Performance

The HPAA PCS P2P application and network performance is a measure for the cross network suitability for HPAA PCS applications. Delay, jitter, packet loss and bit error rate are indicators that measure the overall network quality. Figure 5.5 shows HPAA PCS application time delay between the farthest two Controllers in each domain; CNT10 and CNT20. The simulation outcomes show the application request/response roundtrip time delay is 4 ms. The one way HPAA PCS application delay was at 2 ms.

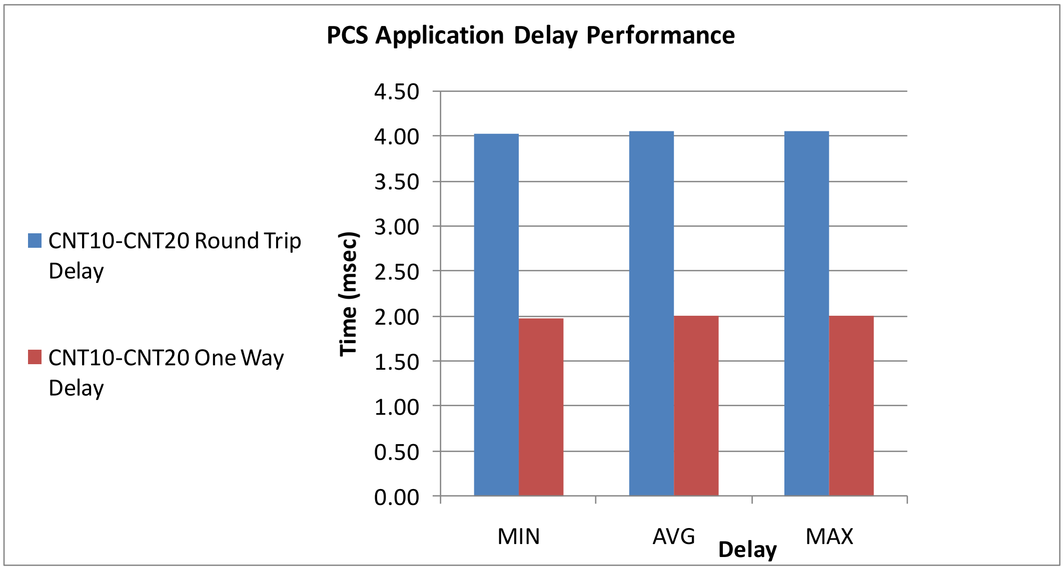


Figure 5.5 Dedicated Network: Peer-to-Peer Application Performance-Delay

The maximum IP network delay was 0.241 ms and jitter was negligible at 51 μs as depicted in Figure 5.6. As expected, a dedicated Ethernet network provides an ideal platform for supporting HPAA PCS applications. The number of Ethernet switch nodes is the primary source for delay since traffic load is minimal, below 10% utilization.

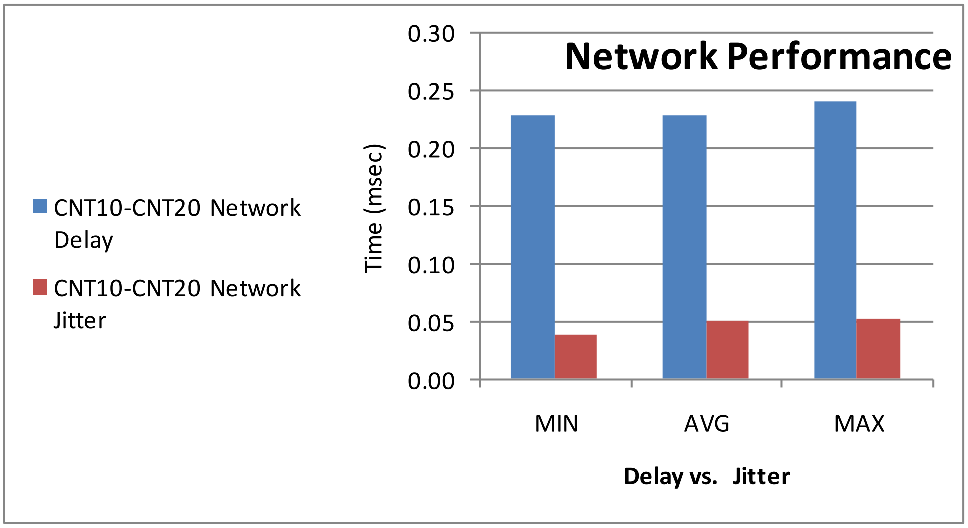


Figure 5.6 Dedicated Network: Peer-to-Peer Network Performance- Delay and Jitter

5.2.3 Packet Loss

The packet loss or dropped packet performance in a simulated network model for a dedicated network was tracked and analyzed. The simulation outcomes show zero packet dropped at the network layer. Moreover, the packet loss was zero at the application layer. This was demonstrated by examining the total packets sent and received as compared to packet dropped as shown in Figure 5.7.

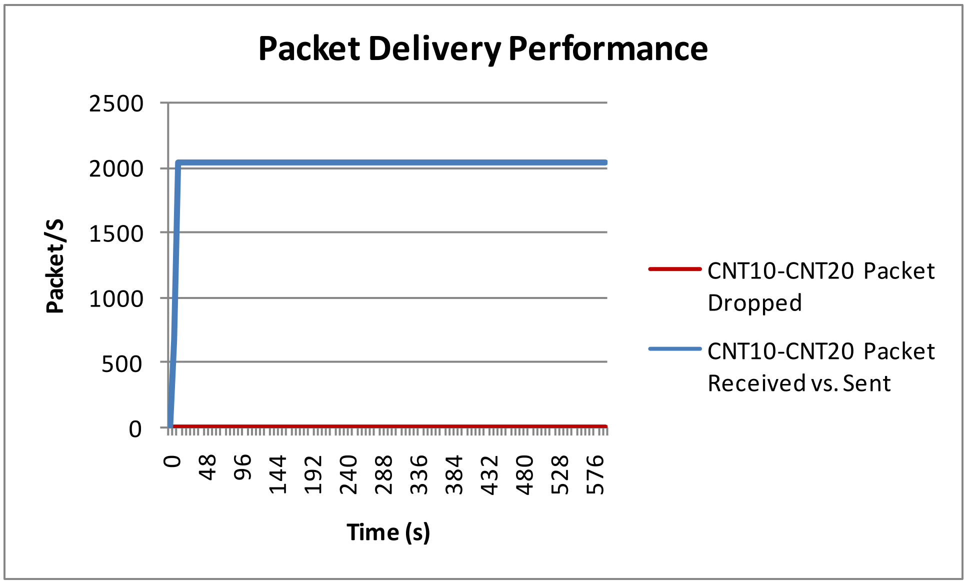


Figure 5.7 Dedicated Network: Packet Delivery vs. Dropped

5.3 CONVERGED LAN IP NETWORK WITH BEST EFFORT (BE) SETTINGS

The converged IP LAN network performance with BE QoS settings was explored based on the 50%, 80%, and 100% network utilization models. HPAA Master Controller (MSC) communicating to subtending Controllers and the Peer-to-Peer (P2P) Controller behavior performance were tracked. IP telephony and media streaming applications performance were also examined. Traffic generator was placed at the farthest two ends of the domains in question to maximize the switching and bandwidth loading impacts. Simulation results are illustrated and presented in the subsequent sections.

5.3.1 Master Controller and Subtending Controllers Performance

The simulated traffic injector was varied at 50%, 80%, and 100% network utilization models of the available bandwidth. The injected traffic, large file transfer, was superimposed at a maximum constant rate with the HPAA PCS Controller, IP telephony, and video traffic. Delay, in both the application and network response time, was apparent. The network delay primarily resulted from both the switching buffer congestion caused by injected traffic load and support services such as video streaming. This is due to the high traffic volume of these two services video at 1,000,000 bytes and file transfer (traffic injector) at 6,500,000 bytes as compared to the Controller at 1024 bytes and the IP telephony at 8,000 bytes. Video and injected traffic applications were acquiring most of the bandwidth. Hence, it was causing higher delay to the other two applications, namely PCS Controller and IP telephony Traffic.

The performance for MSC Controller with subtending Controllers was degraded when non-PCS traffic was injected into the network and this was also impacted by the Controller's cascaded traffic impact driven by the simulated bus network topology. The PCS Controller application, media streaming and voice performance was impacted in a direct relation to the network loading. Figure 5.8 depicts the PCS Controller application round trip delay between the MSC and CNT10. The BE effort application round trip average delay contributed by the network at 50% and 80% is between 5 ms and 7 ms accordingly. However, at 100% utilization, the delay was at 122s.

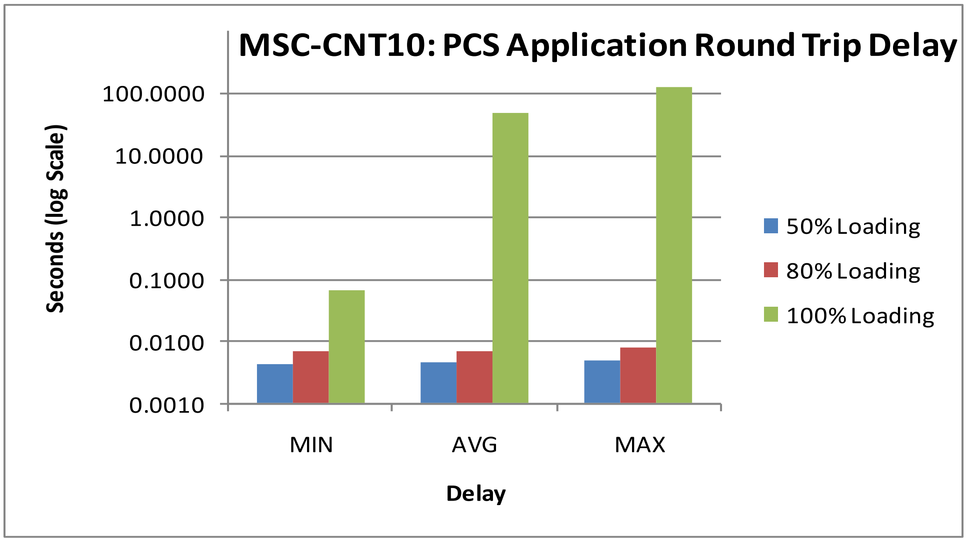


Figure 5.8 Converged Network: Master Controller to Controller Application Round Trip Delay Performance

The PCS Controller application one way delay, response, is depicted in Figure 5.9. The average delay at 50% and 80% is below 5 ms as compared to 29 ms at 100%. This delay resembles the application network delay in that it does not include the allocated intra-node processing time. The increase in delay is due to superimposed traffic contributed by IP telephony, media streaming, and large file transfer.

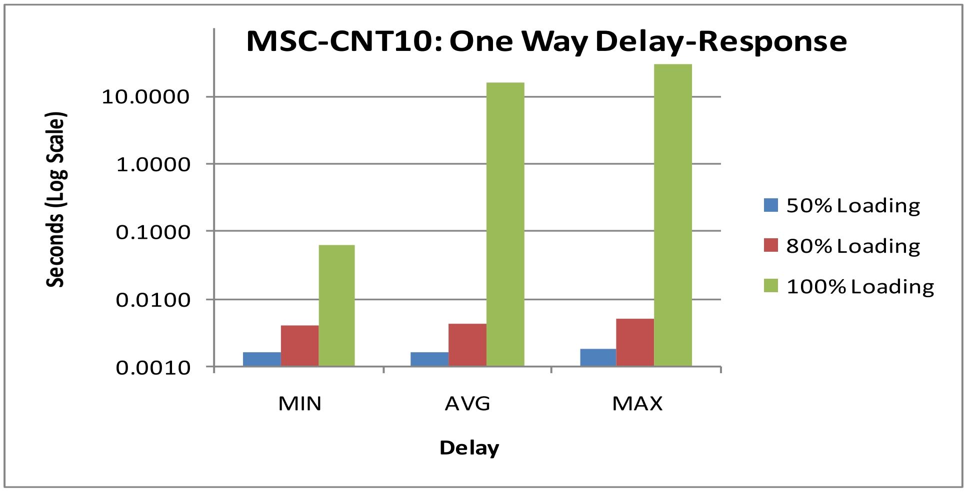


Figure 5.9 Converged Network: Master Controller to Controller Application One-Way Delay Performance

Figure 5.10 depicts network delay performance between the MSC and subtending Controller. Network delay is directly proportional to the subtending Controller location in the network. The nearest Controller, CNT1, to the MSC had the lowest network delay at 0.6 ms as compared with the farthest Controller, CNT10, at 0.8 ms. In all cases, the farthest Controller from MSC (i.e., CNT10) incurred most of the delay as the injected traffic load increased. The average increase in delay was 118% when comparing the dedicated network to 50% load utilization. Another 14% delay increase from the 50% load to 80% load. The application response delay performance for the 100% load was excessive, extending in the range of 28 seconds. The overall performance suggests a semi-exponential relationship between the network delay and the traffic load over time.

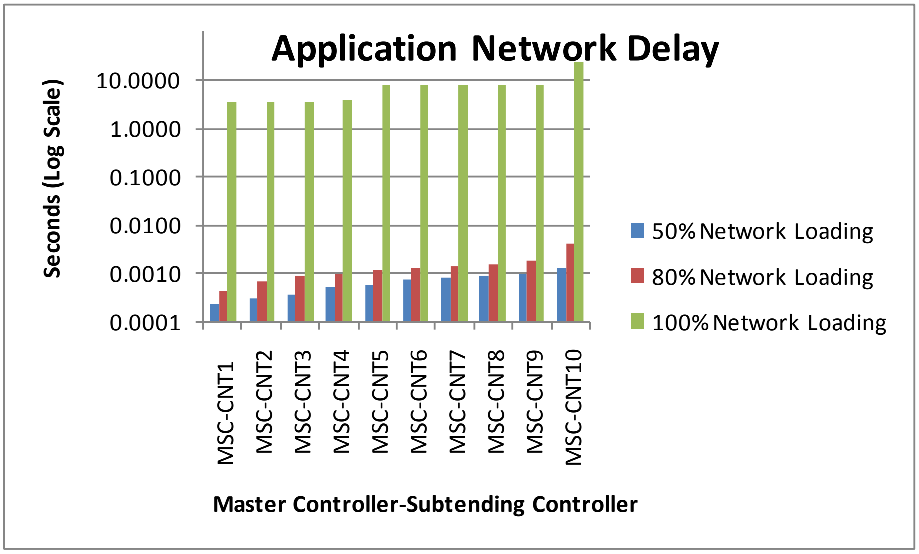


Figure 5.10 Converged Network: Master Controller to Subtending Controller Application Maximum Network Delay

From the above, traffic load above 80% is likely to have an adverse effect on the HPAA PCS traffic performance. Therefore, the 50% network utilization model for the MSC Controller provided a compromise between network efficiency and tolerable network delay. Also, the network jitter is shown in Figure 5.11 to be correlating to the delay. The farthest Controller from MSC (i.e., CNT10) has incurred most of the jitter. The jitter is very excessive at 100% and is not acceptable.

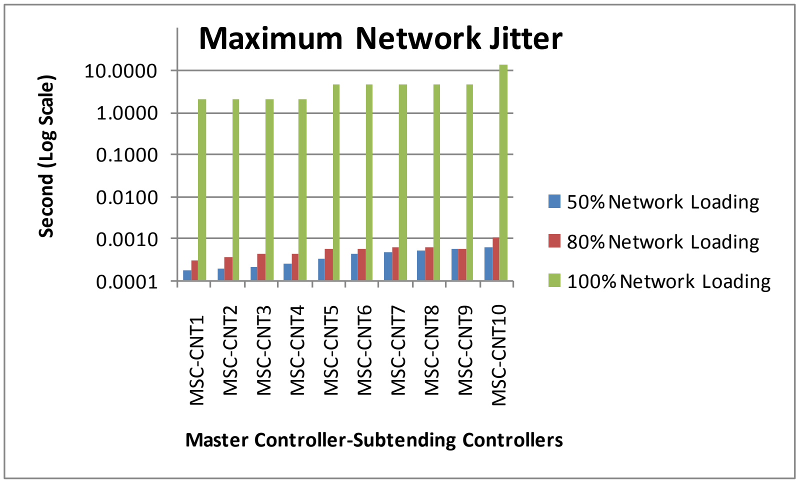


Figure 5.11 Converged Network: Master Controller to Controller Network Jitter Performance-Varying Traffic Load

Next, the simulation test case scenario examined the TCP retransmission timeout between the MSC and CNT10. The TCP timeout was apparent at 100% utilization and reached over 40 seconds. A semi-exponential relationship was established between the increase of network traffic loading and the TCP retransmission timeout. On the other hand, the TCP retransmission timeout was minimal at 50% and 80% utilization. Figure 5.12 shows the results.

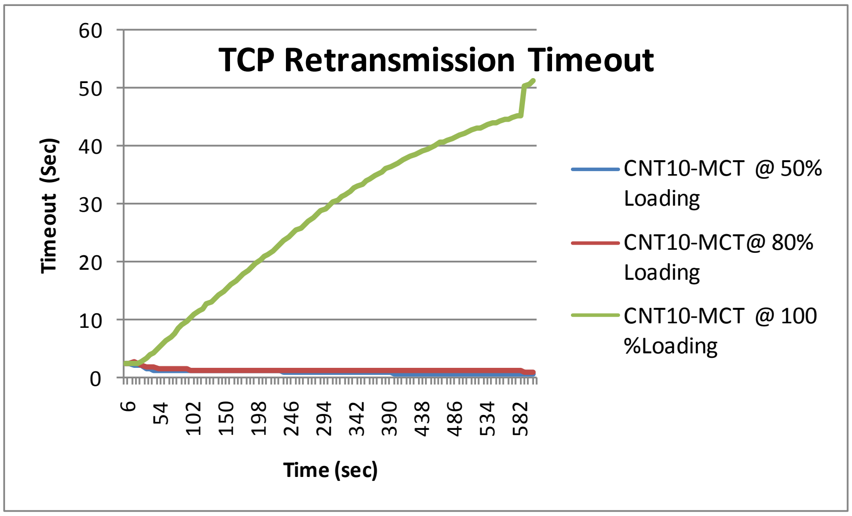


Figure 5.12 Converged Network: Master Controller to Controller Network TCP Retransmission Timeout Performance

Packet loss was examined in this BE CIP network. The high network utilization model impacted directly the HPAA PCS Controller packet delivery performance, depicted in Figure 5.13. The figure shows close to18% packet loss during the 100% traffic loading. However, at the 50% and 80% utilization, traffic loss was not observed.

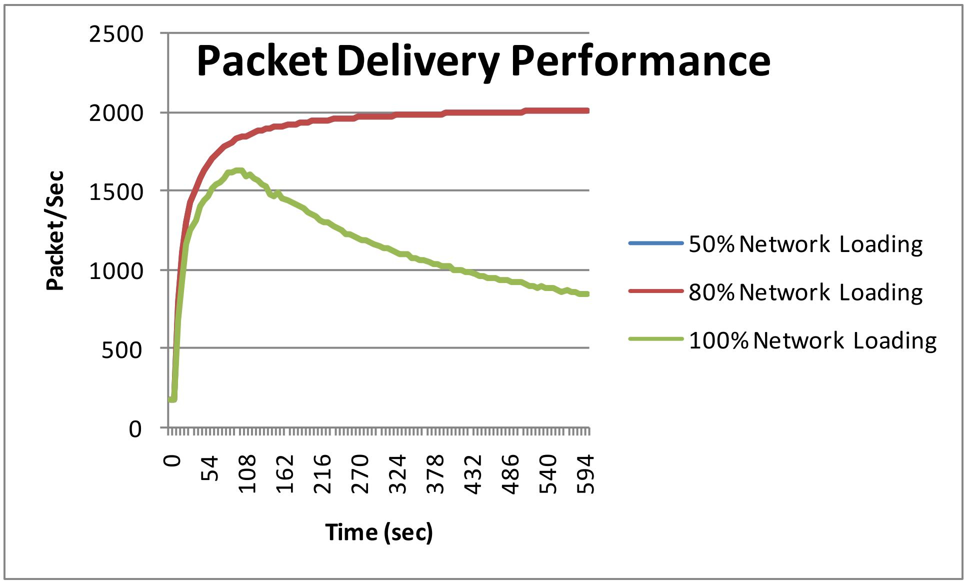


Figure 5.13 Converged Network: Packet Delivery Performance

5.3.2 Peer-to-Peer Controller Performance

The P2P performance between the inter-domains is considered a benchmark for the converged IP BE QoS network performance endurance for cross domain high traffic load when comparing it to dedicated network. In this test case scenario, CNT10 in the first domain communicating to CNT20 in the second domain; while both video and IP telephony traffic is progressing. The injected traffic load was increased from 50% to 80% and then to 100%**.**All the controllers CNT1 through CNT20 were also sending their traffic concurrently to the Master Controller. So, the composite impacts of HPAA and non-HPAA were examined.

Figure 5.14 illustrates the delay for the application and network. The application delay was extended from 0.83 ms at 50% to 4.0 ms at 80% and up to 18 seconds at 100%. As shown in the same figure, the network delay is in correlation to the application delay and following the traffic load increase semi-exponentially.

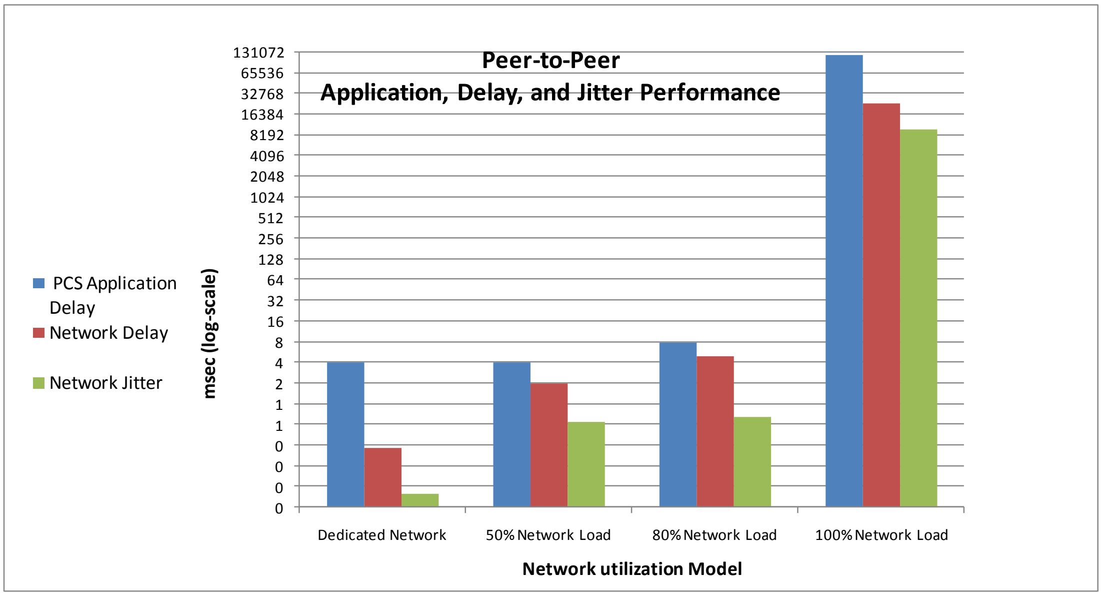


Figure 5.14 Converged BE Network: Peer-to-Peer Network Delay Performance-Varying Traffic Load

Another key performance indicator for the converged IP network is the TCP retransmission count, which is an indicator of network congestion in this case. The simulation outcomes were depicted in Figure 5.15. The results shows 38 counts of TCP retransmission for P2P in inter-domain as compared to four counts between the CNT20 to the MSC i.e., within the same domain during the simulated time. This increase stems from the number of increased Ethernet switches between the two P2P Controllers (CNT10-CNT20).

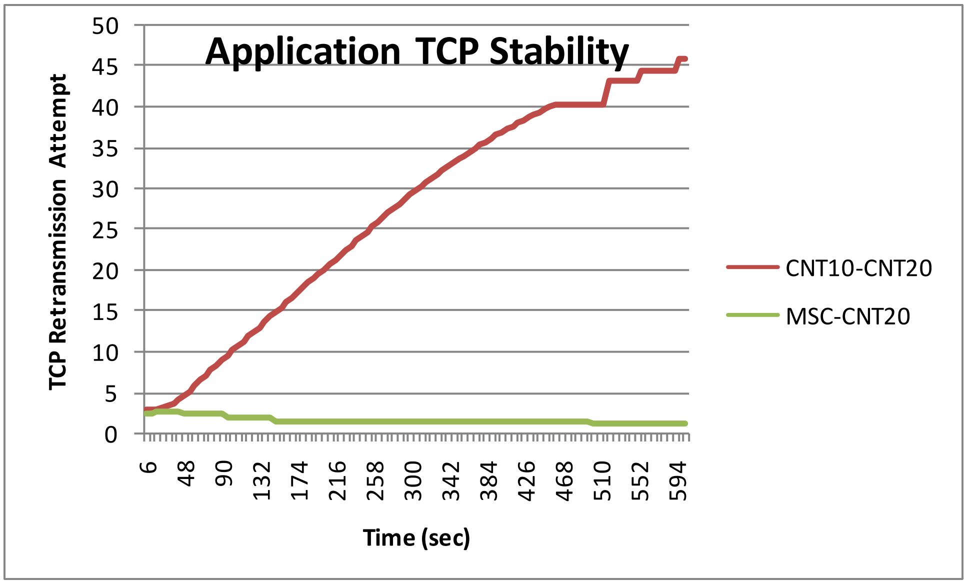


Figure 5.15 Converged Network: TCP Retransmission

This signifies the impact of traffic utilization between the P2P in cross domain converged network. Moreover, the Best Effort network robustness is exploited. TCP retransmission is not favorable behavior. PCS application may attempt to retransmit when TCP retransmission is encountered for certain number of tries and will revert to a safe shutdown if the subsequent transmission attempts are not successful.

5.3.3 Support Services Media (Video) Streaming and IP Telephony Performance

Support services, Video streaming and IP telephony performance were considered in the converged LAN IP network and were exposed to the traffic loading of 50%, 80%, and 100%. These services were provisioned based on BE application configuration, similar to the remaining applications to ensure a consistent network setting. The 100% loading had direct impact on both the IP telephony and Video quality.

Moreover, support services performances in cross domain traffic were simulated. The simulation includes IP Telephony and video streaming within the same domain. In addition, cross domain support service, voice, was simulated. IPTel-10 to MSC IPTel-10_10 and IPTel-10 to IPTel-20 voice sessions were running during the simulation period. Moreover, CNT10 in the first domain was communicating to CNT20 in the second domain. The injected traffic load was increased from 50% to 80% and then to 100%. The application and network delay was correlated to the increased traffic load, resulting in extended delay of voice and video service to unacceptable levels within the same domain.

Table 5.1 illustrates the application performance as compared with the different traffic load increases. An increase of 8% in voice packet delay was noted, when going from 50% to 80%. On the other hand, video had an increase in delay close to 41%, mainly attributed to the actual video bandwidth as well as the additional injected traffic load. An exponential increase in delay is witnessed for both services when the traffic load increased from 80% to 100%.

Table 5.1 Support Service, IP Telephony & Video Streaming Intra-domain Performance

Maximum Delay (ms)	**Dedicated**	**Best Effort**		
Traffic Loading	0%	50%	80%	100%
Master Controller	0.28	5	7	47000
P2P	0.29	0.83	4	18000
IP Telephony	NA	60	65	38000
Media Streaming	NA	0.001	7.8	8000

The IP Telephony inter-domain performance, IPTel-10 to IPTel-20, shows a slight increase in delay between the 50% and 80% loading. The 50% loading impact on delay was 60 ms as compared with the 80% loading at 65 ms. This shows an increase of 8.3%.

The 100% utilization shows an excessive and intolerable delay of over 38 seconds, as depicted in Figure 5.16.

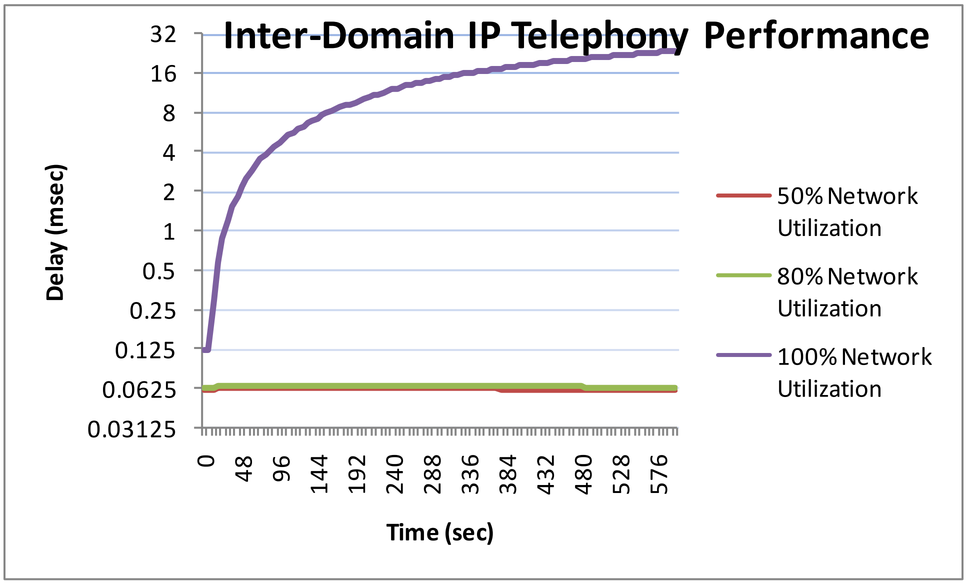


Figure 5.16 IP telephony Inter-Domain Performance

5.3.4 Packet Loss

The high network loading impacted directly the HPAA PCS Controller packet delivery performance, as depicted in Figure 5.17. The figure shows the inter-domain packet delivery as having close to 47% packet loss during the 100% traffic loading for a period of 10 minutes of simulation time. However, at the 50% and 80% utilization traffic loss was not observed. Since the nature of the HPAA application is TCP based, packet loss is not desirable as it will result in data retransmission. This behavior creates a compounding effect, which overtime may increase the packet loss to a much higher level than the 47%.

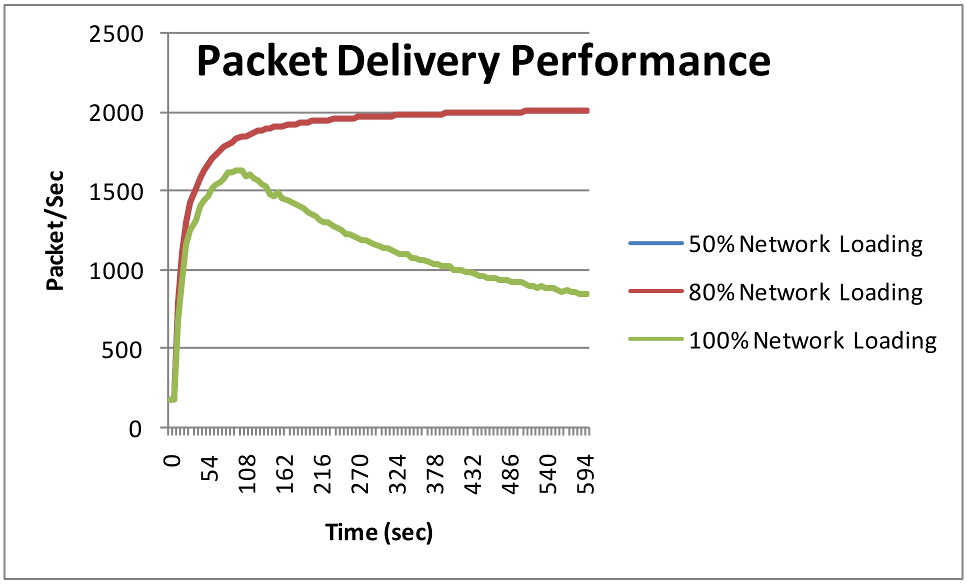


Figure 5.17 PCS Inter-Domain Controllers Packet Loss Driven by Network Loading

Concurrently, the support service such as IP Telephony packet delivery was impacted by the traffic loading, specifically at the 100% loading, as shown in Figure 5.18. At 100% loading, an average of 14% of the traffic was lost. Traffic loss was not observed at 50% and 80%.

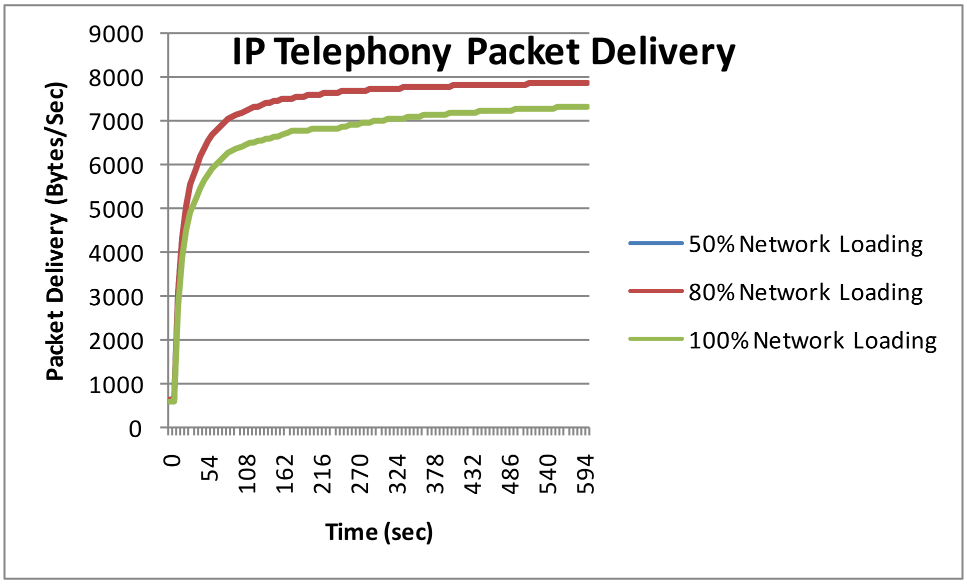


Figure 5.18 IP Telephony Packet Loss Driven by Network Loading

The media streaming packet delivery was partially degraded at 80% utilization. The estimated packet loss is close to 1%. However, at 100%, the packet delivery loss was close to 8% as shown in Figure 5.19. This is not acceptable for such an operating environment since media streaming is TCP based and the nature of TCP is to retransmit lost packets, hence, increasing the traffic load unnecessarily may cause more lost media packets over time.

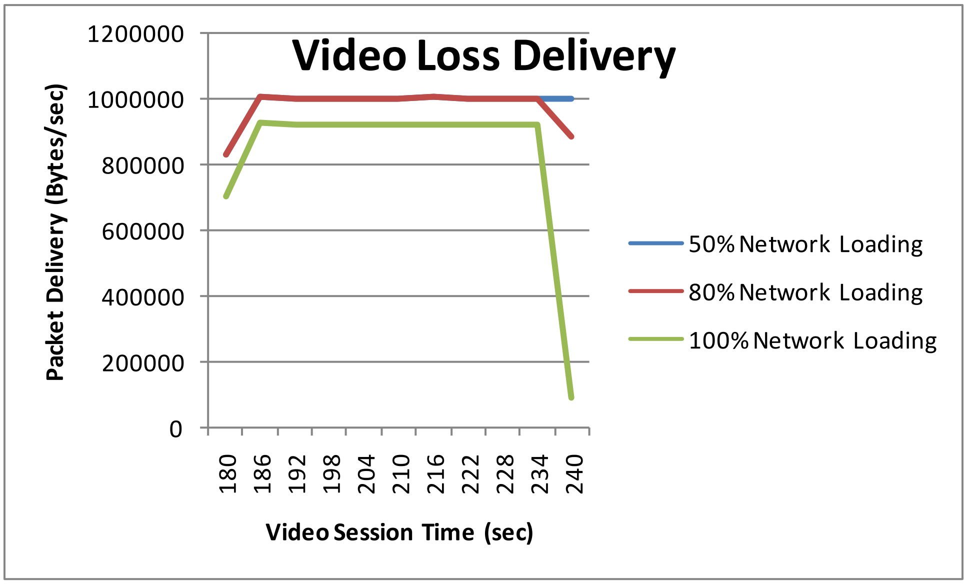


Figure 5.19 Media Streaming Packet Delivery

5.4 PRIORITY BASED SCHEDULING QUALITY OF SERVICE CONVERGED IP LAN ENABLED NETWORK

This section shows the simulation case study scenarios' results of converged IP LAN network with Priority based Scheduling QoS setting for multi-service and multi-priority environment. The highest priority, priority 7, was assigned for the HPAA PCS Controller application. This convention will secure allocating the highest network resources for the HPAA PCS Controller's traffic. Support services such as voice was assigned priority 6; video streaming priority 5, large file transfer was assigned lowest priority; best effort priority 0. The objective is to examine the HPAA PCS and support services performance to a predefined traffic load; 50%, 80%, and 100% network utilization.

5.4.1 Master Controller and Subtending Controllers Performance

The HPAA PCS Controller application IP network performance under the different loads, 50%, 80%, and 100% are simulated and results are depicted in Figure 5.20. As expected, Priority based Scheduling will allocate the highest level of network resources for the application that has highest priority and this case HPAA. The maximum, average, and minimum time delay performance are close to each other for the traffic loads in question. The average time delay increased by 0.2 ms (i.e., 4.2 ms to 4.4 ms) when loading was increased from 50% to 80% utilization and also the delay increased by another 0.4 ms (i.e., 4.8 ms) when loading is progressed from 80% to 100%.

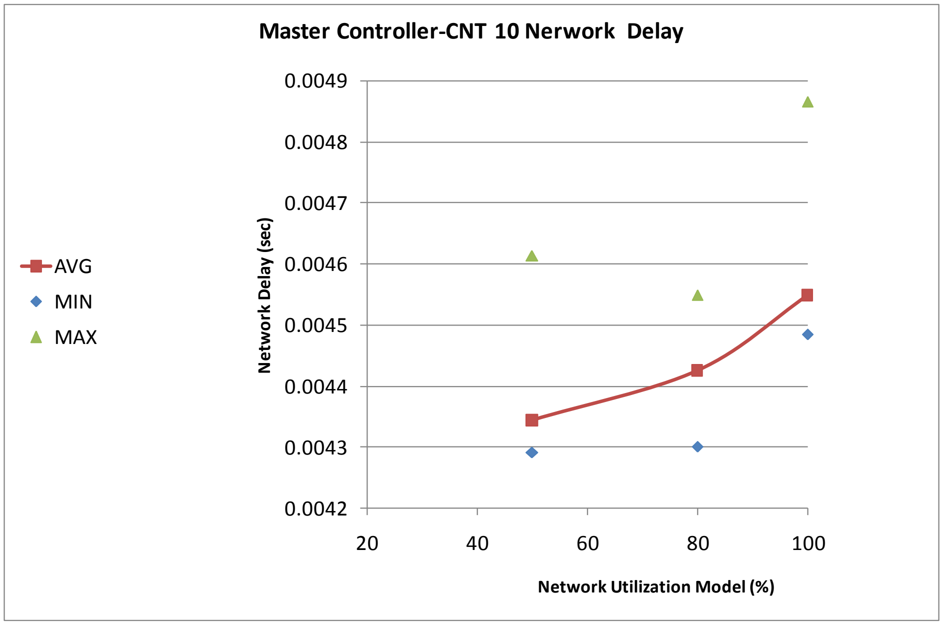


Figure 5.20 Master Controller Network Delay

Next, the simulation test case scenario for HPAA PCS demonstrated the network performance relating to TCP. Both TCP retransmission count and timeout were tracked. The simulation shows the TCP retransmission timeout is at 1s which is within the maximum allowable application pull cycle of 1 second. The application TCP retransmission timeout is depicted in Figure 5.21. The TCP retransmission count was zero.

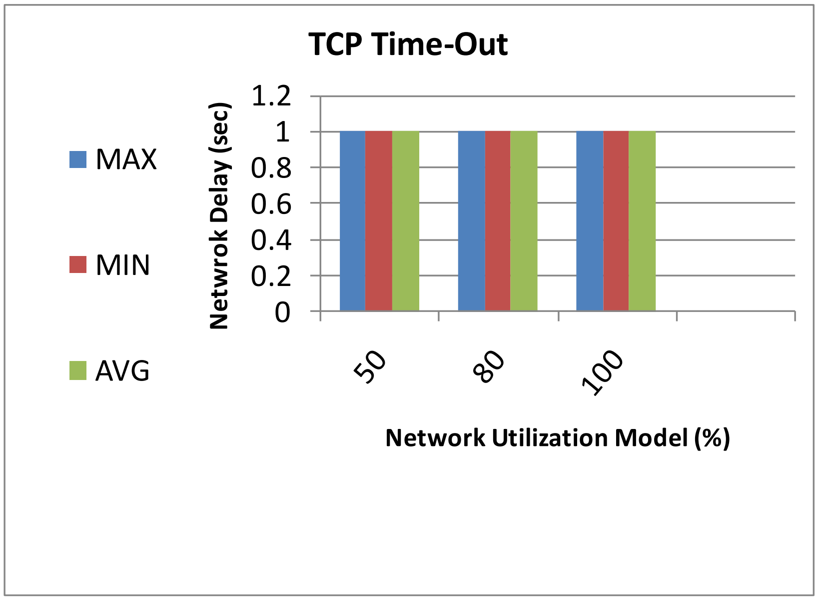


Figure 5.21 TCP Retransmission Timeout

Packet delivery integrity was also demonstrated in the simulation results. The intent is to measure the priority based schedule QoS setting on the packet delivery. As expected, the HPAA dropped IP packet for the application under the different loading scenarios was zero as shown in Figure 5.22. This is consistent with the traffic sent and received where both are equal (i.e., no traffic loss) as shown in the same Figure 5.22

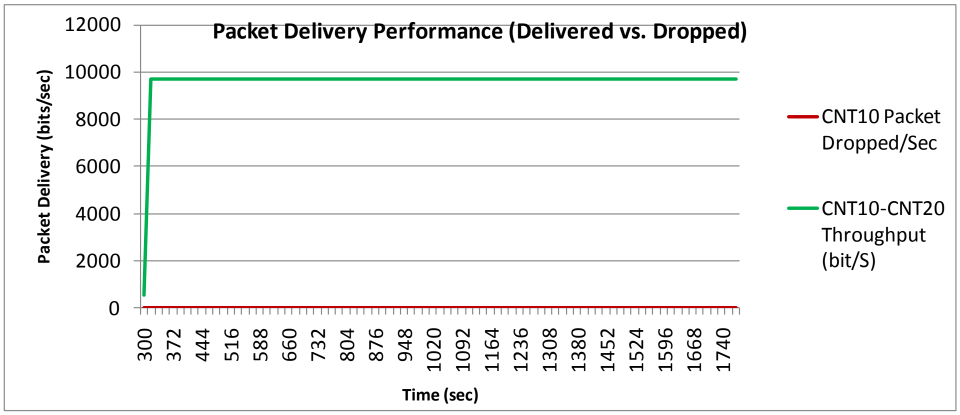


Figure 5.22 Dropped Packet vs. Traffic Sent/Received

5.4.2 Peer-to-Peer Controller Performance

The Peer-to-Peer (P2P) HPAA PCS Controller application performance results are focused on examining the traffic loading impacts on the farthest two Controllers in each domain. And, in this case CNT10 in Domain-1 and CNT20 in Domain-2 when communicating with each other. Network delay, TCP retransmission, and packet dropped are key parameters that are utilized in defining the impacts. A linear trended relationship is formed between the increase in traffic loading and the application delay. The 50% utilization showed least network delay followed by the 80% and then 100%. The application delay performance is depicted in Figure 5.23. The maximum round trip delay is 5.2 ms. As illustrated in the subsequent network and application's performance measures, the delay is minimal and below 10ms which is seamless to the application behavior. This outcome is very important as it shows the strength of QoS priority based settings which lead to acceptable application performance in a heavily loaded network.

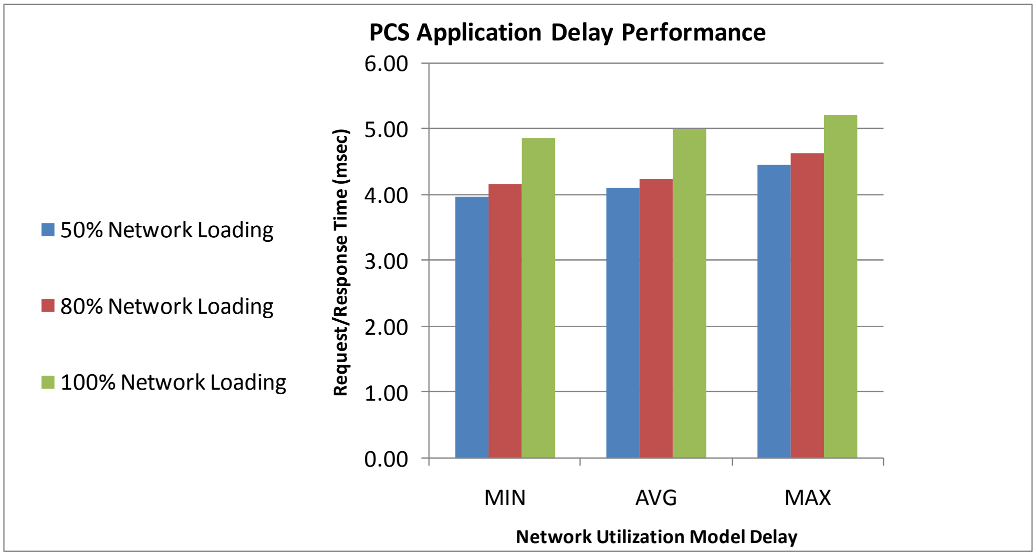


Figure 5.23 P2P Application Round-Trip Time Delay Performance

The one way application delay is illustrated in Figure 5.24. The maximum response time delay is 3.2 ms. And, this is equal to 62% of the round trip delay. The increase in response delay is mainly attributed with the other non-HPAA traffic being sent in the direction of CNT10, Domain-1.

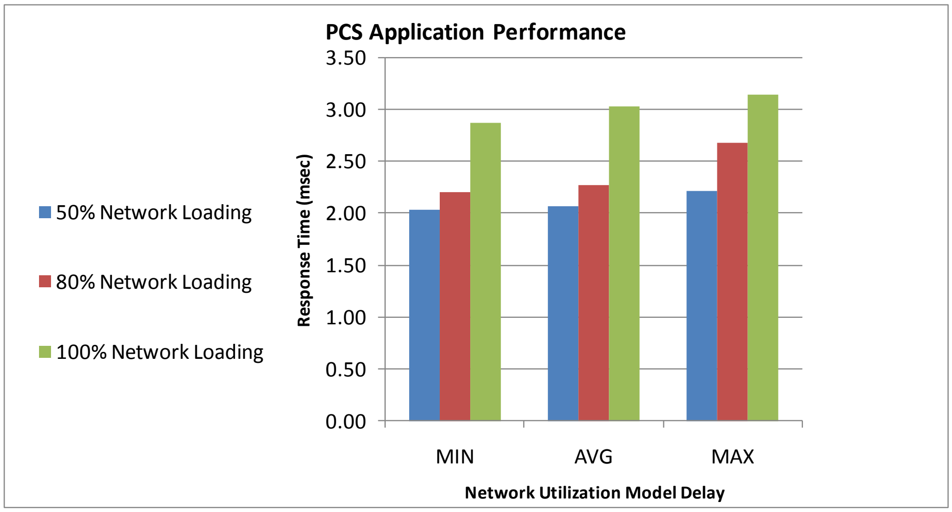


Figure 5.24 P2P Application One Way Time Delay Performance

The IP network layer delay performance for P2P PCS application is depicted in Figure 5.25. The simulation results show a maximum delay of 3 ms. This is less than the expected application delay by 0.2ms. Number of IP Ethernet switches, nodes, is key contributor to the IP network delay.

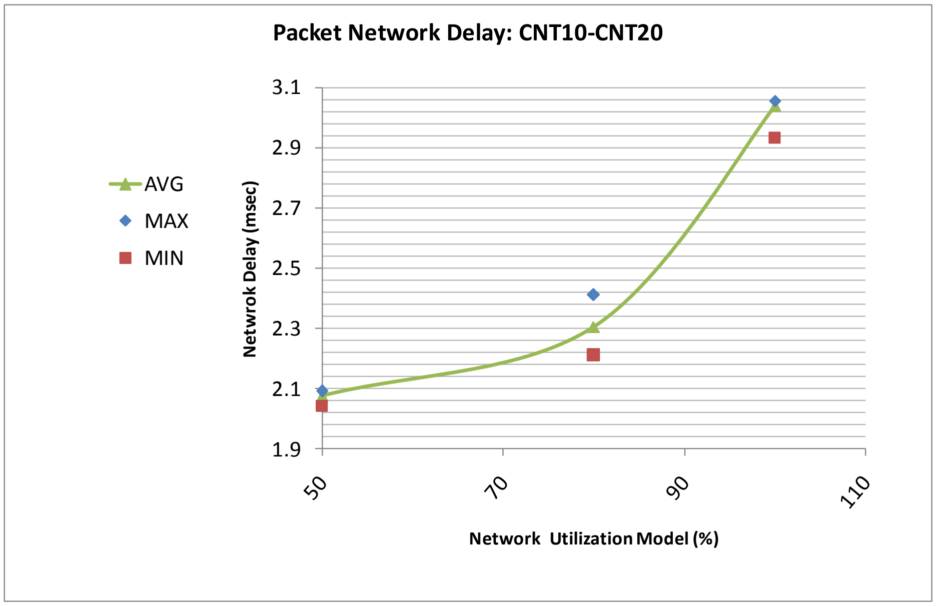


Figure 5.25 Peer-to-Peer IP Network Delay Performance

In this test case simulation scenario, the packet delivery for the P2P PCS Controller has zero dropped packets. This was attested by both packet dropped rate and the packet sent/received as depicted in Figure 5.26. This finding is very important as it shows cross traffic reliability being achieved through enabling priority based scheduling.

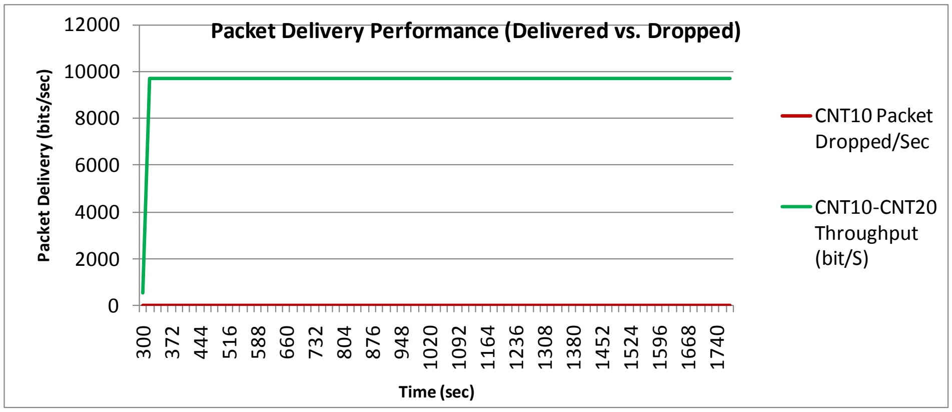


Figure 5.26 P2P Packet Dropped vs. Delivery Performance

The P2P TCP session performance was healthy in Priority based Scheduling QoS network model. The simulation shows zero TCP retransmission count and a 1s maximum TCP retransmission timeout as defined by the application pull cycle as shown in Figure 5.27. This demonstrates TCP session performance for the PCS application.

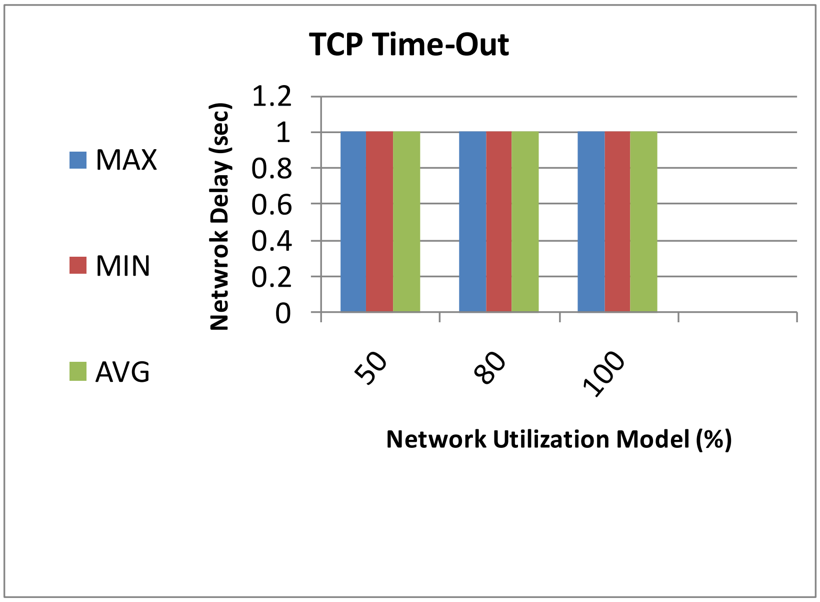


Figure 5.27 Peer-to-Peer PCS TCP Performance

5.4.3 Converged IP Media Streaming and IP Telephony Performance

Support services such as IP telephony and media streaming performance were investigated for the different network traffic loading. Delay, jitter, and packet loss were key parameters to track. The IP telephony network delay for the different traffic load, 50%, 80%, and 100% was within an acceptable delay rate; 59 ms, 60.05 ms and 62 ms accordingly as shown in Figure 5.28.

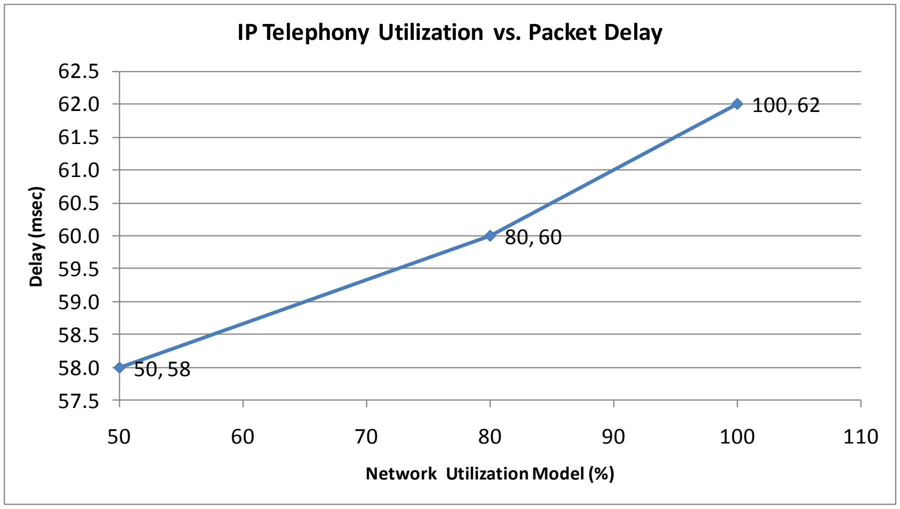


Figure 5.28 IP Telephony Application Delay Performance

Jitter is also another key performance indicator on the communication link integrity. In this simulation’s test case scenario, the jitter was tracked and reflected in Figure 5.29. As expected, under Priority based Scheduling and in all network loading test case scenarios, jitter is performing within an acceptable rate, at the microsecond level. This is transparent to the applications and provides seamless orderly packet communication.

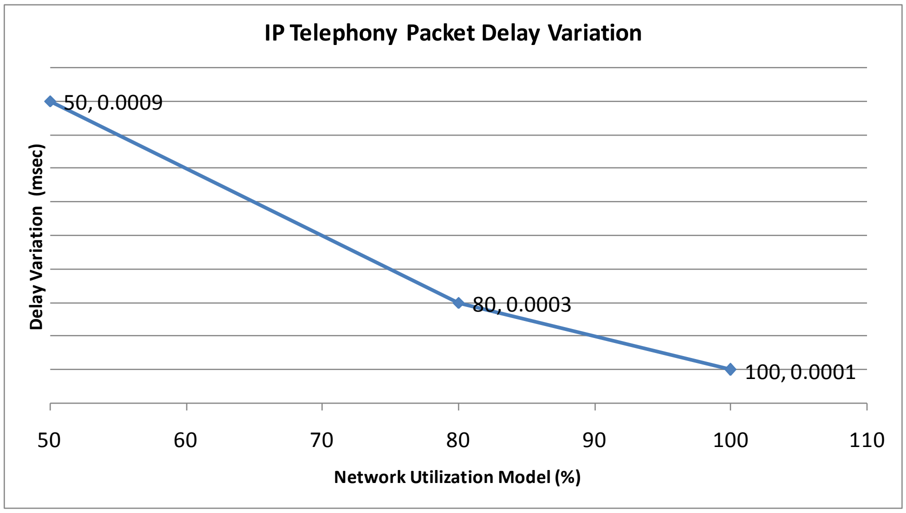


Figure 5.29 IP Telephony Application Jitter Performance

Figure 5.30 illustrates the IP telephony packet delivery integrity. The figure shows the packet loss ratio was zero. Moreover, the input and output throughput was identical implying excellent delivery. Packet loss is an essential measure for the integrity of the voice session.

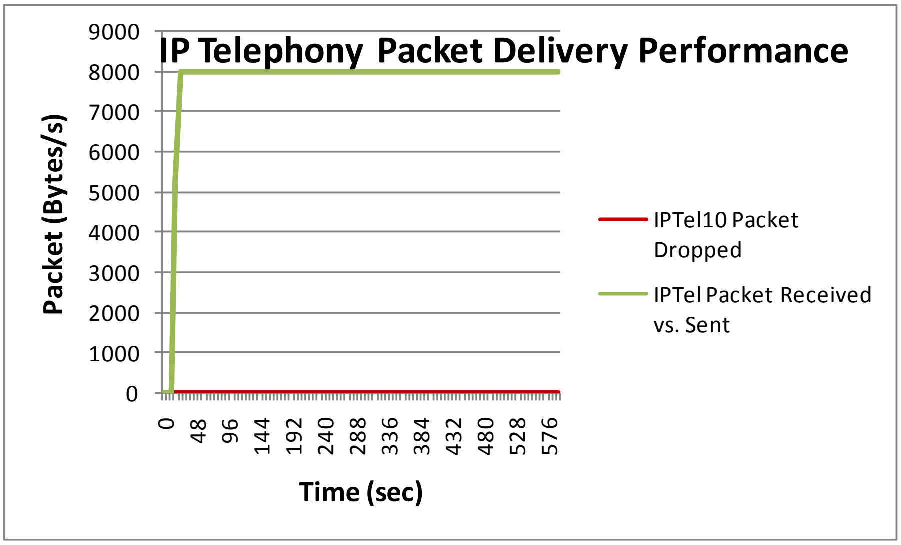


Figure 5.30 IP Telephony Application Packet Dropped and Delivered Performance

The cross domain IP Telephony service measure the timeliness of LAN network as this requires the communication session to traverse multiple network segments. In this simulation test case scenario, IP phones were placed at the two farthest ends of the network to assess how much delay this service will endure. The simulation result depicted in Figure 5.31 shows network delay for cross domain voice traffic at 60.34 ms. This is significantly below to the maximum allowable delay of 150 ms for IP voice service.

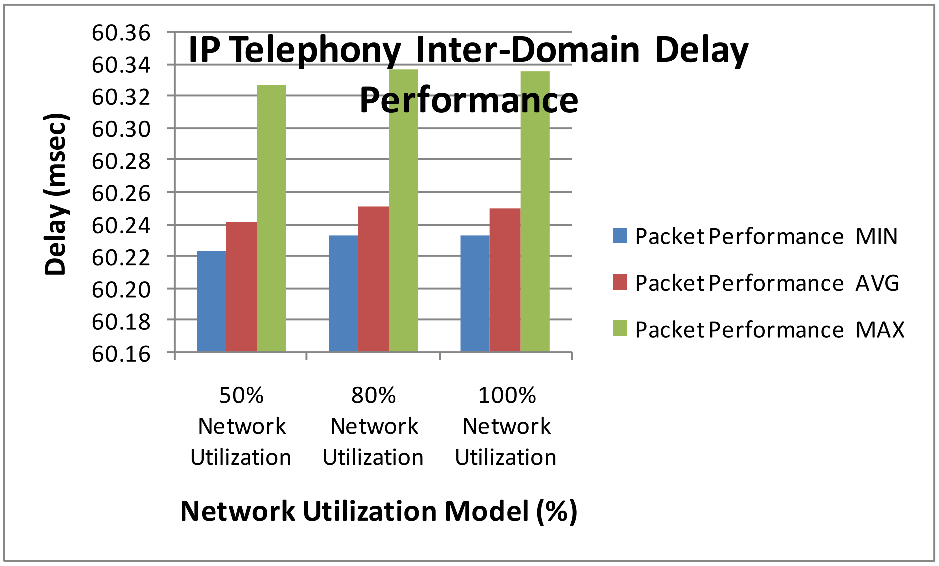


Figure 5.31 IP Telephony Cross Domain Application Delay Performance

IP telephony jitter was also tracked in this simulation test case scenario. It is expected to have minimal jitter due to the nature of IP telephony, utilizing UDP protocol. Moreover, IP Telephony was assigned second in Priority based Scheduling QoS setting. And, as expected, the jitter was in the sub-microsecond as shown in Figure 5.32. IP Telephony uses UDP, hence some packets are dropped.

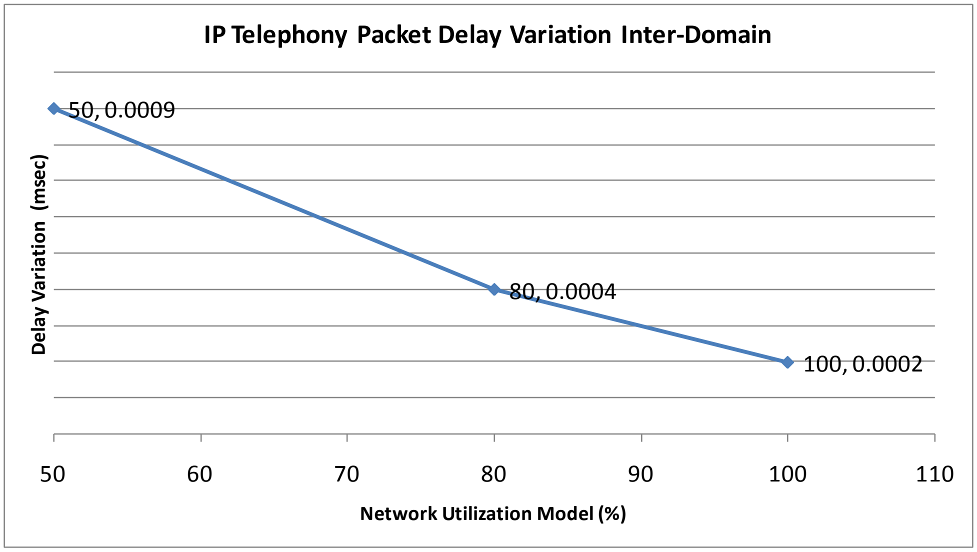


Figure 5.32 IP Telephony Cross-Domain Application Jitter Performance

The media (video) streaming service benefited from the QoS setting, Figure 5.33, even though it was placed with priority 5 i.e., below the PCS Controller and voice traffic. The video streaming application delay was at 78 ms for the highest network utilization, 100% loading. The video streaming application delay was below 15 ms for 50% and 80% network loading.

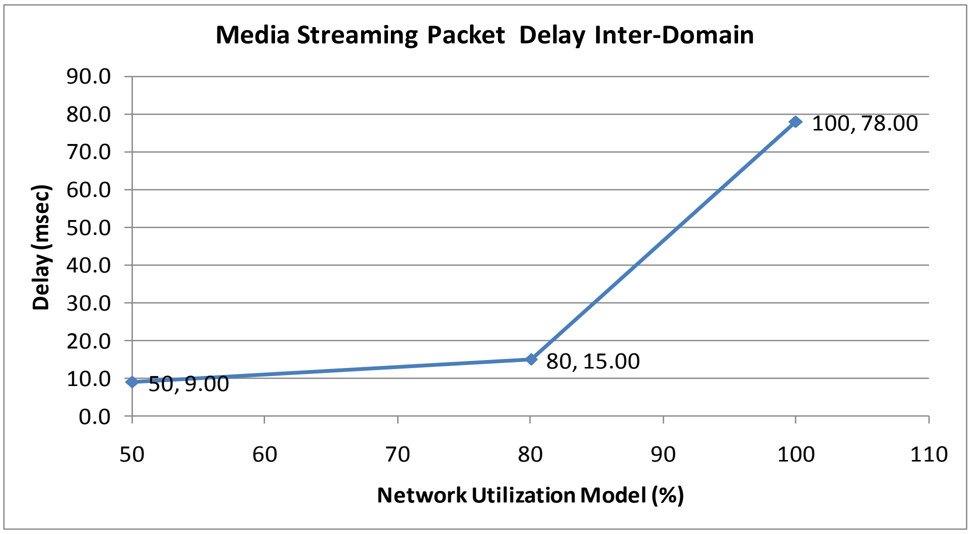


Figure 5.33 Media streaming Application Delay Performance

Jitter was also examined in this simulation test case scenario. In Figure 5.34, jitter for video streaming application is presented. The simulation shows sub millisecond time variation for the media streaming application. This is considered minimal and has no impact on the over quality of the media streaming session. Such an outcome shows the added value of QoS Priority based Scheduling setting on the performance of this application even though it is third in priority.

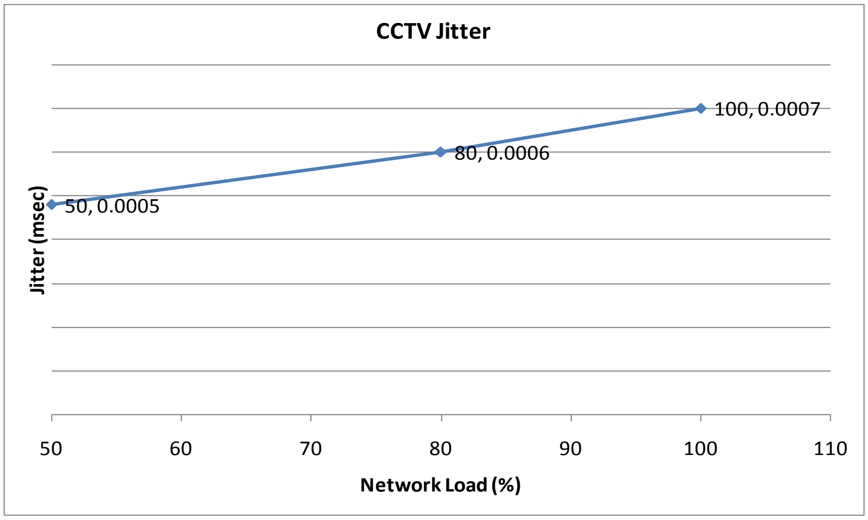


Figure 5.34 Media Streaming Jitter Performance

This concludes the HPAA PCS performance results reporting for the LAN network design. Detailed discussions for the different simulated test case scenarios are reflected in Chapter 6. Support services, IP telephony and media streaming, are also included. In addition, a comparative analysis is conducted to identify relationships between the experimental cases studies of Chapter 4 and the simulated test case scenarios covered in this section.

Next section, Wide Area Network design (WAN) simulation test case scenarios results are reported. Consistent with the LAN network model, test cases are focused on delay, jitter, packet loss, and application stability under predefined network loading.

5.5 CONVERGED IP WIDE AREA NETWORK

Simulation results for HPAA PCS Wide Area Network (WAN) are presented in this section. Performance results for the three different network scenarios; dedicated, BE, and Priority based Scheduling QoS converged IP network are included. Moreover, a remote PCS Area utilizing a wireless backhaul link connected to the WAN was also simulated to explore and reflect the impacts on the WAN network. Similar to the LAN network model, the primary objective is to report the application and network performance behaviors for the HPAA PCS Controllers under different CIP network models exposed to traffic network loading of 50%, 80% and 100% utilization network models. Support services such as IP telephony and media streaming will also be reported. Two key relationships are the primary targets for the simulation test case scenarios. These are: Remote HPAA Controller in a PCS Area communicating to a centralized Controller (HPAA Master Controller), the second is HPAA Controller in one PCS Area that is tightly coupled to another HPAA Controller in another PCS Area. All the Controllers are located in different geographically dispersed sites and connected via high speed Gbps WAN as detailed in Chapter 3 (research design).

As part of all the simulated test case scenarios support services such as voice, and media (video) streaming performance were examined. Figure 5.35 shows the WAN network topology. Four different HPAA PCS Areas are connected together by a high speed backbone network to a PCS Virtual Center (PCSVC) as defined in the research design outlined in Chapter 3.

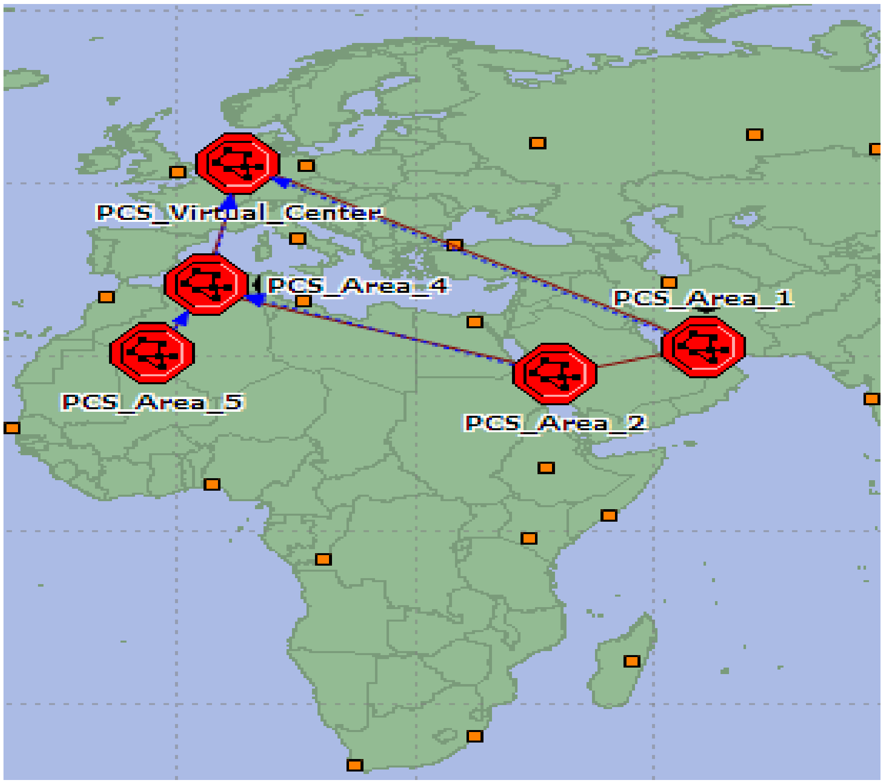


Figure 5.35 WAN Network Topology

5.5.1 Dedicated Wide Area Network

The HPAA PCS Controller application performance utilizing a dedicated WAN was explored by simulation test case scenarios. The dedicated WAN network topology and design assumption were outlined in Chapter 3, Research Design. The focus is to establish a performance benchmark for a dedicated WAN network and compare that to BE and Priority based Scheduling QoS Converged IP network. The traffic load between the different PCS Areas 1 through PCS Area 5 is based on steady state operation addressing both P2P controllers and Master and subtending Controllers message exchange. The Master Controller is located in Area 3 and is identified as PCS Virtual Center (PCSVC).

The quality of service parameters settings for the HPAA application, Controller, network switches, and interfaces were the same. This is to ensure a consistent network platform that will support the intent of the simulation test case scenarios. Delay, jitter, packet loss, application stability such as retransmission attempts, TCP retransmission and TCP retransmission timeout are variable measures that will be examined in the simulation test case scenarios.

5.5.1.1 PCS Virtual Center Performance

The PCS Virtual Center (PCSVC) has the functionality of collecting process variables from all the PCS Areas as well as extend logic control loop over the WAN. In this simulation test case scenario, the intent is to identify the performance of the HPAA PCS Virtual Center. The focus will be on the relationship between the PCSVC and remote PCS Areas' Controllers. Also, P2P logic control will be explored in this simulation. Figure 5.36 depicts the application round trip delay between the Master Controller in the PCSVC and remote site Controllers in PCS Area1 (CNT10), and PCS Area 2 (CNT20) and PCS Area 5 (CNT6) in a dedicated network environment. The roundtrip application delay for these sites ranges from 38 ms to 70 ms.

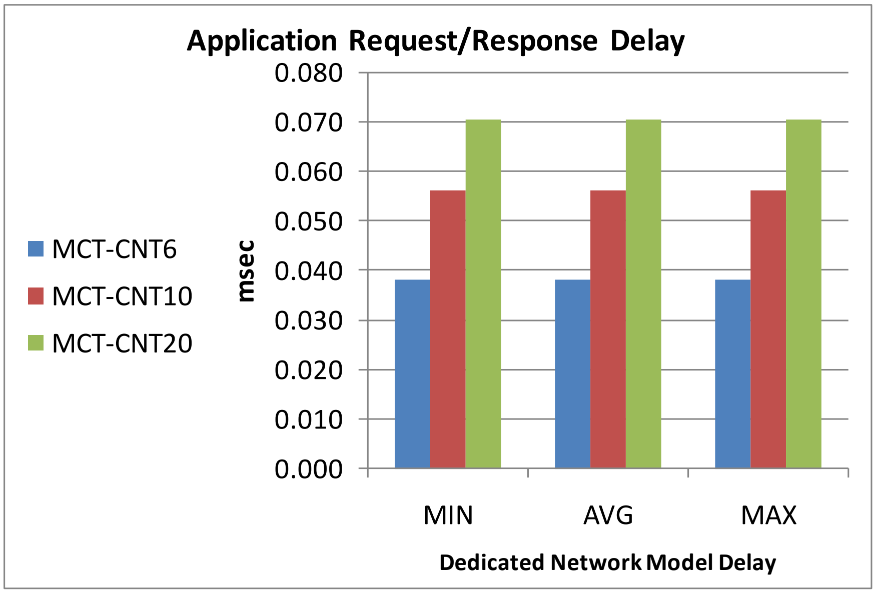


Figure 5.36 PCSVC to PCS Areas Controller Application Two-Way Delay

The one way delay which is an indicator for the network timeliness of a request or a response was obtained from this test case scenario. The outcome is illustrated in Figure 5.37. This figure shows the packet response time delay between PCSVC and each of the active remote PCS areas. The outcomes are not similar for all of the different remote sites since it is fully dependant on the network architecture and topology. For example, PCS Area 2 CNT20 has one intermediate backbone node connecting to the PCSVC to PCS Area 5 which has contributed in additional delay as compared to PCS Area 1 which has direction connection. The one way delay ranges for these different facilities from 19 ms to 33 ms.

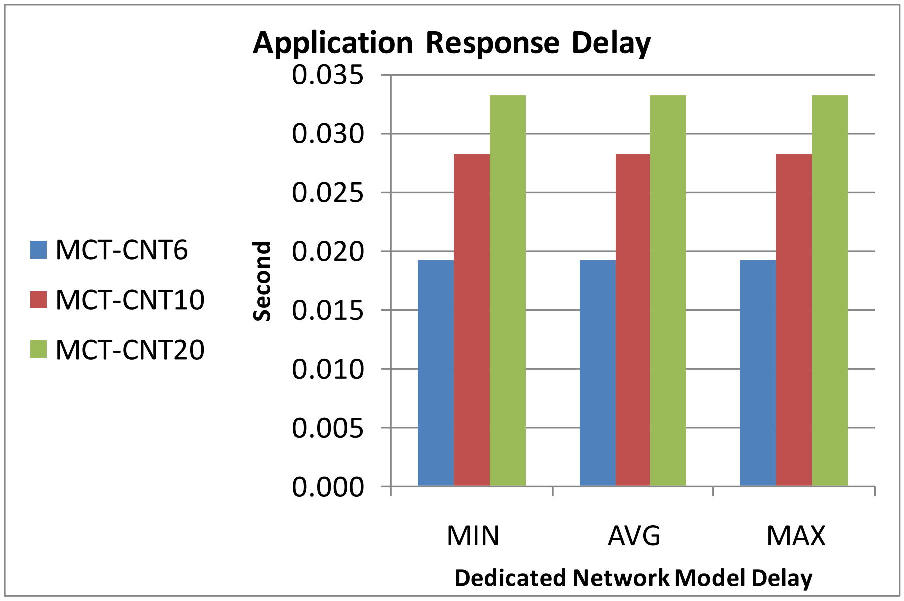


Figure 5.37 PCSVC to PCS Areas Controller Application One-Way Delay

Jitter is illustrated in Figure 5.38 and it ranges in the sub milliseconds for dedicated simulation test case scenario. As expected, the wireless spur backhaul link, PCSVC to PCS Area 5, incurred the highest jitter. The jitter between these two sites was at 313 µs as compared with164 µs for the high speed wired backhaul link connecting PCS Area 1 and Area 2. This resembles a 100% increase in the wireless backhaul link but still in the sub millisecond.

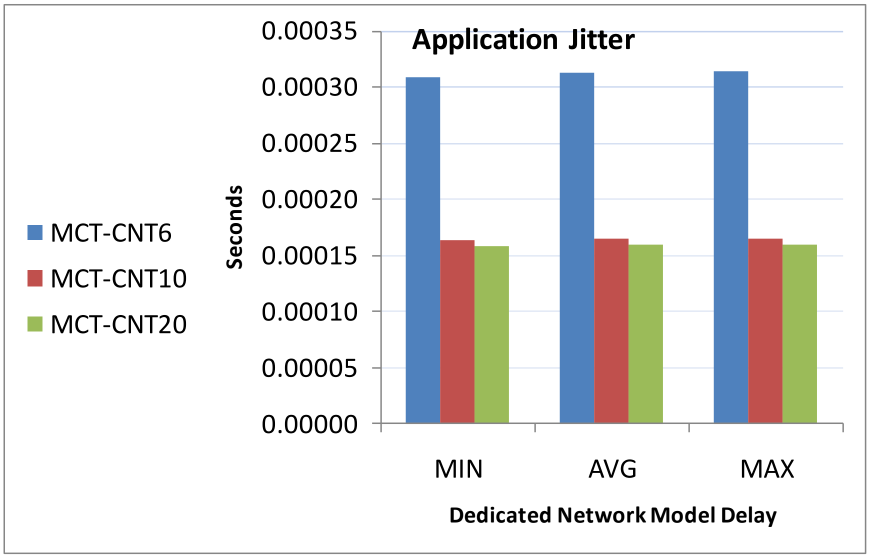


Figure 5.38 PCSVC to PCS Areas Controller Network Jitter

The dedicated network packet loss, as expected, had zero packet loss between the PCS Controllers that are dispersed network wide and the PCSVC. This resembles the strength of dedicating a high speed backbone standard Ethernet network for HPAA PCS application in eliminating packet retransmission. Figure 5.39 shows the sent and received bytes and the numbers reflect identical correlation for each PCS Controller relationship.

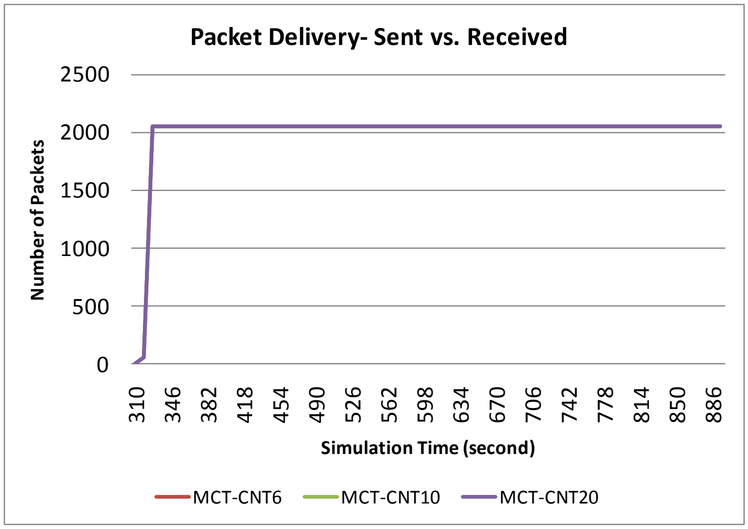


Figure 5.39 PCSVC to PCS Areas Controller Traffic Delivery

As expected, the TCP retransmission count was zero since the network is dedicated and there is no other traffic competing for the same network resources. The TCP retransmission timeout is 1 second for all the simulated test case scenarios and this is attributed to the nature of the application as it is configured based on 1 second cyclic poll. The TCP retransmission timeout performance is depicted in Figure 5.40.

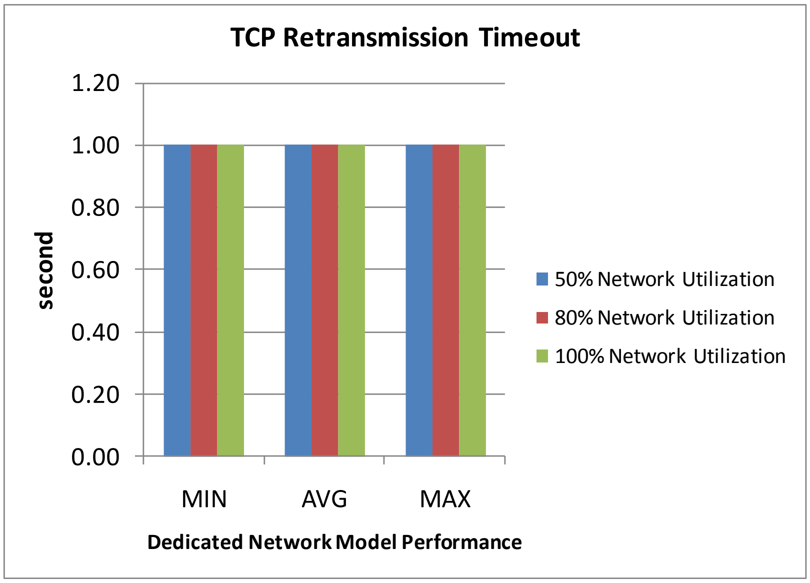


Figure 5.40 PCSVC Master Controller – PCS Areas TCP Retransmission Timeout

5.5.1.2 Dedicated Network Peer-to-Peer (P2P) PCS Controller Performance

The P2P application and network performance is another measure for the cross traffic and its fitness for HPAA PCS application. PCS Area 1 (CNT 10) has two concurrent control logic relationships with PCS Area 2 (CNT20) and PCS Area 5 (CNT6). Application roundtrip delay performance is depicted in Figure 5.41 and is in the range of 20 ms to 85 ms.

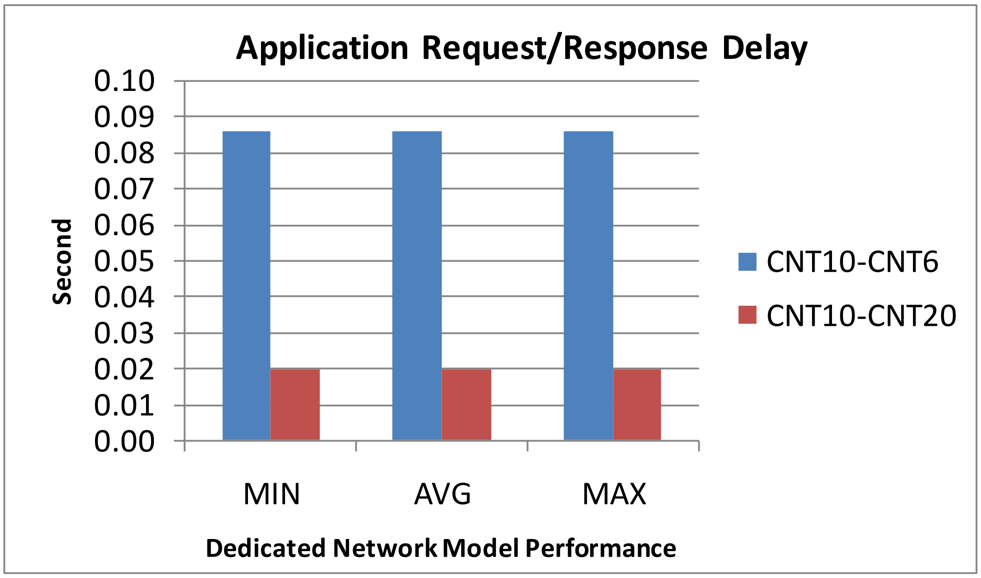


Figure 5.41 Peer-to-Peer PCS Application Delay

The network delay is illustrated in Figure 5.42. Delay is predominately driven by the PCS application as well as by the intermediate nodes connecting the different PCS areas. The intent of this simulated test case scenario is to identify delay for two adjacent nodes and at least one network hub in between. Moreover, both wired and wireless backhaul links as defined in the research design were examined. The results show a network delay that spans from 10 ms to 47 ms. The upper bound of the delay is driven by the wireless high-speed link connecting PCS Area 5, CNT6 to PCS Area 1, CNT10.

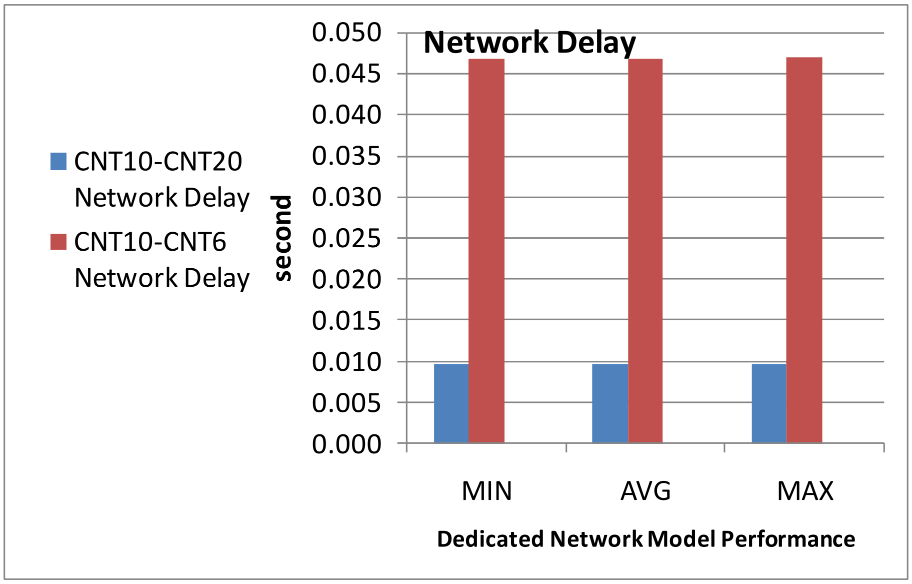


Figure 5.42 P2P IP Network Delay

The network IP layer jitter which is an indication of the routed IP traffic between the different network nodes serving the HPAA PCS is reflected in Figure 5.43. The jitter ranges between 120 μs to 160 μs which is considered transparent to the application layer.

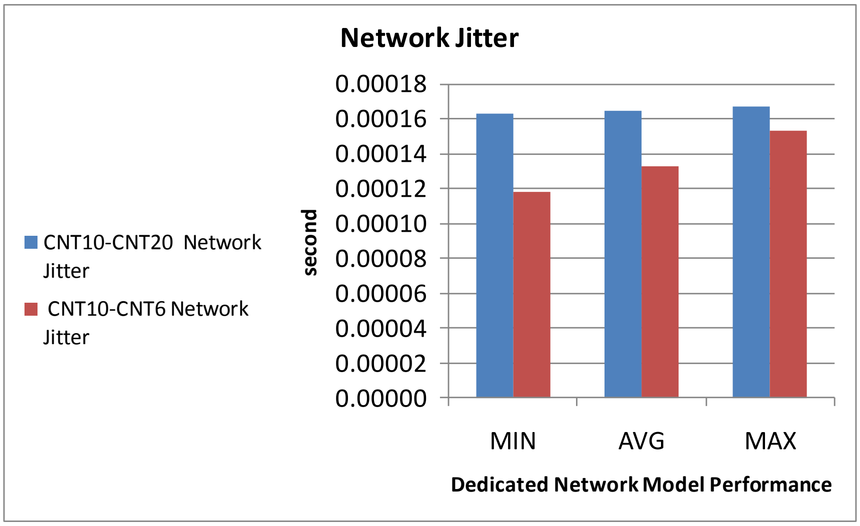


Figure 5.43 Peer-to-Peer IP Network Jitter

Another important result identified is the quality of the application transmission in a P2P mode. Packet loss was used to demonstrate this objective by tracing the number of HPAA PCS traffic packet sent and received between the different PCS Areas. The simulated test case scenario outcomes show zero packets were lost. This is reflected in the simulation results of Figure 5.44.

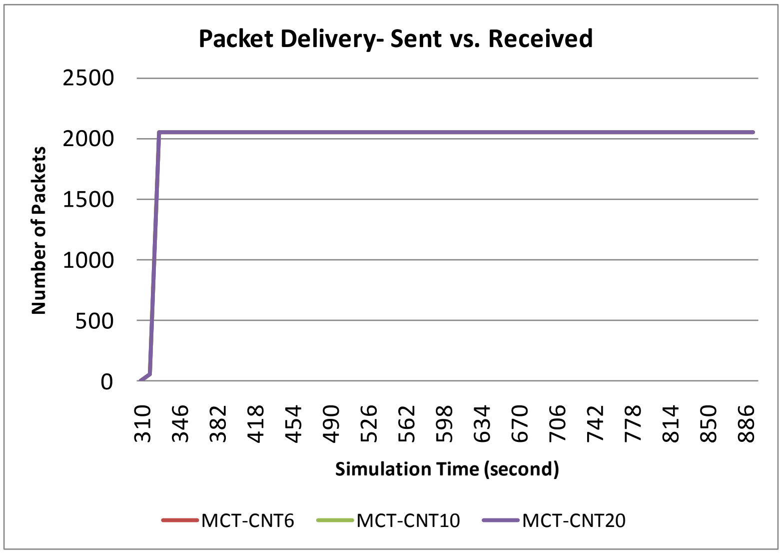


Figure 5.44 PCS Area to PCS Areas Packet Delivery

5.5.2 Converged IP with Best Effort (BE) QoS Network Settings

The converged IP network performance simulated test case scenario with BE settings was explored. In this CIP network, HPAA PCS Virtual Center was communicating to remote PCS Areas as well as the remote PCS Areas communicating to each other. Moreover, services such as IP telephone, media streaming, supported by the same network topology, and were running concurrently with HPAA PCS application. The simulated test case scenarios objective is to answer how will a BE QoS WAN network perform in a CIP network model? Hence, the BE QoS settings were maintained based on the simulation test case scenarios' parameters defined in the research design in Chapter 3.

As part of this test case scenario, the HPAA PCS performance will be examined in a consistent BE QoS parameter settings for all the different network elements. This includes the PCS Controller, network switches, and interfaces. Similarly, support services elements IP phones, IP telephony server, video cameras and video server were also configured with the same BE QoS parameters.

The CIP network was exposed to a network loading that increased from 50%, 80%, to100% network utilization. Traffic generator was placed at the different remote sites to ensure the WAN backbone network links have uniform network utilization as defined in the research design. Simulation results are illustrated and presented in the subsequent sections.

5.5.2.1 PCS Virtual Center Performance

The PCS Virtual Center (PCSVC) has two tightly Controller relationships, PCS Area 1 which is an adjacent node and PCS Area 2 that has at least one hop, a backbone node, in between. Simulated traffic injector was varied at 50%, 80%, and 100% network loading of the available bandwidth (1 Gbps). The injected traffic load was triggered at a steady state for 15 minutes of simulation time while the PCS application is communicating to the different PCS elements, intra-node and inter-node. Moreover, IP telephony and media streaming are establishing their independent communication pairings.

The simulation outcomes show delay in both application and network response time that was apparent. The delay primarily resulted from the switching buffer congestion caused by injected traffic load as well as support services such as video streaming and IP telephony. By inspecting the trunk utilization, Figure 5.45, there is an apparent delay that correlates directly to the network utilization behavior. It must be noted again, the first 900 Mbps for the trunk is sliced out, reserved, and the primary focus is the last 100 Mbps that is supporting the actual network traffic load.

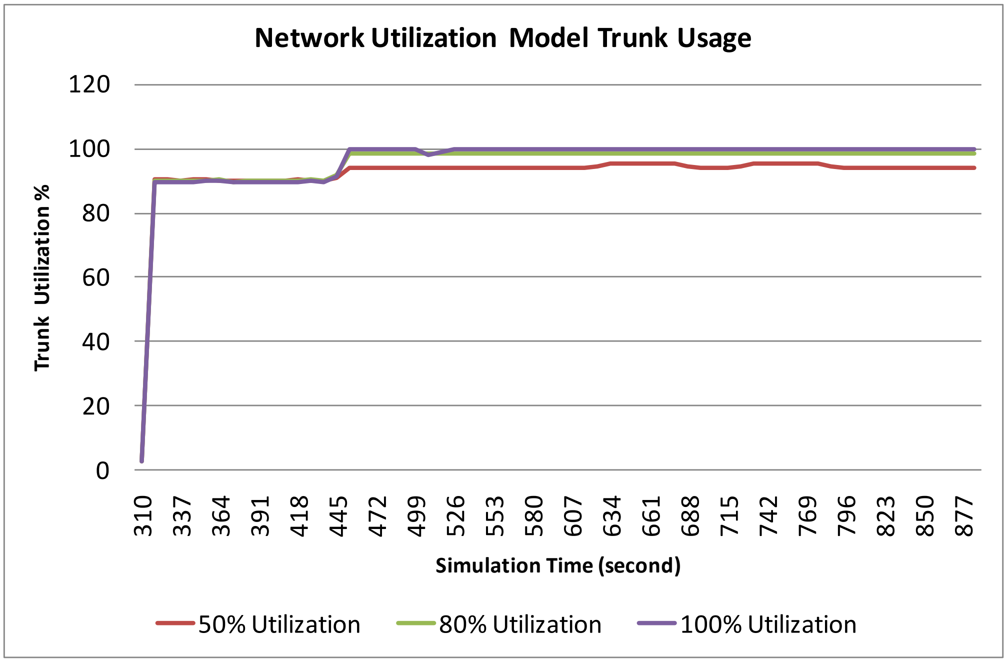


Figure 5.45 WAN Backbone Trunk Utilization

The traffic on the trunk utilization is broken down to support service which is composed of media streaming at a rate of 8 Mbps (1,000,000 bytes/second), and IP Telephony at a rate of 64 Kbps (8,000 bytes/second). The file transfer (traffic injector) was varied from 6,500,000 bytes (50% utilization) to 12,500,000 (100%). The HPAA PCS application per Controller is at 8 Kbps (1024 bytes). Similar to LAN simulation results, media and injected traffic applications were acquiring most of the bandwidth driven by the nature of BE (i.e., large application acquire more bandwidth). Hence, it is causing higher delay to the smaller two applications; HPAA PCS Controller and IP telephony Traffic.

As depicted in Figure 5.46, the HPAA PCS application encountered most of the delay at 100%, average 2.33s and maximum of 3.65s. However, at 80% utilization the delay was in sub-second and had significant increase as compared to the 50% utilization, from an average of 56.4 ms to 223 ms (295% increase).

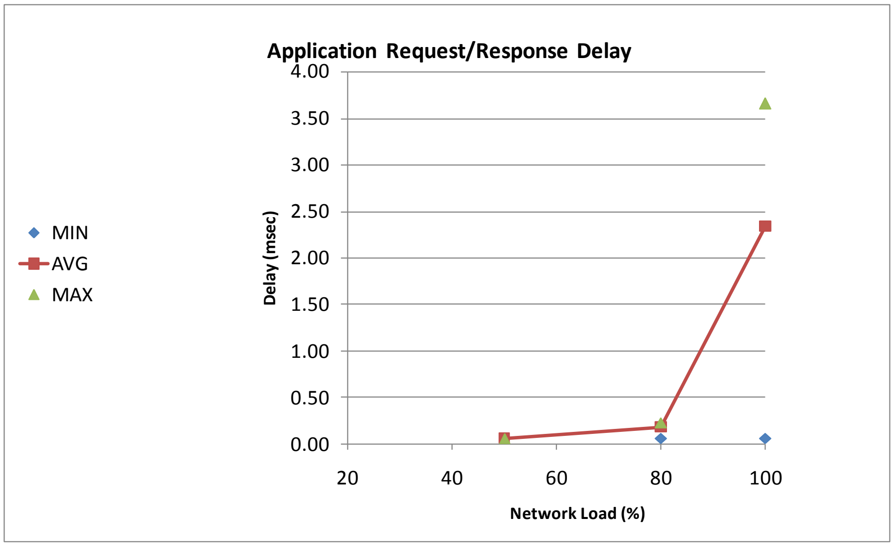


Figure 5.46 PCSVC Master Controller – PCS Area 1 Controller-Delay Performance at 50%, 80%, and 100% Utilization

The one way application delay is illustrated in Figure 5.47. This simulation test case scenario demonstrates the application timeliness in support a unidirectional message that may be triggered by a change in the actual process. In this test case scenario, the packet response average time delay between PCSVC and PCS Area1 is depicted in the figure and was in the order of 2.27s for 100% network utilization. At 50% and 80% the packet response was in the order of 28 ms and 91 ms accordingly.

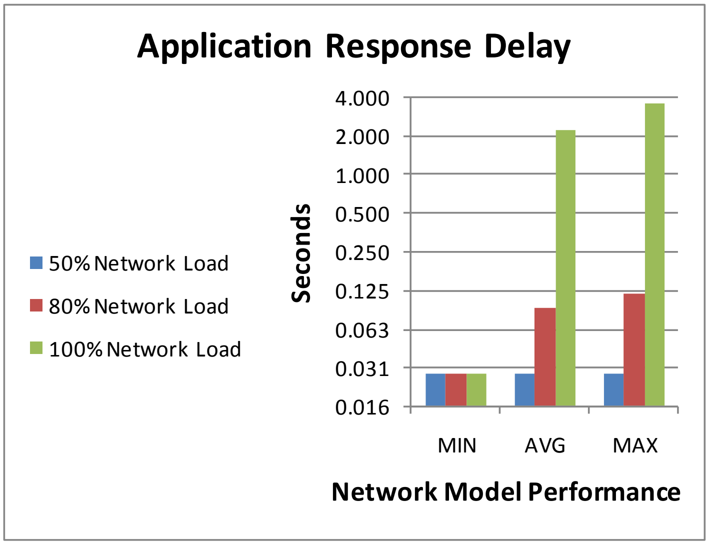


Figure 5.47 PCSVC to PCS Areas Controller Application One-Way Delay

The simulated test case scenario for the IP network delay between PCSVC and PCS Area 1 and Area 2 was examined. This is to test the CIP network performance carrying the different traffic mix and being exposed to the different network loadings. The results are depicted in Figure 5.48. The maximum network delay, at 100% utilization, was 300 ms. This is followed by the 80% utilization at 266 ms. When the utilization was at 50%, the delay was at 33 ms, 10th of the delay that incurred at 100%. The 300 ms network delay at 100% and 266 ms at 80% utilization are considered high and not acceptable.

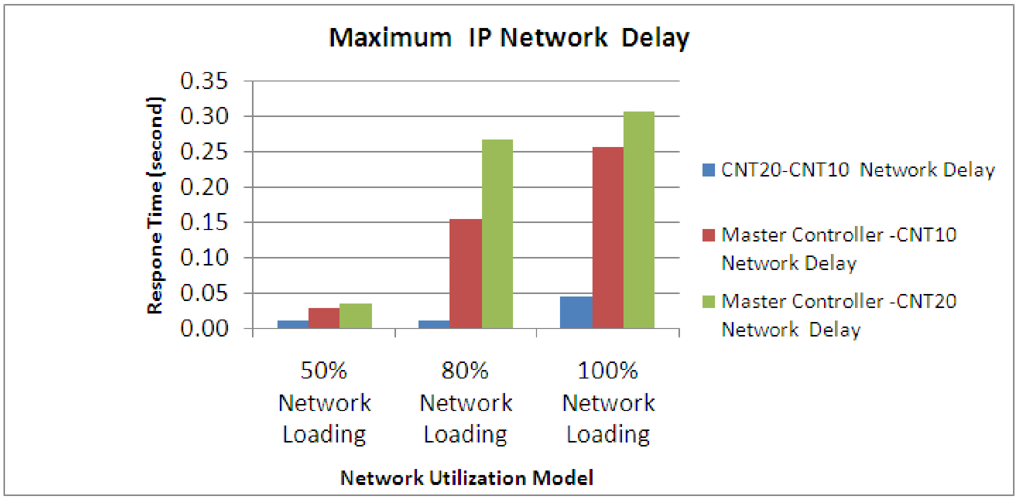


Figure 5.48 PCSVC to PCS Areas IP Network End-to-End Delay

The jitter which is an indication of the packet arrival variance time is depicted in Figure 5.49. The jitter for the network loading of 100% shows a time variation in order of 226 ms between the Master Controller and Controller 20, followed by 223 ms between the Master Controller and Controller 10, and 43 ms between Controller 10 and Controller 20. The 226 ms and 223 ms in jitter are considered high and not acceptable for a PCS application.

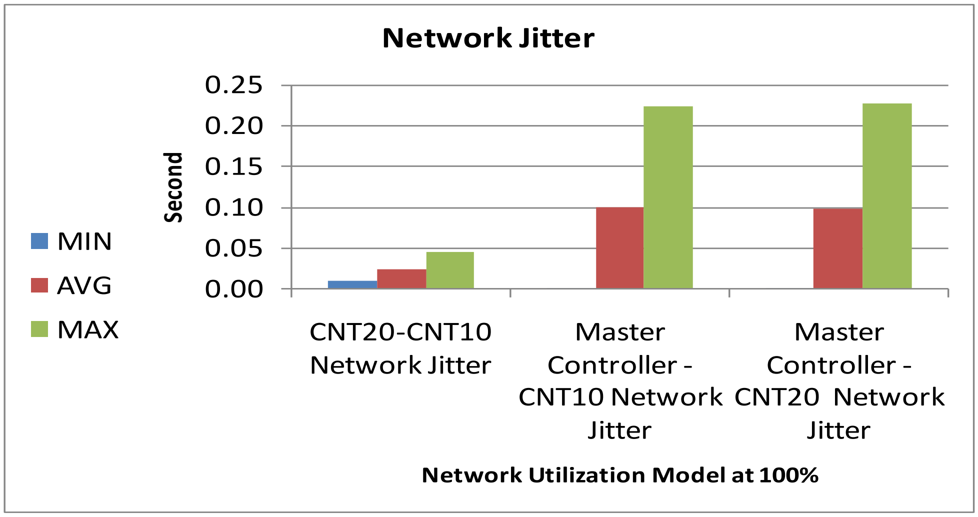


Figure 5.49 PCSVC Master Controller – PCS Area 1 Controller Network Jitter

The packet sent and received by the PCS application encountered major degradation in quality when the utilization increased from 50% to 80% and 100%. The packet loss performance is depicted in Figure 5.50. On the average, packet loss went from zero at 50% to 1300 (65%) at 80% to 1373 (68%) at 100% utilization.

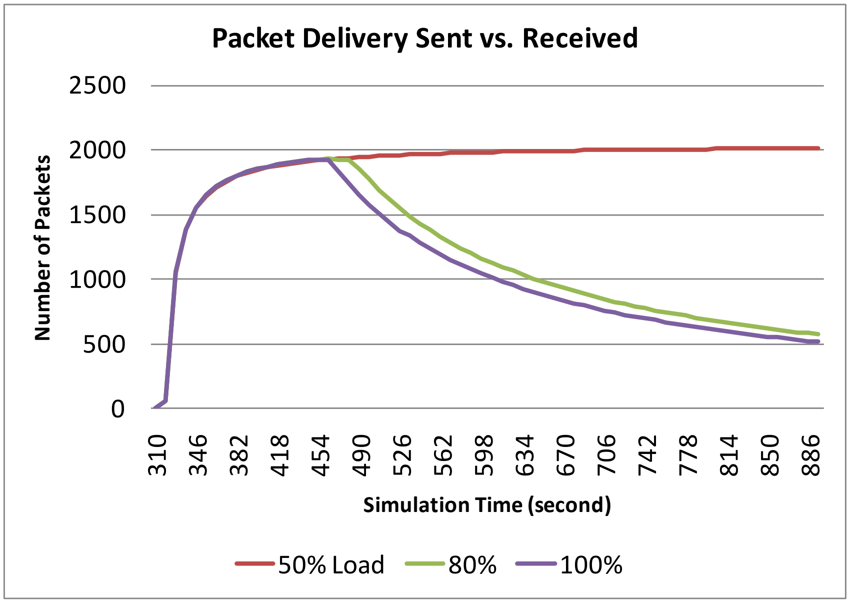


Figure 5.50 PCSVC Master Controller – PCS Area 1 Controller Packet Delivery

Also, HPAA PCS application stability performance was examined in this simulated test case scenario by identifying the TCP retransmission timeout. It was apparent to have TCP retransmission timeout at the 80% and 100% utilization, as depicted in Figure 5.51. The timeout extended for a period of 43 seconds in both network loading. As expected, the 100% loading resulted in an early retransmission rate that started five second earlier than the 80% loading. This is an indicator that network congestion buildup was experienced earlier at high network loading.

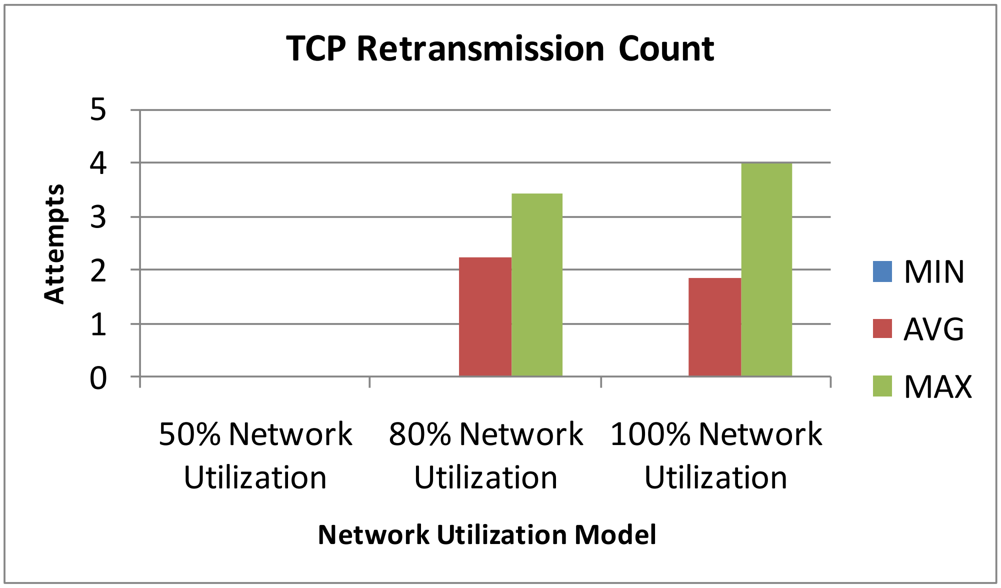


Figure 5.51 PCSVC Master Controller – PCS Area 1 Controller TCP Retransmission Timeout

The PCS network delay between the PCSVC and the PCS Area 2 was also investigated. In this simulated test case scenario the non-direct network connection impacts were tested. This was represented by tracing the performance between PCS Area 2 connected to PCSVC i.e., there is an interim backbone network node between them. So, additional delays should be encountered due the switching node in between.

Figure 5.52 shows the delay performance. Consistent with the PCS Area 1, the delay was correlated to the increase in backbone trunk utilization. Most of the delay, 4.23s, was at 100% loading. The delay at 80% loading was close to 1.44s. Finally, the delay at 50% utilization was close to 66 ms second.

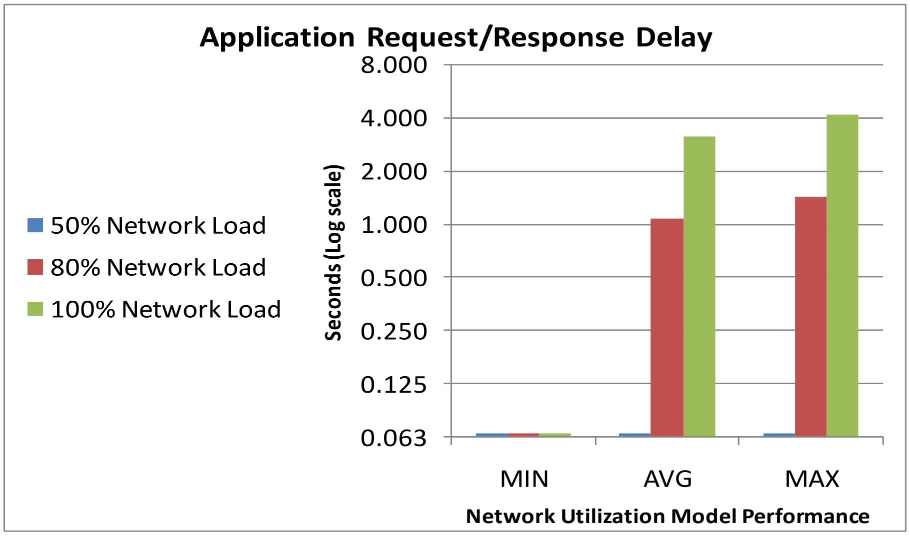


Figure 5.52 PCSVC Master Controller – PCS Area 2 Controller-Delay Performance at 50%, 80%, and 100% Utilization

Also, in this simulation test case, the jitter was examined. The jitter between PCSVC and Area 2 is shown in Figure 5.53 for the network utilization at 100%. The jitter is 226 ms as compared to 220 ms at 80%. The jitter was at 200 μs at 50%.The jitter results were indirect correlation with the utilization increase.

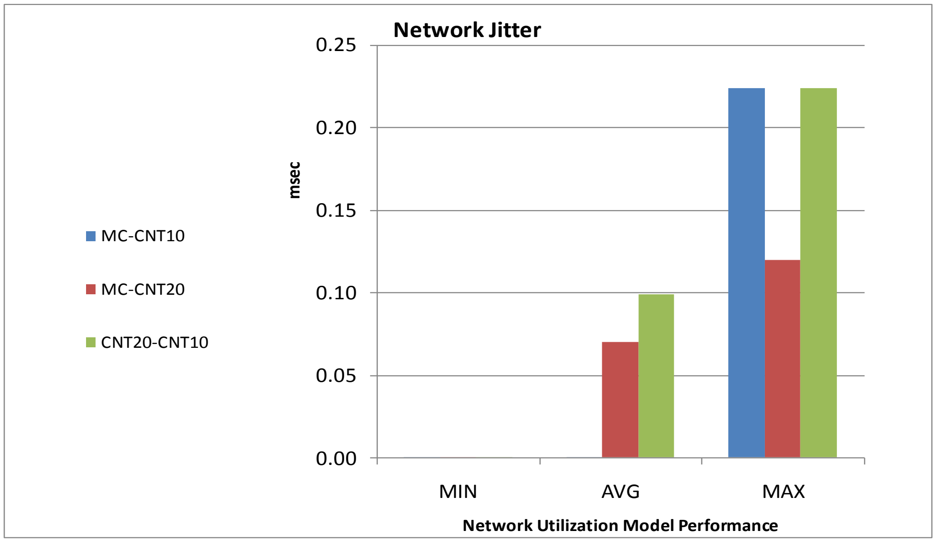


Figure 5.53 PCSVC Master Controller – PCS Area 2 Controller Jitter

Packet delivery integrity was apparently suspected at 100% and 80% utilization since the packet sent and received for the application was not the same. The packet loss increased up to 50% overtime. However, at 50% utilization the packet sent and received are equal. Figure 5.54 depicts the simulation outcomes for packet loss for these three different scenarios.

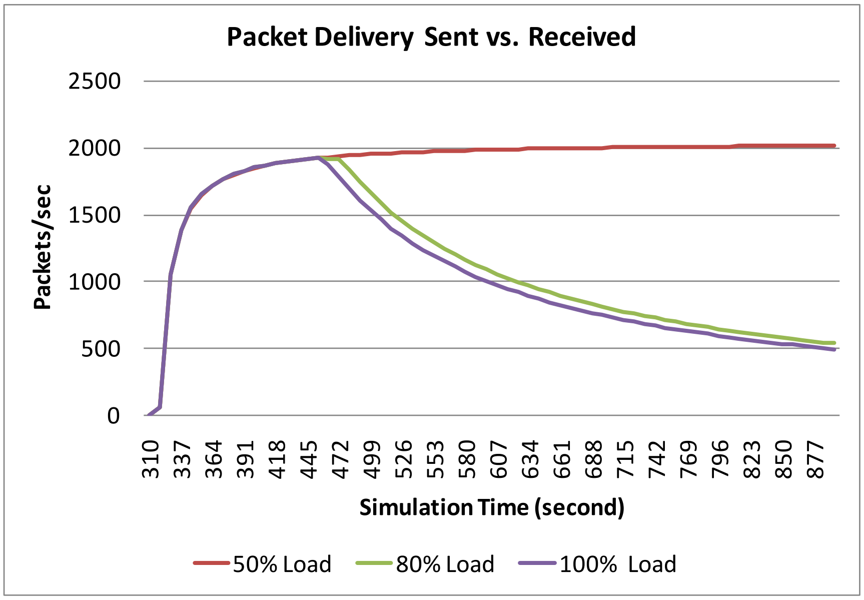


Figure 5.54 PCSVC Master Controller – PCS Area 2 Packet Delivery

The simulated test case scenario also tracked the TCP retransmission to confirm the application stability. It was present at both 80% and 100% utilization. As shown in Figure 5.55, the TCP retransmission was at 4 counts, maximum, for 100% as compared to 3.4 counts at 80%.However, it was zero at 50% utilization.

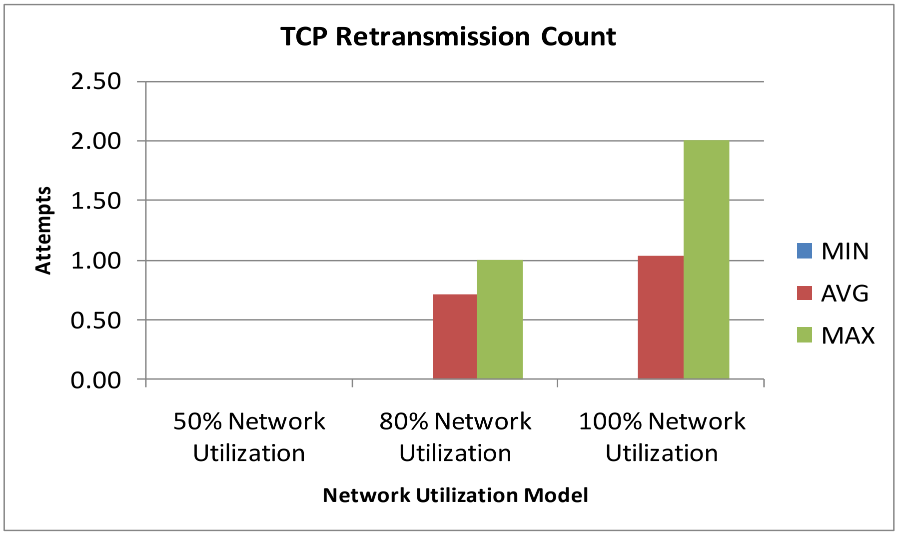


Figure 5.55 PCSVC Master Controller – PCS Area 2 Controller TCP Retransmission

The TCP retransmission timeout is depicted in Figure 5.56 based on this simulated test case scenario. The network loading had an adverse impact on the performance of the application. At high utilization the timeout reached 43s and 41s accordingly. This is considered excessive and not acceptable for HPAA PCS application. At 50% network utilization or less the time out was about1 second TCP timeout.

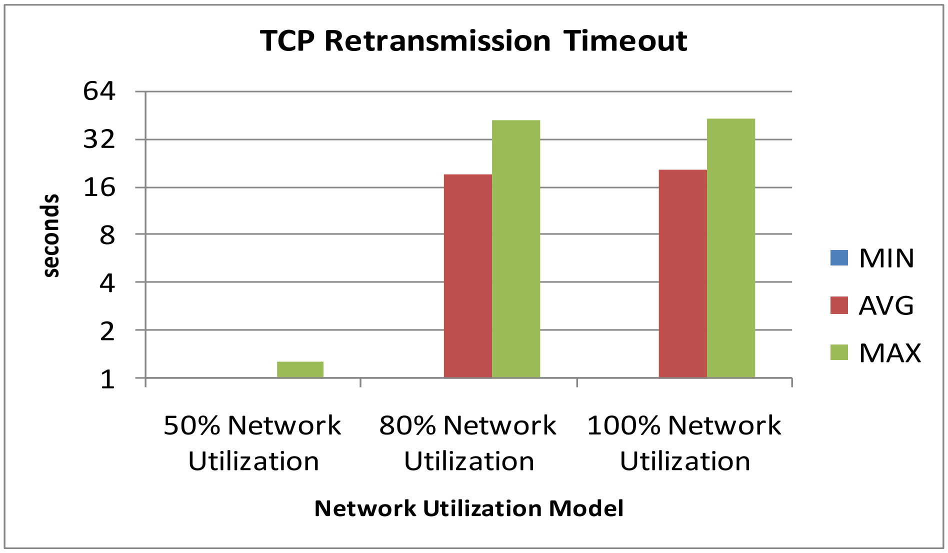


Figure 5.56 PCSVC Master Controller – PCS Area 2 Controller TCP Retransmission Timeout

5.5.2.2 BE Converged IP for Peer-to-Peer Controller Performance

The Peer-to-Peer HPAA PCS Controller behavior in a converged IP BE network model was examined. In this simulation test case scenario, two HPAAPCS areas were engaged in a control loop strategy where Controller 10 (CNT-10) in PCS Area 1 is communicating with CNT-20 in PCS Area 2. All the different network and application related parameters that are part of this test case were configured and implemented in the simulator based on the research design detailed in Chapter 3. This is required to ensure consistent and systematic results that can be used in the comparative analysis and discuss of Chapter 6.Delay, jitter, packet loss, TCP retransmission count, and timeout are performance indicators that were examined to identify the network robustness at 50%, 80% and 100% utilization. The simulated test case scenario maintained similarity in simulation time, parameters, and order as compared to the same test cases for the different CIP network model.

The simulation test case scenario result for HPAA PCS delay is depicted in Figure 5.57. The PCS maximum delay between CNT10 and CNT20 was close to 180 ms at 100% utilization. However, the delay at 80% and 50% were close to 20 ms and 0.21 ms accordingly as shown in Figure 5.57. This is slightly less than the delay between each of these two Controllers to the PCSVC Master Controller.

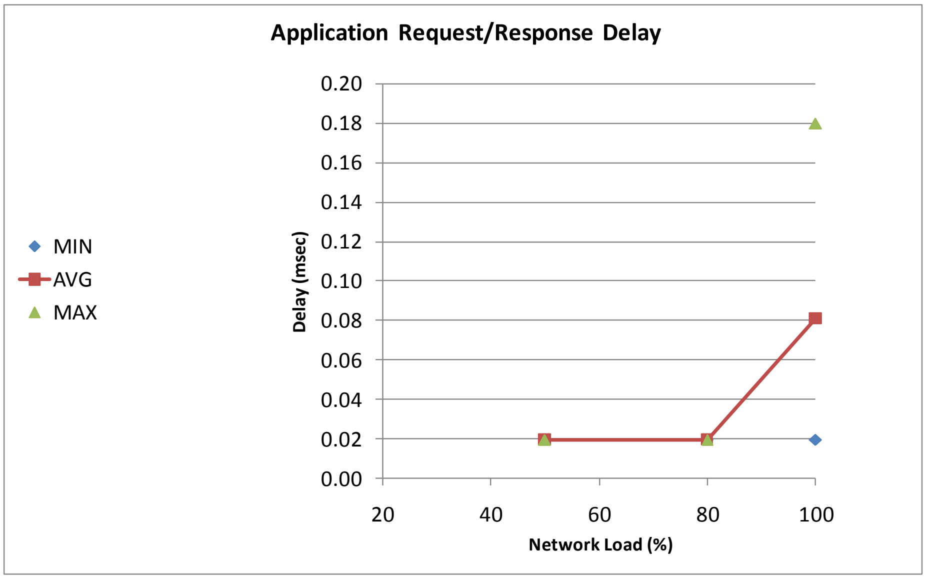


Figure 5.57 PCS Area 1 – PCS Area 2 Controller-Delay Performance at 50%, 80%, and 100%Utilization

Jitter was also explored in this simulation test case scenario, shown in Figure 5.58. The jitter between CNT10 and CNT20 was excessive; at 43 ms when utilization was 100%. However, the jitter was at 160 µs and 162 µs at 50% and 80% accordingly.

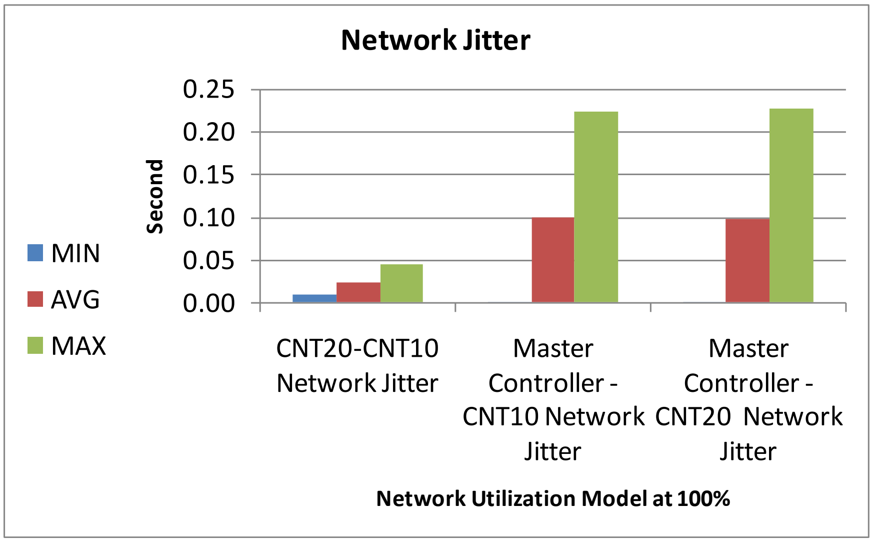


Figure 5.58 PCS Area 1 (CNT10) and PCS Area 2 (CNT20) Jitter

The data sent and received between the two Controllers were healthy at 50% and 80% as compared to the 100% as shown in Figure 5.59. There were some data loss, 110 packets, that occurred at 100%. This resemble a 5% dropped packet and is critical indicator of lack of fitness of BE network.

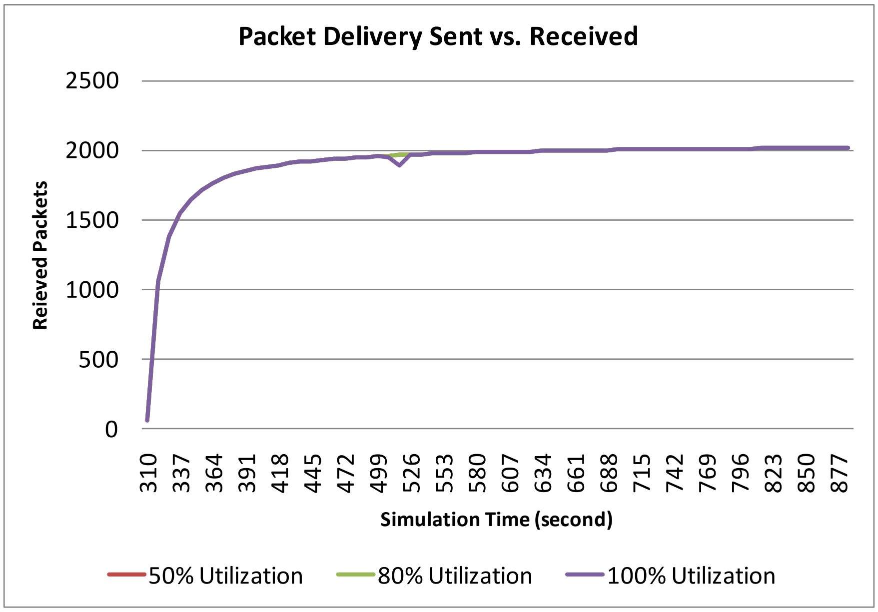


Figure 5.59 PCS Area 1 (CNT10) and PCS Area 2 (CNT20) Packet Delivery

To further explore the impacts of packet loss, we further explored the test case scenario from a TCP transmission quality: TCP retransmission count and TCP timeout, The TCP retransmission count was apparent at the 100% and 80% utilization ranging from 2 counts to 8 counts accordingly. Figure 5.60 demonstrates the TCP retransmission performance. At 50% utilization, there was no TCP retransmission.

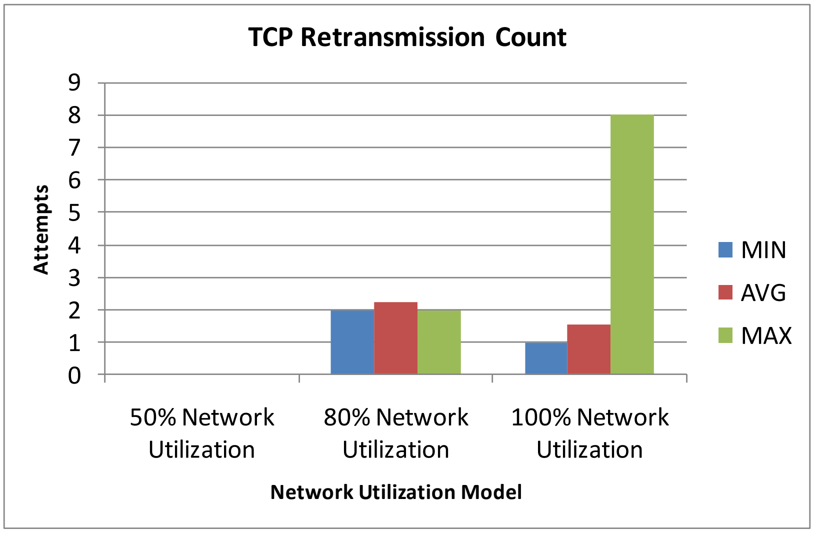


Figure 5.60 PCS Area 1 (CNT10) and PCS Area 2 (CNT20) TCP Retransmission Count

In addition, TCP retransmission timeout was also examined as shown in Figure 5.61. This is an indicator on how hard the application was trying to transmit the message content in question (i.e., HPAA). The maximum TCP timeout was at 4 seconds at 100% utilization as compared to 1s at 80% and 50% utilization. The 1s time is acceptable as it is within the application request/response allocate time.

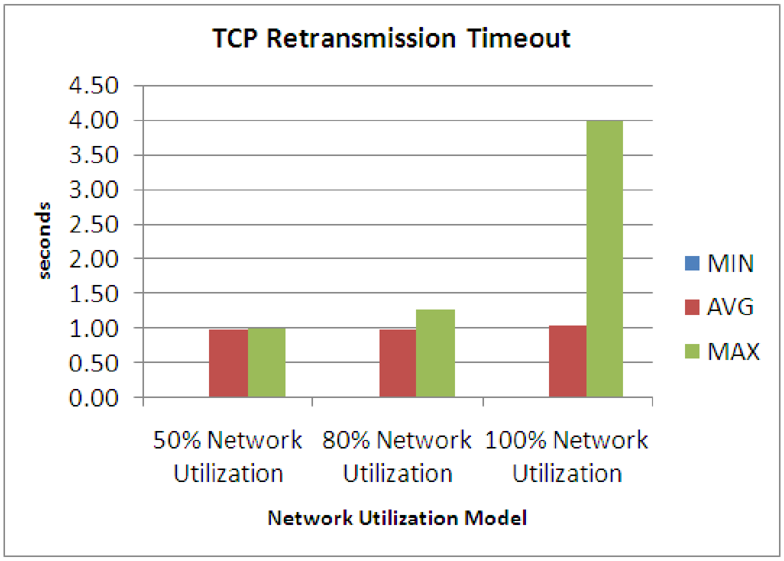


Figure 5.61 PCS Area 1 (CNT10) and PCS Area 2 (CNT20) Timeout

5.5.2.3 Support Services Video Streaming and IP Telephony Performance

Support services, IP telephony and video streaming, were considered in the converged IP network and were exposed to the traffic loading of 50%, 80%, and 100%. These services were provisioned based on BE application configuration, similar to the remaining applications to ensure a consistent network setting. Similar to HPAA PCS simulation test case scenarios, the support services were examined under two different communication relationships. The first is based on PCSVC communicating to remote PCS Areas. The second is when the remote PCS Areas are communication with each other. Both IP telephony and media streaming data source and sink were configured and implemented in the simulator. The performances of time delay, jitter, and packet loss and application stability were examined.

IP telephony is based on UDP protocol as compared to media streaming which uses TCP so the traffic behavior were different, driven by the actual transports protocol that were used for these services. This was kept in mind when the traffic load was applied and increased from 50% to 100%.The results for time delay and jitter were captured from the simulated test case scenario and presented in Table 5.2. The delay had an exponential relationship increasing from 87ms for IP telephony to 765ms as utilization increased. Moreover, the Jitter was in similar form depicting the negative impacts of the increase in traffic utilization in a BE CIP network. The media streaming delay and jitter did have the same challenge as IP telephony with the exception delay was much higher due to the media streaming uses TCP protocol.

Table 5.2 Support Services, IP Telephony & Video Streaming Intra-domain Performance

Support Service Performance	50% Network Model (msec)	80% Network Model (msec)	100% Network Model (msec)
IP Telephony Packet Delay	87	730	765
IP Telephony Packet Delay Variation	0.001	119	137
CCTV Packet Delay	0.038	930	1820
CCTV Jitter	0.0002	0.0017	0.05

IP telephony encountered performance degradation as the network utilization increases from 50% to 100%. The IP telephony delay was 765 ms at 100% as compared to 730 ms at 80% utilization. However, at 50% the delay was 87 ms.

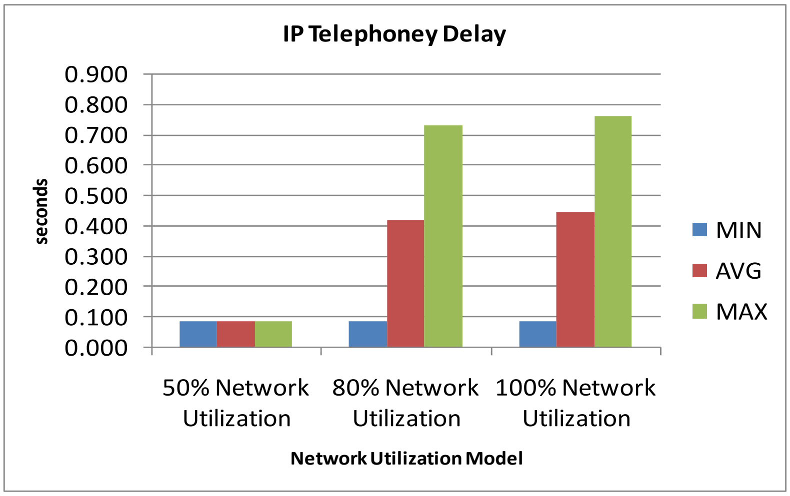


Figure 5.62 IP Telephony Network Delay

Jitter performance was also degraded as utilization increased and was in correlation to delay. At 100%, the IP telephony jitter was at 137 ms. However, at 80% it was at 119 ms and 0.028 ms at 50% utilization. Figures 5.62 and 5.63 show the average delay and jitter at 100% network model utilization, respectively.

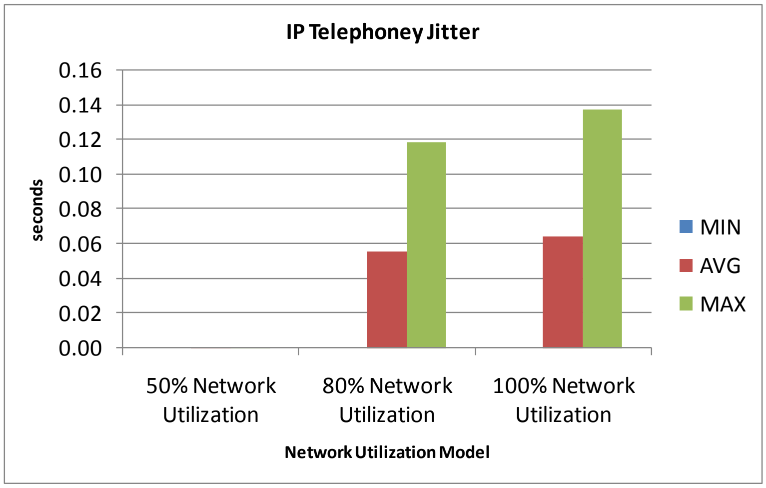


Figure 5.63 IP Telephony Network Jitter

The traffic increase from 50% to 80% and then to 100% also have demonstrated the negative impact on the performance of video as shown previously in Table 5.3. Video steaming encountered a 1.82s delay at 100% loading as compared to 1.63s at 80% and 38 ms at 50% as shown in Figure 5.64. Jitter was minimal but observed at 100% utilization showing 0.5ms. However, at 80% and 50% utilization was 0.002 ms.

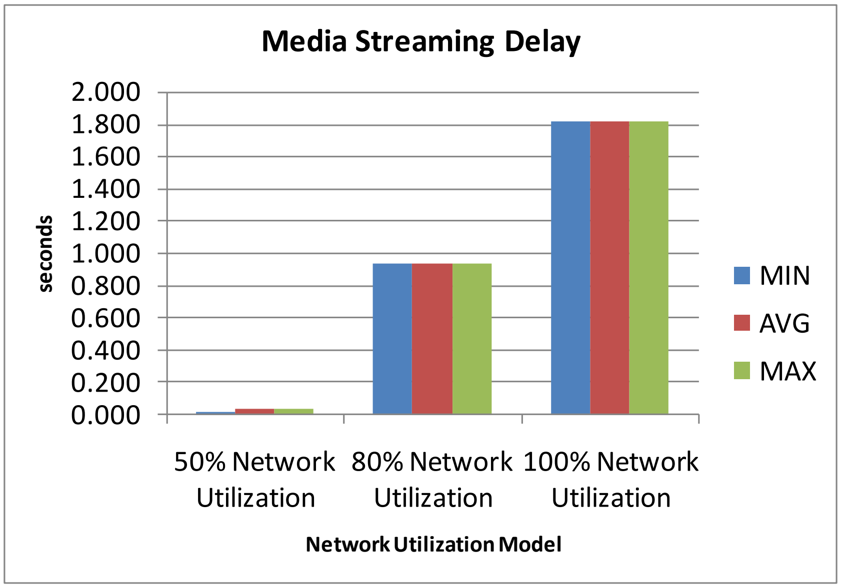


Figure 5.64 Video Streaming Average Delay

5.5.3 Priority Based QoS Converged IP Enabled Network

This section shows the results of converged IP network with Priority based Scheduling Quality of Service (QoS) setting for multi-service and multi-priority environment. Similar to the LAN simulation, the WAN CIP network model element and supported applications were configured with QoS priority based scheduling. The highest priority, priority 7, was assigned for the PCS Controller application. Support services such voice were assigned priority 6; video streaming priority with priority 5, and the inject traffic load with the lowest priority (i.e., best effort priority 0). The objective is to explore the PCS and support services performance to a predefined traffic load; 50%, 80%, and 100% network utilization in WAN CIP based on Priority based Scheduling QoS.

Similar to previous simulation test case scenarios two communication relationships are examined. These are: Remote HPAA Controller in a PCS Area communicating to a centralized Controller (HPAA Master Controller) located at the PCS Virtual Center-PCSVC; the second is HPAA Controller in one Remote PCS Area exchanging real-time HPAA message with another Controller located in another Remote PCS Area. In all simulation test case scenarios, the network, application, and interface elements were configured and implemented in the simulator based on the research design detailed in Chapter 3.

5.5.3.1 PCS Virtual Center (PCSVC) and Subtending Controllers Performance

The PCSVC has two concurrent PCS relationships that extend over the CIP wide area network. One PCS relationship is with PCS Area 1 and the second is with PCS Area 2. The two HPAA PCS relationship are based on control strategy that is running simultaneously as defined in the research design earlier. The simulated test cases traffic performance of delay, jitter, packet loss, and TCP performance (retransmission count and timeout) was tracked. The network loading was systematically increased from 50% to 100% utilization. The results indicated in Figure 5.65 depict the delay between, PCS Area 1 (CNT1) to PCSVC (MSC). The maximum two-way application delay is at 56.4 ms at 100% utilization. The delay at 50% and 80% can be rounded up to 56.4ms and this shows the positive impact of QoS Priority based Scheduling on HPAA PCS performance.

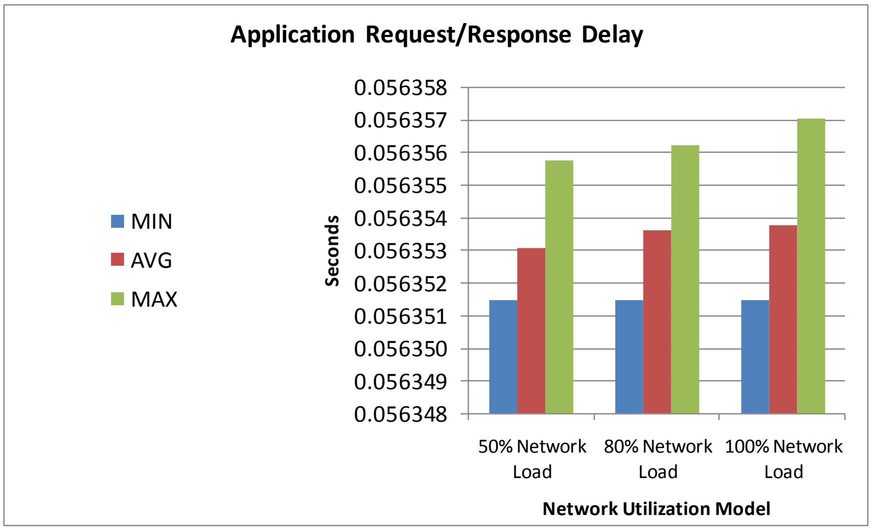


Figure 5.65 PCSVC to PCS Area 1 Application Round Trip Time Delay

The one way application delay is 28.2 ms depicted in Figure 5.66; showing packet response. This shows the HPAA time for either a request or a response traversing the WAN CIP network model and is considered very encouraging result.

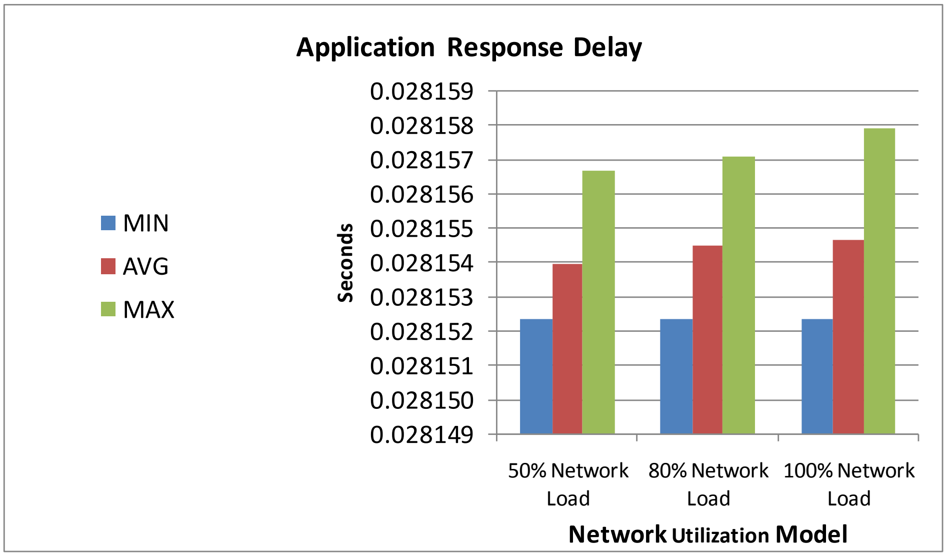


Figure 5.66 PCSVC to PCS Area 1 Application One-Way Time Delay

The IP network delay for the PCS application was also investigated in the simulation test case scenarios and was mapped to the different network loadings. The results are shown in Figure 5.67. The IP network delay appears to be the same regardless of the network utilization. Also, as expected, the IP network delay was lower than the application one way delay. This validates the IP network layer fitness in supporting HPAA PCS in a WAN CIP network model.

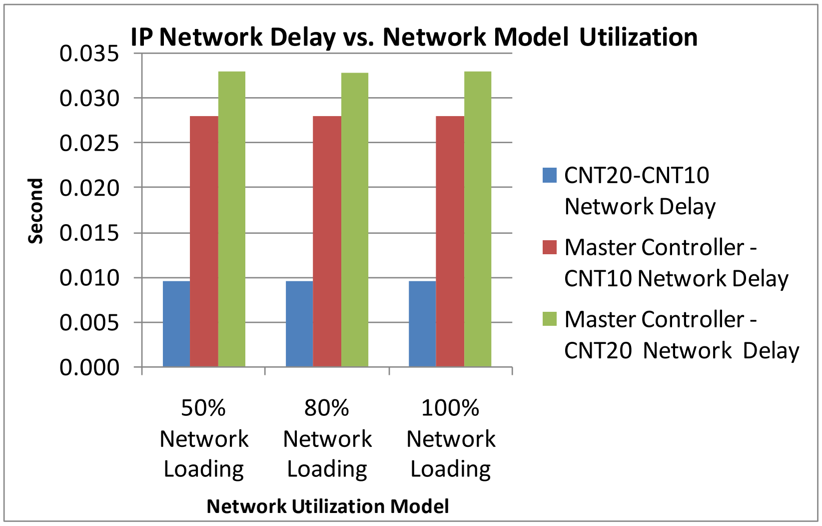


Figure 5.67 PCS IP Network Delay vs. Network Utilization

Jitter was explored in this simulation test case scenario and as expected, the HPAA PCS application, which was assigned highest priority, had minimal jitter. The HPAA application IP network jitter between PCSVC and the different remote areas is shown in Figure 5.68 for network loading of 100% (i.e., worst case scenario). The maximum jitter was at 187 µs which is very minimal.

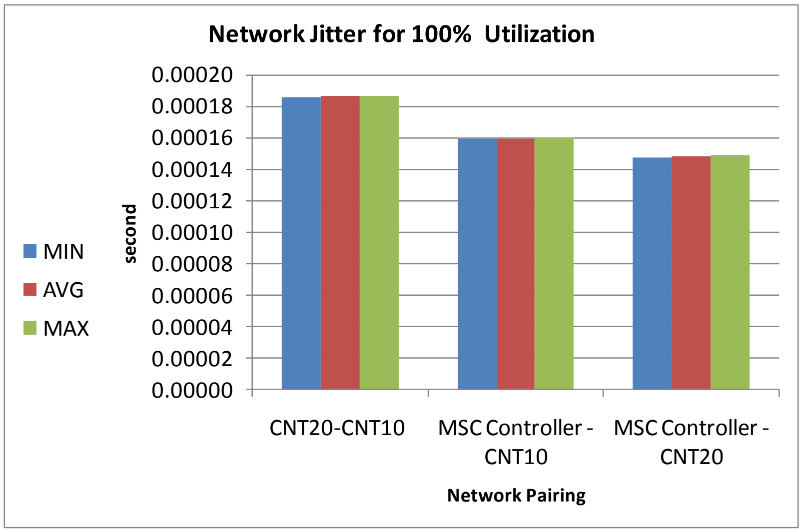


Figure 5.68 PCS IP Network Jitter for 100% Network Utilization Model

Packet loss was examined in this simulation test case scenario. The sent and received packets for PCS application between PCSVC and PCS Area 1 and or Area 2 was examined and depicted in Figure 5.69. The figure demonstrates that both sent and received packets are equal. Hence, none of the HPAA PCS data was lost. This provides an early indicator for TCP retransmission count and timeout to be also minimal since there is no packet loss.

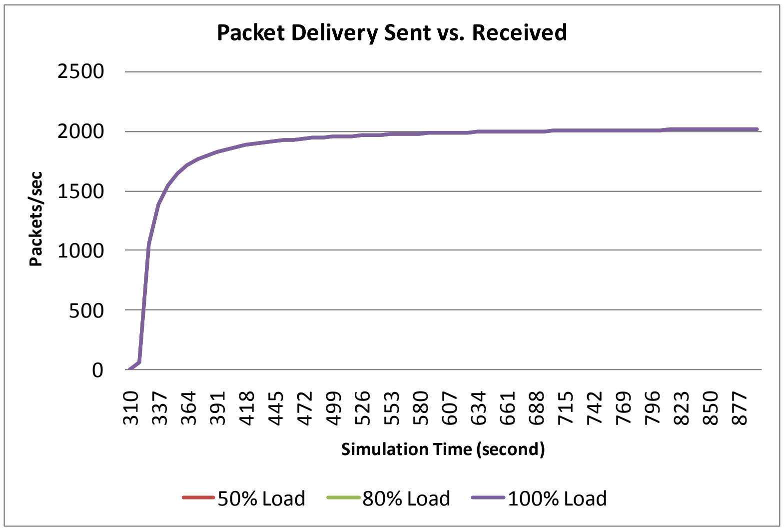


Figure 5.69 PCSVC to PCS Areas Packet Delivery

The TCP retransmission timeout was examined to validate the earlier finding regarding packet loss. The result shows a 1s timeout for PCSVC and PCS Area 1 and PCS Area 2 as shown in Figure 5.70. This is within the fundamental request and response poll cycle of 1s as defined in the research design. And, this finding was validated by identifying zero count for the TCP retransmission for the HPAA PCS application under network loading of 50%, 80%, and 100% CIP network model.

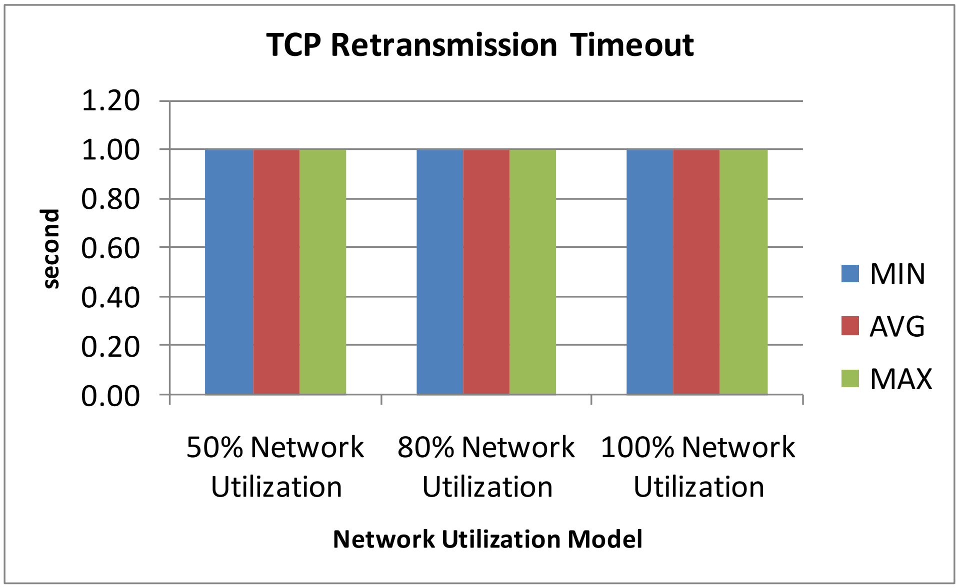


Figure 5.70 PCSVC to PCS Area TCP Retransmission Timeout

5.5.3.2 Priority Based QoS Peer-to-Peer Controller Performance

The HPAA PCS P2P application between PCS Area 1 and PCS Area 2 was simulated based on Priority based QoS as defined in the research design in Chapter 3. The purpose of this simulation test case scenario is to assess PCS performance over a wide area network in a form of P2P. These two PCS areas are engaged in control loops were Controller 10 (CNT10) in PCS Area 1 is communicating with CNT20 in PCS Area 2. The outcome of this simulation is illustrated in this section.

The primary focus is on delay, jitter, packet loss, and TCP retransmission performance on the Priority based Scheduling CIP network model. Consistent with earlier simulation test case scenario, the network utilization model was increased from 50%, 80% and to 100% utilization. The HPAA PCS delay between CNT10 and CNT20 was 1 ms regardless of the % of utilization as shown in Figure 5.71. This is very positive result as compared the earlier test cases scenario of BE QoS setting for CIP WAN.

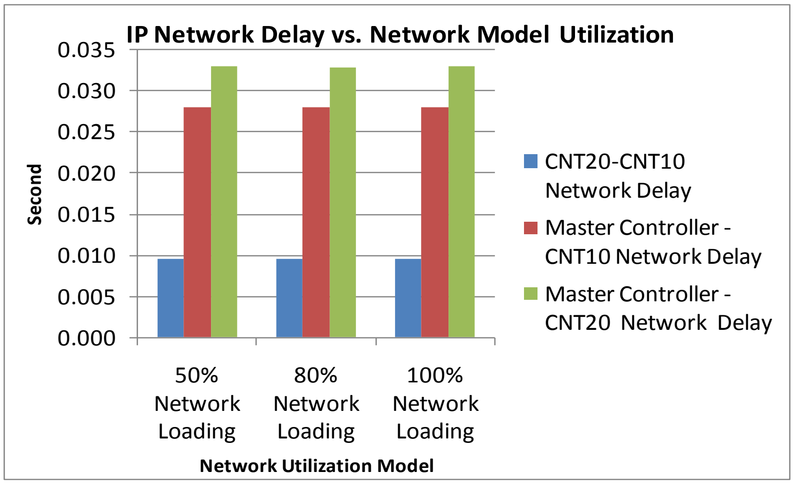


Figure 5.71 PCS Area 1 – PCS Area 2 Controller-Delay Performance at 50%, 80%, and 100% Network Utilization Models

The jitter between CNT10 and CNT20 was at 187 µs regardless of the network utilization as depicted in Figure 5.72. This further validates the advantage of enabling QoS Priority based Scheduling.

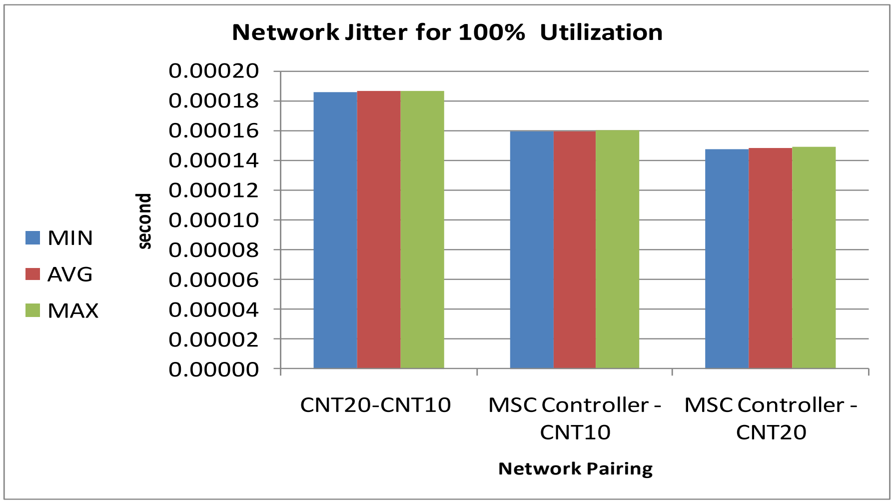


Figure 5.72 PCS Area 1 (CNT10) and PCS Area 2 (CNT20) Jitter

In addition, the simulation test case scenario examined packet loss by focusing on the sent and received packet between the two Controllers in question. The results are shown in Figure 5.73. The outcome illustrates sent and received data were healthy at the different utilization level (i.e., 50%, 80% and 100%); zero packet loss.

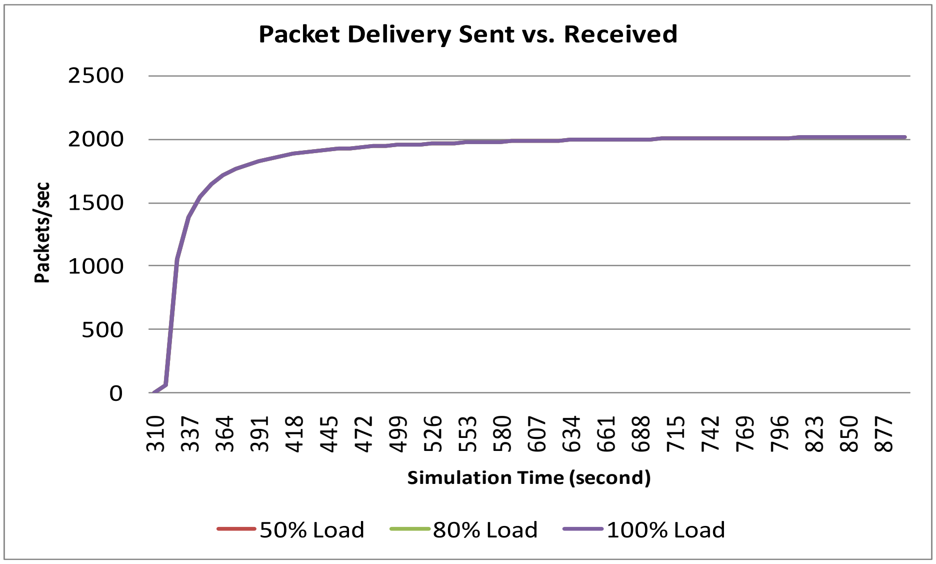


Figure 5.73 PCS Area 1 (CNT10) and PCS Area 2 (CNT20) Packet Delivery

Moreover, the TCP retransmission timeout was investigated. As expected, the timeout was 1s independent of CIP network utilization as shown in Figure 5.74. This is within the HPAA PCS application cycle and reaffirm that packet loss for the HPAA was zero.

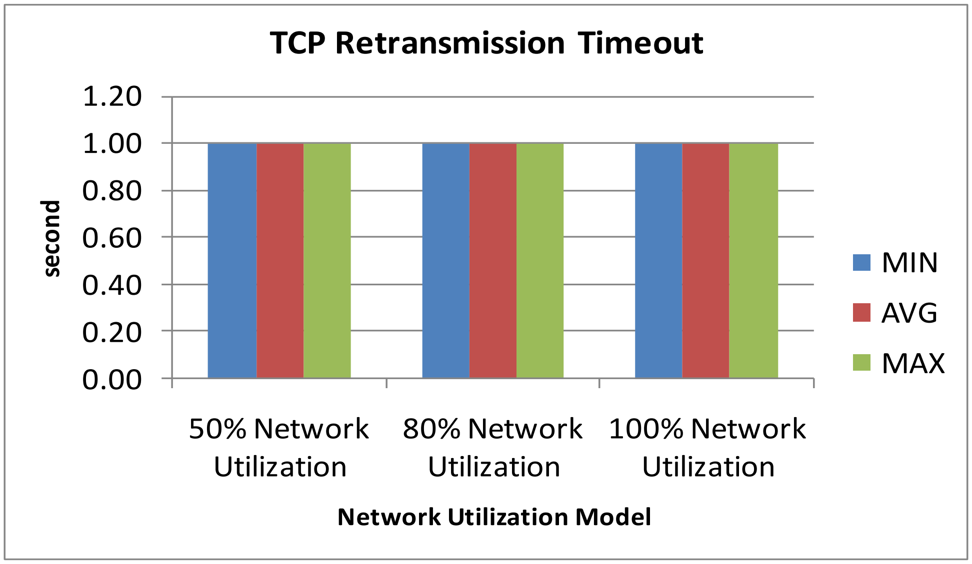


Figure 5.74 PCS Area 1 (CNT10) and PCS Area 2 (CNT20) TCP Retransmission Time Out

5.5.3.3 Support Services IP Telephony and Video Streaming and Performance

Support services of IP telephony and video streaming performance was examined in converged IP network model. These services were provisioned based on priority based QoS application configuration: IP telephony (Voice) next in priority to HPAA PCS application and then followed by media streaming. Both HPAA and support services were traversing the WAN network concurrently and following the research design defined environment. Network traffic injection was placed in the different WAN network sites and systematically increased network loading from 50%, 80% to 100%.

To experience and examine cross network traffic, IP telephony and media streaming established both Master/client and P2P relationship. This was essential to identify the network endurance during high utilization among these relationships. This section provides a summary of the simulation results as depicted in Table 5.3.As expected by enabling QoS priority based Scheduling, IP telephony and video streaming encountered minimal delay and jitter as traffic loading was increased from 50% to 100%. The maximum IP telephony delay was at 87 ms and for video was 44 ms. Jitter was insignificant and was in the sub micro-second for both voice and video.

Table 5.3 Support Services, IP Telephony & Video Streaming Intra-domain Performance*(Table revise)*

Support Service Performance	**50% Network Model (msec)**	**80% Network Model (msec)**	**100% Network Model (msec)**
IP Telephony Packet Delay	88	88	88
IP Telephony Packet Delay Variation	1.E-07	1.E-07	1.E-07
CCTV Packet Delay	0.038	1.63	1.82
CCTV Jitter	2.E-04	2.E-03	5.E-03

The outcomes of Priority based QoS scheduling is essential in the discussion and analysis of this research, outlined in Chapter 6. The result will be used in the comparative analysis between the wired WAN CIP network Dedicated, BE, and Priority based Scheduling QoS network models. Relationships will be derived to conclude an optimum CIP network model.

Next, the result of the wireless backhaul link is presented. The primary focus is to examine wireless link as the last mile connection method for an HPAA PCS remote site. The simulated test case scenarios were limited to one link as defined in the research design, Chapter 3.

5.5.4 Converged IP for Remote Wireless Spur Site Connected to WAN

The wireless backhaul link is used as a last mile connection for remote site. The physically characterization were defined in the research design and is not the focus of this research. The primary goal of the simulation test case scenarios is to examine the IP and application performance. The simulation is based on connecting a remote site, PCS Area 5 (spur), to the WAN network, Figure 5.75.The intent is to explore the PCSVC Controller communication to the PCS Area 5 Controller (CNT6). Moreover, support services such as voice and video streaming are also investigated. The performance of the wireless link connectivity is reflected in this section with emphasis on BE converged IP network and Priority based Scheduling QoS.

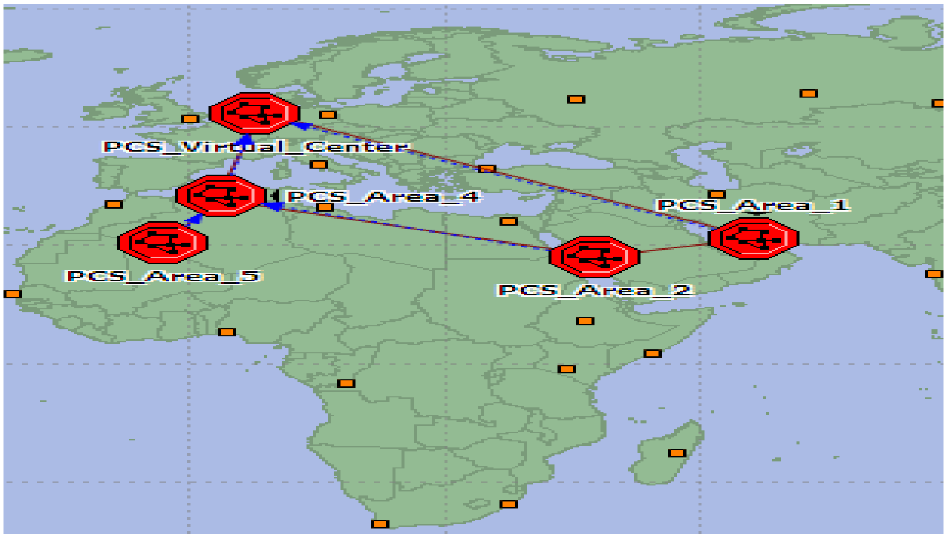


Figure 5.75 PCS Area 5 Spur Site Connected to WAN via Wireless Link

5.5.4.1 Best Effort QoS Converged IP Network for Remote Wireless Site

The intent of this test case is to examine wireless backhaul remote site delay between the HPAA PCS site to the PCSVC when utilizing a BE CIP network model. The end-to-end round trip application delay between PCSVC and PCS Area 5 Controller is depicted in Figure 5.76. The maximum delay is estimated to be at 4.09s at 100% utilization and 3.6s at 80% utilization. The delay was at 38 ms at 50% utilization.

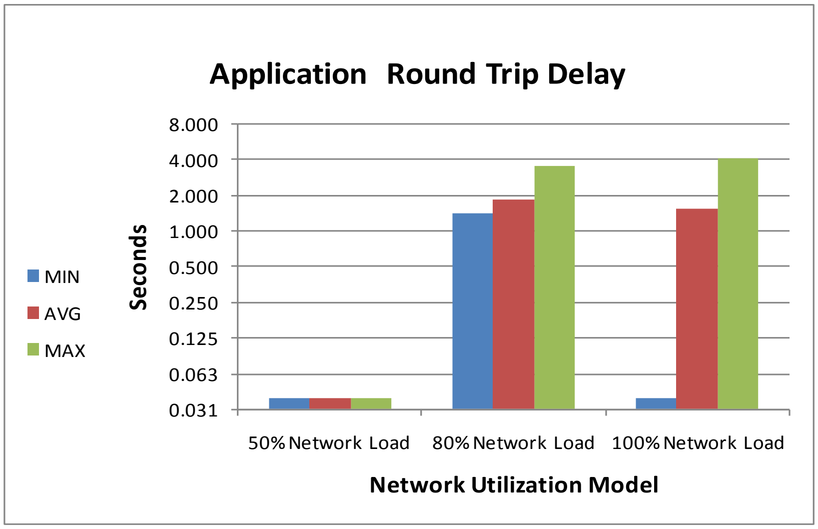


Figure 5.76 PCSVC to PCS Area 5 Application Round Trip Delay

The one way application response delay is 3.78s at 100% network utilization. And, 2.5s and 19 ms at 80% and 50% network utilization accordingly as depicted in Figure 5.77. The increase from 50% to 80% and then to 100% illustrate an exponential relationship. This highlights BE weakness for the CIP network model.

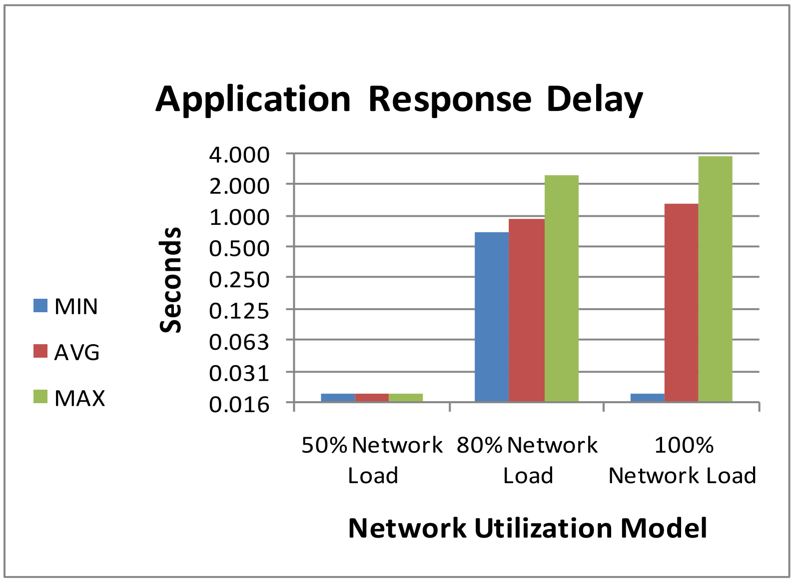


Figure 5.77 PCSVC to PCS Area 5 Application One-Way Delay

The IP layer network end-to-end delay is illustrated in Figure 5.78. The intent of this simulated test case scenario is to gauge network timeliness to the increase in network utilization. The results show excessive network delay at 100% network utilization as compared to 80% and 50% utilization. This displays the discomfort operating zone for BE wireless backhaul link.

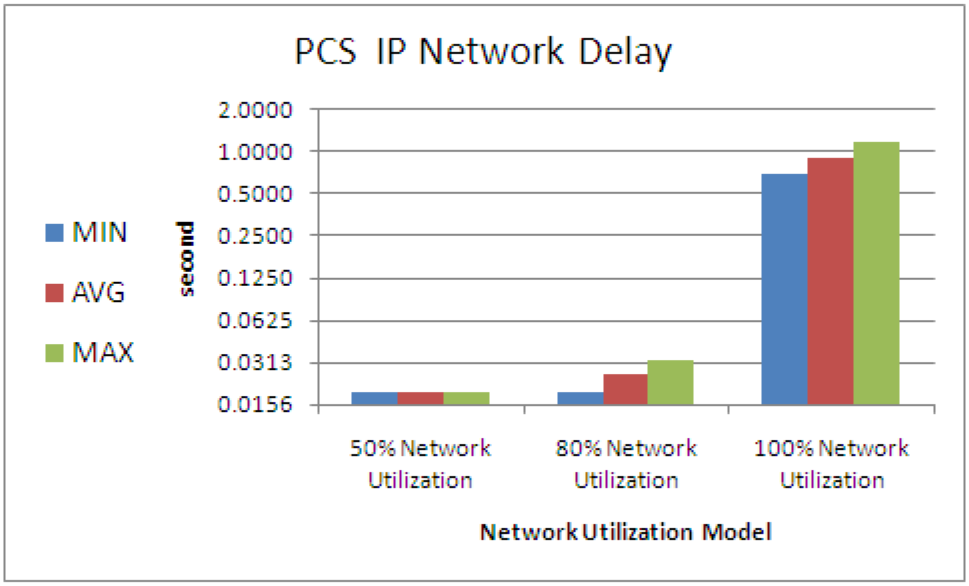


Figure 5.78 PCSVC to PCS Area 5 IP Network Delay

The IP network jitter behavior was directly correlated to the traffic loading. The jitter reached up to 300 ms at 100%. This is considered a very negative behavior as it will impact the application layers and packet delivery quality. Figure 5.79 depicts the jitter performance. At low network utilization, 50% or lower, the jitter in the sub millisecond.

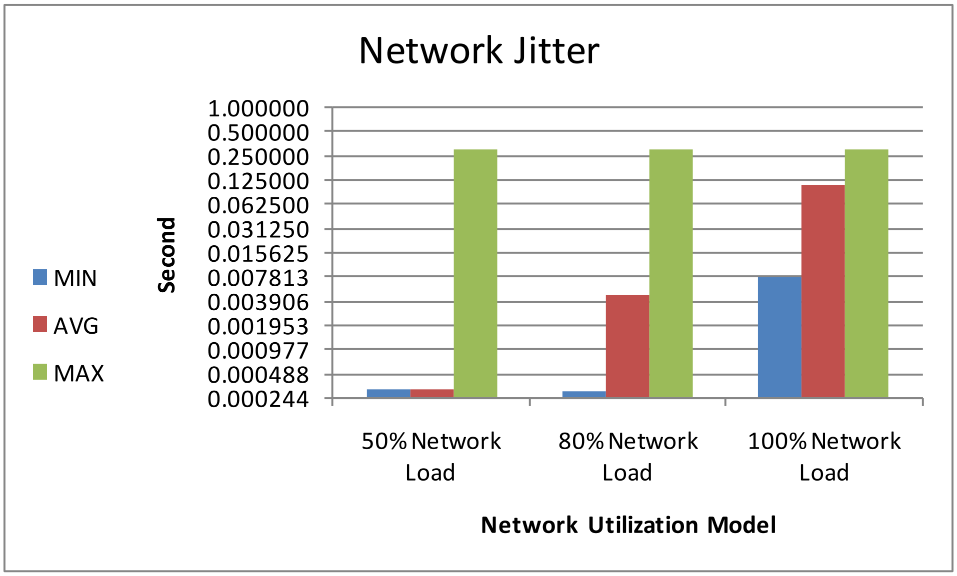


Figure 5.79 PCS Area 5 to PCSVC PCS IP Network Jitter

The packet loss was examined in this simulated test case scenario. The packet sent and received at 50%, 80%, and 100% utilization is depicted in Figure 5.80. The 100% utilization displayed unsatisfactory results as packets in both directions were lost randomly. This is further confirms the weakness of BE CIP network model as discussed in chapter 2, section 2.4.5.2.

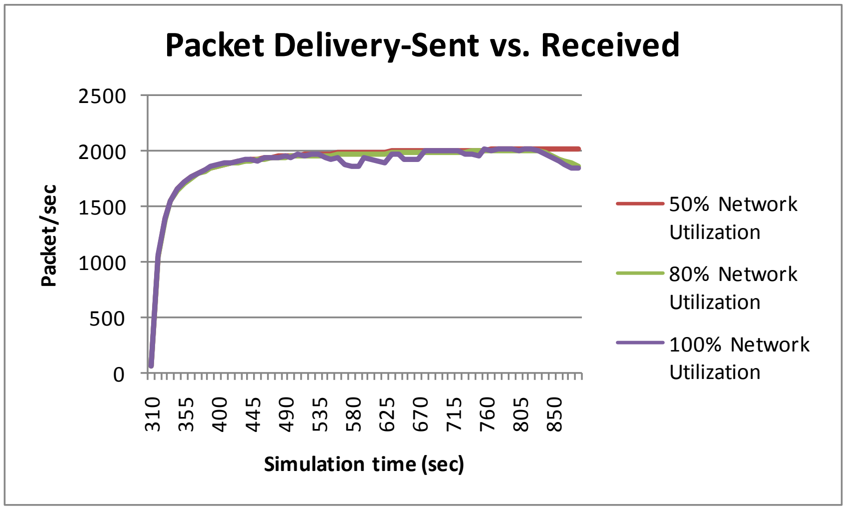


Figure 5.80 PCS Area 5 to PCSVC PCS Packet Delivery

The TCP retransmission which is either driven by packet loss due to high network loading or application synchronization was examined. The HPAA PCS retransmission was 7 as depicted in Figure 5.81 for 100% utilization. At the 50% network loading the TCP retransmission was within the 1 second count.

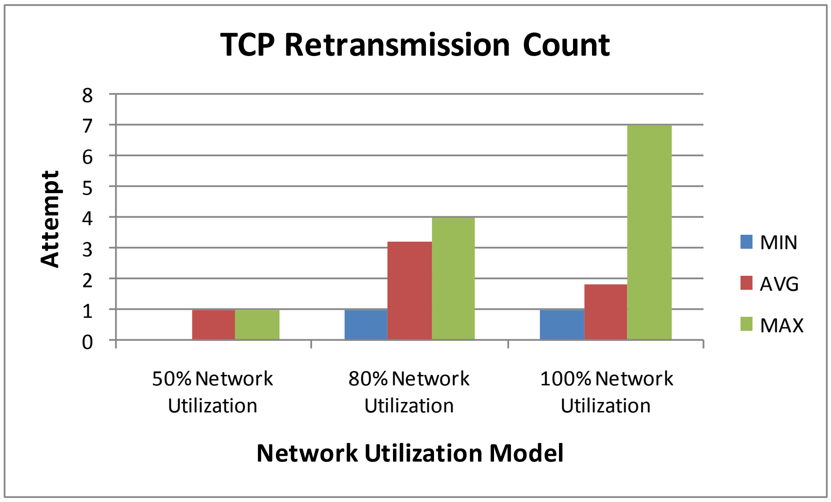


Figure 5.81 PCS Area 5 to PCSVC PCS TCP Retransmission Count

In this test case, the TCP retransmission timeout was examined. The results show TCP retransmission timeout was increased by 143% when the network loading increased by 20%, from 80% to 100% utilization. As shown in Figure 5.82, the timeout was 2.4s at 100% network loading. The results also show the TCP retransmission timeout was 1.67s at 80% and 1s at 50%.

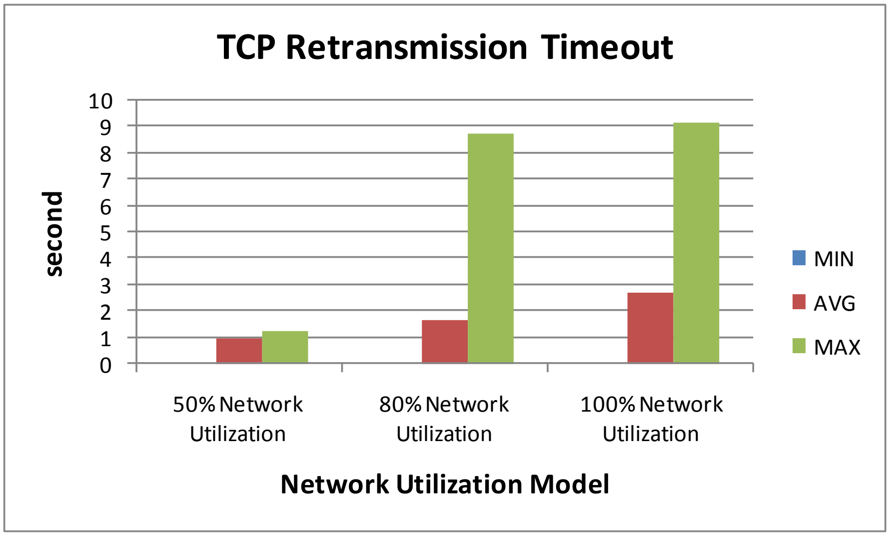


Figure 5.82 PCS Area 5 to PCSVC PCS TCP Retransmission Timeout

Support services, IP telephony and media (video) streaming also know as Closed Circuit Television, were simulated in this test case and examined. Similar to earlier test cases, the master/client and P2P were enabled on the CIP network model. The model was exposed to 50%, 80%, and 100% network loading. The simulation results are depicted in Table 5.4.The results show delay and jitters' exponential relationship in performance degradation as the BE CIP network utilization increased from 50%, 80% and 100%.This resembles a gauge on the feasibility of this network model for HPAA CIP.

Table 5.4 Support Services, IP Telephony & Video Streaming Intra-domain Performance

Support Service Performance	**50% Network Model (msec)**	**80% Network Model (msec)**	**100% Network Model (msec)**
IP Telephony Packet Delay	78	91	1250
IP Telephony Packet Delay Variation	0.00001	0.05	242.00
CCTV Packet Delay	28.80	1453	1752
CCTV Jitter	0	1450	1750

5.5.4.2 Priority Based QoS Converged IP for Remote Wireless Site

This section shows the results of converged IP network with Priority based Scheduling QoS setting for the remote wireless backhaul site. The simulated test case scenario was configured and implemented as defined in the research design in Chapter 3. In this network model, the PCSVC in engaged in acyclic control loop per second with PCS Area 5 (CNT6).Also, both IP telephony and Video streaming sessions are running between the two facilities. The highest priority was assigned for the HPAA PCS application, followed by IP telephony and then video streaming. The network model was exposed to a traffic load of 50%, 80%, and 100% network loading. The outcomes of the simulation are depicted in this section.

As shown in Figure 5.83, the HPAA PCS application round trip delay for this test case scenario was 44.4 ms regardless the network loading levels; 50%, 80%, and 100%. This demonstrates the added value of priority based QoS setting for this application.

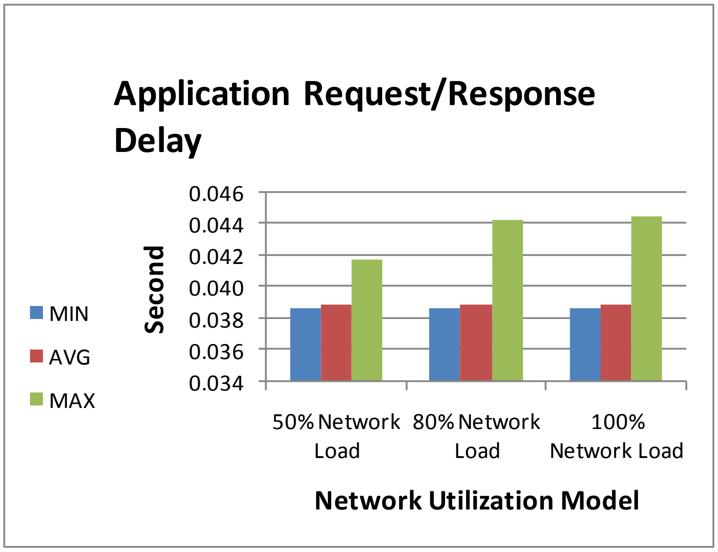


Figure 5.83 PCS Area 5 to PCSVC PCS Application Round Trip Delay

The one way PCS application delay was estimated at 24.9 ms in all the different scenarios as shown in Figure 5.84. This shows the timeliness of the WAN CIP for a remote site with backhaul wireless length. Moreover, the network loading increase had no impacts on the timeliness of the application performance.

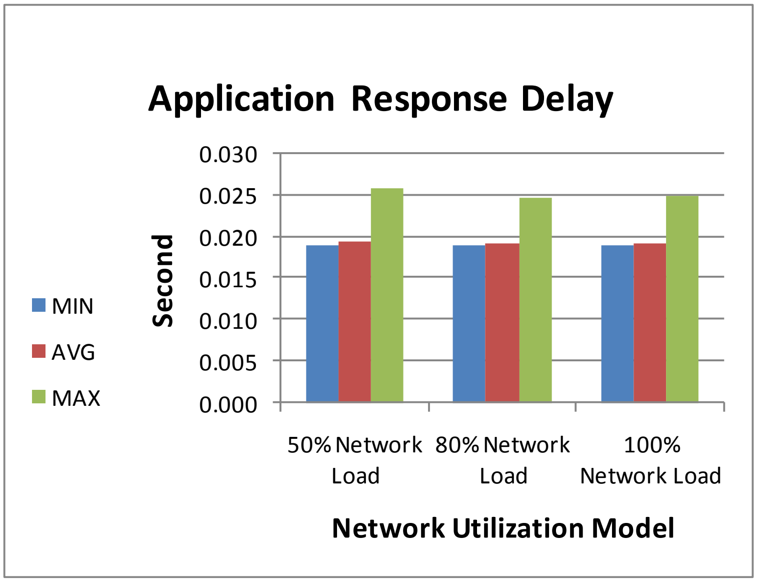


Figure 5.84 PCS Area 5 to PCSVC PCS Application One Way Delay

The IP network delay was averaged at 18.8 ms for the different simulation test case scenarios as shown in Figure 5.85. This is considered an encouraging result for a wireless backhaul link.

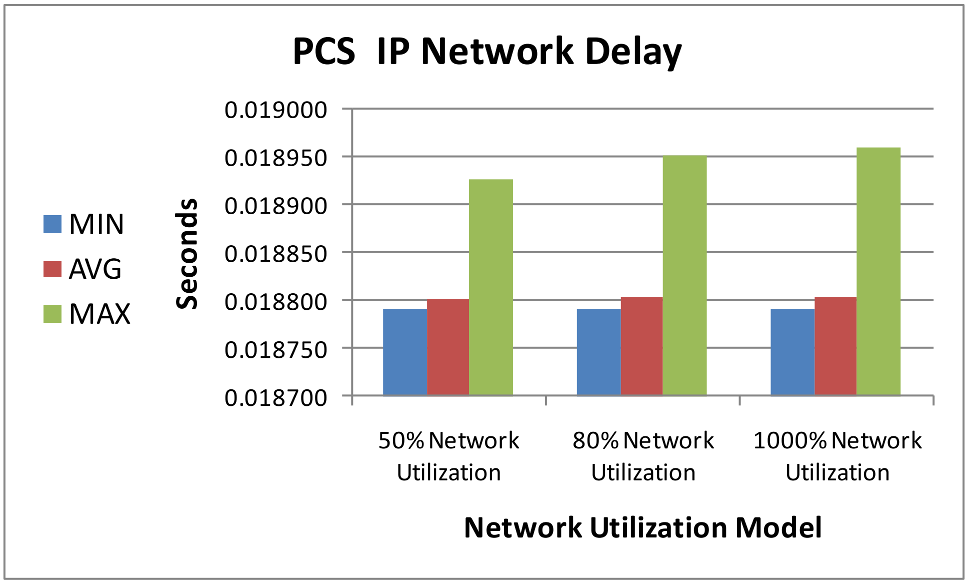


Figure 5.85 PCS Area 5 to PCSVC PCS IP Network Delay

IP network jitter was at an average of 0.03 ms as shown in Figure 5.86 for the different network loading; 50%, 80%, and 100%. Jitter is higher than expected but this is mainly contributed the wireless backhaul link.

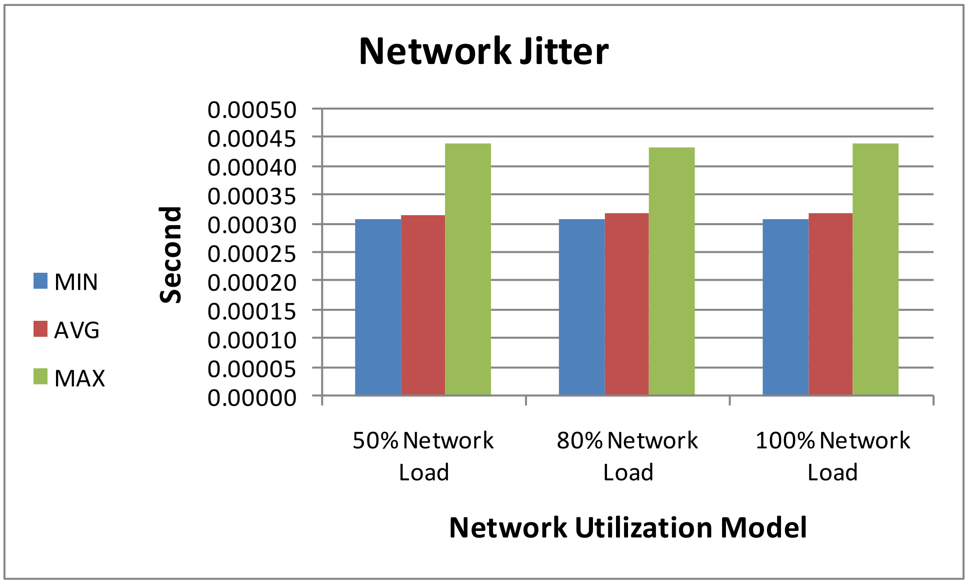


Figure 5.86 PCS Area 5 to PCSVC PCS IP Network Jitter

In this simulated test case scenario, the packet loss for HPAA PCS application was zero for both sent and received. This was demonstrated for the 50%, 80%, and 100% network utilization as shown in Figure 5.87. This is mainly attributed to the QoS priority based settings.

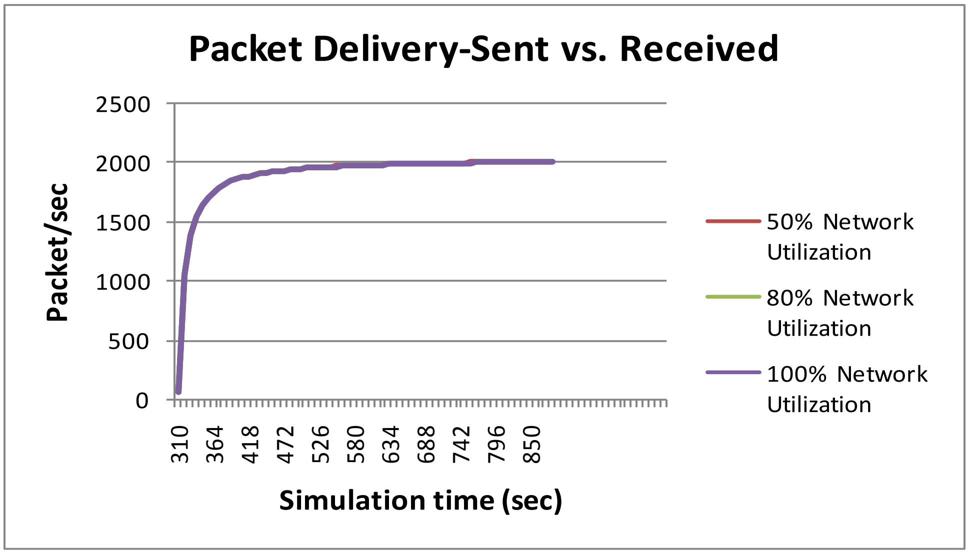


Figure 5.87 PCS Area 5 to PCSVC PCS Packet Loss

Moreover, the TCP retransmission count was 3 counts at the different loading scenarios. The HPAA TCP retransmission count continues to be an inherent problem mainly driven by the wireless backhaul link. The network loading increase did not have an impact on the TCP retransmission count and this is mainly driven by the QoS Priority based scheduling as shown in Figure 5.88.

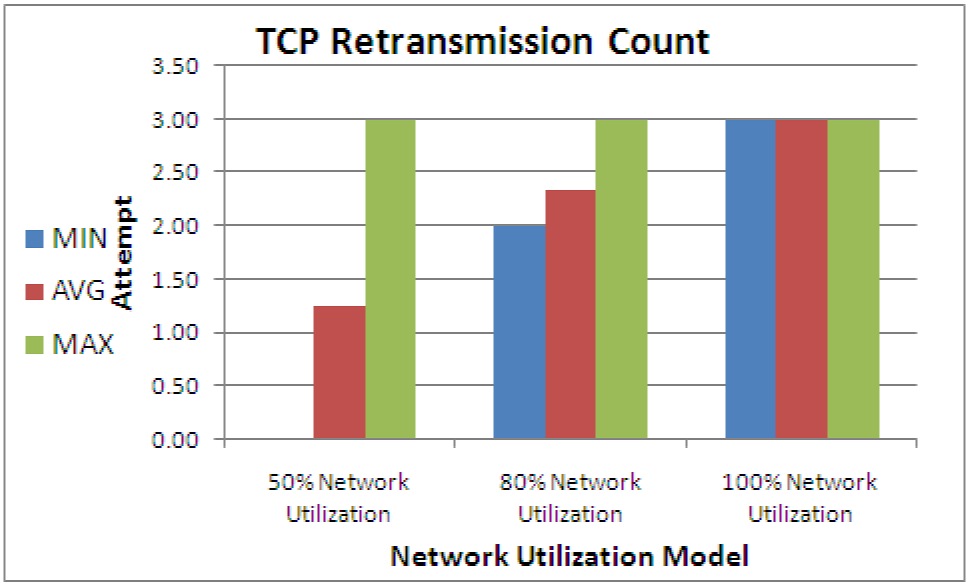


Figure 5.88 PCS Area 5 to PCSVC PCS TCP Retransmission Count

In this simulated test case scenario, the TCP retransmission timeout was examined. The results show an average of 1s encountered during the HPAA PCS application communication. The network loading at 100% shows an increase in the timeout by an additional 1 second as shown in Figure 5.89.

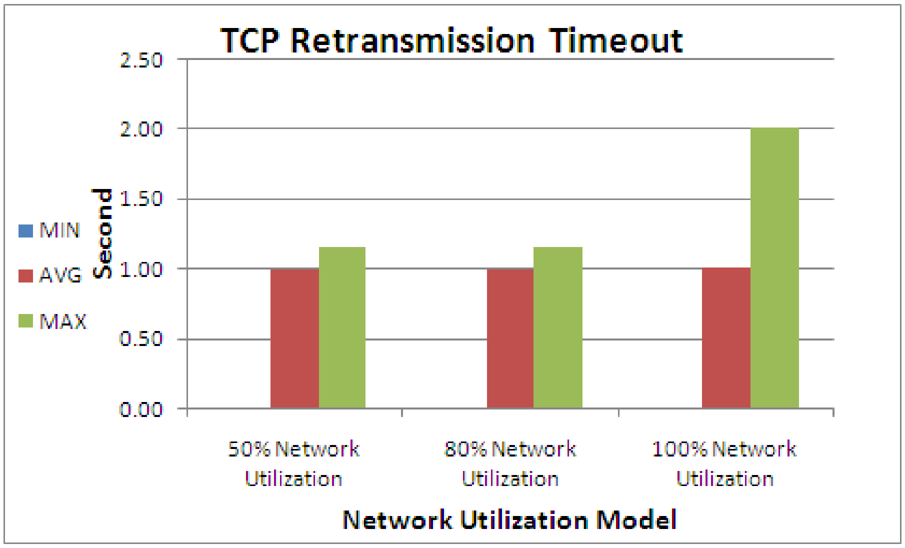


Figure 5.89 PCS Area 5 to PCSVC PCS TCP Retransmission Timeout

Support services, IP telephony and video streaming performance, were simulated at 50%, 80%, and 100% test case scenarios network model. IP telephony was assigned second after HPAA PCS and the video streaming as third in priority. The simulation results are depicted in Table 5.5. The results show Priority based Scheduling effectiveness in support these services on the wireless backhaul link. Both delay and jitter conformed to their application timeliness requirements.

Table 5.5 Support Services, IP Telephony & Video Streaming Intra-domain Performance

Support Service Performance	**50% Network Model (msec)**	**80% Network Model (msec)**	**100% Network Model (msec)**
IP Telephony Packet Delay	79.8	80	80
IP Telephony Packet Delay Variation	0.00002	0.00031	0.00037
CCTV Packet Delay	185.00	186	185
CCTV Jitter	0	1450	1750

5.6 Summary

This chapter provides comprehensive and detailed results for the different simulated test case scenarios. The HPAA PCS Controller was examined in dedicated and CIP network models. The CIP network models were configured and implemented with BE and Priority based Scheduling Quality of Service settings. Support services such IP telephony and media streaming were defined in the simulated test case scenarios and ran concurrently with the HPAA application in the CIP network model.

The applications, network elements, and interface were configured and implemented in the simulator based on the research design in Chapter3. Two network designs were used to examine the application and network performance. The primary focus is on time delay, jitter, packet loss, application stability which includes TCP retransmission count and time. These are LAN and the WAN network model. Moreover, a wireless backhaul link was simulated to examine the use of wireless as a last backhaul link connecting remote sites.

In the simulated test case scenario, the HPAA master/client and P2P relationship in a converged IP network model were examined. Also, the network models were exposed to a network load of 50%, 80%, and 100% network utilization. The results show degradation in performance with the increase in network utilization. BE CIP performance was least preformed and was not in compliance to the application performance specification; delay was at 300% or higher than what is required. Moreover, packet loss was in the range of 20% as network utilization reached 100%. The application stability showed excessive TCP retransmission count and timeout. The Priority based QoS settings showed its effectiveness by minimizing delays in the millisecond range regardless the traffic loading. The jitter was minimal in the sub millisecond. Moreover, packet delivery was at 100% success for both sent and received. The application stability was consistent and independent of the utilization where TCP retransmission and timeout were within the application predefined windows.

The wireless backhaul link connecting remote “spur” HPAA PCS site was examined. The results shows wireless link as a backhaul has a drawback even with the QoS implementation. The TCP retransmission and timeout were apparent as utilization exceeded the 80% threshold even though HPAA PCS was assigned highest QoS priority. The best effort model was unsuccessful and delay, jitter, packet loss and application stability were poorly rated. On the other hand, support services for IP telephony and media streaming, results were presented in this chapter and their outcomes were consistent and correlated to the HPAA PCS application performance.

The results of this chapter will be discussed in detail in the upcoming Chapter 6. The simulation test cases will be cross examined to experimental test case scenarios for validation and to identify relationship between the different network models and their performance. This chapter provides ample data that will be used in Chapters 6 and 7 to establish relationships, deduce new outcomes, and provide areas of improvements.

CHAPTER 6 DISCUSSION

6.1 OVERVIEW

In this chapter we will discuss the results of the simulation and experimental case studies for HPAA PCS CIP network model. The experimental test case studies were used to build the initial simulation test case scenarios' model parameters. This includes the HPAA PCS Controller processing time, cyclic and acyclic message behavior, and the application and network QoS settings for BE and Priority based Scheduling network model. Moreover, the experiment test case results were used to validate the simulation test case scenarios. Since experimental test case scenario lacked the flexibility due to network resource limitations (i.e., number of nodes, exact traffic loading injection load timing, etc.), the simulation test case scenarios were used to expand the test cases and obtain more results. Simulation provided the needed flexibility to explore and test different parameters that are easier to track and configure than experimental test cases. The simulator was configured with essential parameters for HPAA PCS application behavior, support services, network nodes, and links as defined in the research design. In the experimental and simulation test case scenarios, the network model such dedicated BE, and Priority based Scheduling were examined in both LAN and WAN CIP networks. The network models were exposed systematically to a network loading of 50%, 80%, and 100% utilization.

The obtained results from Chapter 4 and 5 for both experimental and simulated test case scenarios will undergo comparative analyses and cross examination to draw new finding and validation. Also, this includes synthesis for the results by revisiting the previous work that reviewed and discussed in Chapter 2 as part of literature review.

6.2 SIMULATION FOR HPAA PCS LAN NETWORK

The simulation for HPAA PCS LAN network includes three different HPAA PCS LAN network models. These are Dedicated, BE and Priority based Scheduling QoS converged

IP network. The network model was exposed to traffic load of 50%, 80%, and 100%. HPAA PCS master/client and P2P relationships with IP telephony and video streaming were simulated and test case scenarios were conducted to identify key performance indicator for the proposed network model. The primary focus was on delay, jitter, packet loss, and application stability. The application stability includes TCP retransmission and TCP timeout since HPAA PCS is based on TCP as discussed and identified from the literature review in Chapter 2.The application and network element simulation configuration and implementation was kept consistent in these different test cases to provide an environment where resulted are linked, compared, and relationships are identified. Moreover, the simulation input was confined to the research design detailed in Chapter 3. The results were presented in chapter 5 and will be discussed in this section.

6.2.1 Simulation HPAA PCS Dedicated IP LAN Network

In the dedicated LAN network model simulation which is based on utilizing standard Ethernet switches and full duplex high-speed links, the Controllers in each network domain generated intra-domain PCS application’s traffic and cross domain data exchanges. The network simulation outcomes have shown remarkable performance for time delay, jitter, packet loss, and application stability (i.e., TCP re-transmission attempts and TCP timeout).The dedicated network model maximum network delay was well below 1ms, which implies seamless network connection between the HPAA PCS Controllers and their peering relationship. Jitter was in the sub-microsecond. As PCS application demand increased, the Ethernet network utilization and delay increased but continued to be in the millisecond level. This confirms earlier findings by [40] regarding delay for cross-traffic on a dedicated network environment where network Ethernet switches and links used to connect traffic sources and sinks motivate delay due to switching time and specifically when the traffic load increases randomly and with sudden bursts. The delay is in direct relation with the Ethernet backplane switching speed so the lower the speed the more delay will occur.

Previous studies [40], [57], and [58]have identified an observable network switching delay and defined a direct relationship between delay and application traffic volume even though the network resources were fully dedicated for PCS application in question. The delay can be mainly attributed to buffering and the bit serialization/de-serialization process which is driven by the traffic switching process in the switch interfaces. The contributed link delay was found negligible due the high-speed fiber optic connection utilizing light to carry data. Moreover, the HPAA PCS application, by nature, is very light in traffic load, 64 bytes minimum and a maximum of 1024 bytes (i.e., less than 1500 bytes of Ethernet frame). Therefore, HPAA packet loading does not require the need for jumbo super-frames (i.e., no frame fragmentation) resulting in less switching delay.

As for packet loss, the simulation showed zero packets dropped, or loss ratio, for both intra-domain and inter-domain message exchanges this mainly attributed to the LAN switch and links, Gbps, which have ample bandwidth providing the needed capacity to process traffic load without any adverse effects on the application and network congestion and or delay. This demonstrates the packet delivery quality which has a direct effect on the application performance. In [29], discussed in detail the packet delivery impacts on the process automation traffic and control loops, as packet loss increases, the application request/response mechanism is triggered. In other words, if the application does not receive the expected data, the application has the option to revert back to the process variables lower bounds that are part of a control loop. And therefore, this may result in unplanned reduction in the overall productivity of the plant operation.

The dedicated LAN network's TCP retransmission count was found also to be zero. TCP retransmission, if excessive, may result in overloading the network with unusable traffic load and may result in degrading PCS application performance, an issue that was discussed in [38] and [63] highlights the inherent behavior of TCP under unreliable and or loaded network links. TCP is disciplined protocol that keeps trying to send the unconfirmed messages until the application timeout. In [38] and [63], discuss a modification for the TCP/UDP/IP protocol stack to optimize and administer the interface between the PCS application and the TCP layer such a modification concept was outside the scope of this research as the aim of this research is using standard based Ethernet technology without any special alteration to the stack. Finally, the simulated HPAA PCS Controller design reflect the evolution of the Controller as discussed in [23] and [25] where PCS layers evolution was highlighted. The primary trend is the Ethernet interfaces are being extended down to the lowest layer (sensors) because the instruments are becoming an intelligent node (i.e., microprocessor-based and communication enabled devices) and their adoptions at the lowest layer of process automation instrumentation and control in the manufacturing field has risen. Hence, the increased traffic by the instrument will increase Ethernet penetration as a transport network supporting multiple application relationships, control strategies, and providing more information on the process behavior.

In general, for any given HPAA controller, it supports a multiple concurrent applications with different peering relations. For example, Controller # 10 (CNT10) has two different concurrent peering relationships; one with CNT20 and the other with the Master Controller. Moreover, one important finding is that modern Controllers have significant data retention capabilities, as demonstrated in the Case Study #1. Therefore, source to destination traffic bursts are expected to occur resulting in higher than expected traffic surge. This is especially noticeable whenever the Controller communication is momentarily off lined from the network due to node or link failure.

6.2.2 Best Effort Converged IP LAN Network

For best effort CIP network, the simulation model for the LAN Ethernet network performance and application response time shows interesting results. In this model, traffic mix was sent across the IP network either by using standard TCP or UDP without additional protocol modification features (i.e., no protocol alteration) to improve QoS. This data transmission approach is attributed to the standard IP protocols that make an attempt (effort) to transfer packets to their destination, but packets may be delayed, transferred with jitter, and/or lost as discussed in [9], [10] and [64]. This is due to first come first served approach and the lack of consideration to prioritization or scheduling.

Hence, BE transmission approach handles different applications by allocating bandwidth based on a weighted average of their traffic size. So, bandwidth starvation and or switch node backplane speed limitation will impacts those applications with less weighted average if sent concurrently with large applications on the same network substrate.

The simulation test case scenario confirmed BE network model bandwidth appropriation for each application and was mapped to a weighted average that is directly related to its traffic volume as outlined in Table 6.1, for example, large file transfer acquired most of the bandwidth as compared with smaller applications such as HPAA PCS.

Table 6.1 Bandwidth Allocation by Weighted Average

Bandwidth Resource Allocation Ration vs. Network Loading	**Weight Average Per Application**		
	50% Network Utilization Model	**80% Network Utilization Model**	**100% Network Utilization Model**
Controller	0.000136	0.000112	0.000073
IP Telephony	0.001065	0.000876	0.000571
Media Streaming	0.133173	0.109481	0.071383
File Transfer (Traffic Injector)	0.865625	0.889531	0.927973

It can be noticed that network traffic loading and traffic mix have an impact on both the HPAA PCS application and the network performance variables such as delay, jitter, packet loss, and TCP retransmission. Moreover, support services such as voice and media streaming will have similar impacts. The simulation provided that traffic arrival rate is based on the maximum constant uniform distribution rate that the network can process as discussed in [47]. As a result, the simulation test case scenario account for maximum peakedness and bursts by applying constant traffic rate at 100% traffic utilization. This was dominated in the CIP network models that are defined with a network loading of 100%.

The HPAA PCS application in a converged IP BE LAN network did encounter delay that spans from 1.1 ms to 122 seconds. The delay increase was correlated to the systematic increase in traffic loading from 50% to 80% and then 100%. The delay resulted by the

80% and 100% network model is not acceptable for HPAA PCS system as some of the application as defined in Table 2.2 (HPAA Application characterization) time delay specification range from 10ms to 40ms. Such an increase in delay will result in missed real time updates and may trigger system safe shutdown. Jitter also had a similar relationship to delay. The jitter was increased from below 30 µs to 50 µs. The jitter was considered minimal as compared to the application tolerance, below 10 ms, so there were no impacts to the HPAA PCS application.

The TCP packet retransmission count was increased significantly from zero, at 50% and 80% loads, to over 38 counts at 100% during a limited simulation period of 15 minutes. This is an indication on the struggle the HPAA PCS application encountered during data transmission when network utilization became high. HPAA PCS TCP retransmission is not a favorable pattern and in fact for a safety system, packet retransmission can be used as a threshold to trigger a safe shutdown as discussed in [47]. The previous work highlight link stability by ensuring there is no bandwidth starvation and or transmission links physical quality. A stable physical link with bandwidth starvation forces those impacted applications to retransmit their unconfirmed messages (missed updated). As the missed updates are recognized by the application layer, the application will either revert to preset thresholds to ensure stabilized process operation or safe shutdown to prevent unsynchronized system shutdown. This is similar to the findings in this research from simulation as well as experimental test cases as it will be demonstrated later in this section.

As discussed in [13] and [19], cross traffic utilizing high-speed link has higher level of packet delivery success from data transmission (sent/received) when network utilization is maintained at low level (i.e., ample overhead capacity to absorb traffic surge). The results of this simulation test case scenario provide similar outcomes for HPAA performance in a BE CIP network model. At utilization 50% or lower, the HPAA PCS application had minimal delay and jitter, no packet loss, and TCP retransmission count and timeout were within the application defined windows.

The simulation results confirmed network utilization model had a direct impact on the HPAA PCS Controller packet delivery performance. For 100% traffic loading there was 47% of the total packets were lost at 100% traffic loading. However, at the 50% and 80% utilization, traffic loss was not observed. This primarily driven by the BE weighted average bandwidth allocation even though HPAA PCS uses TCP/IP protocol. Other applications such as large file transfer, TCP/IP, and media streaming, TCP/IP, had better success in sending their traffic than smaller applications as in the case of HPAA PCS, TCP, and IP Telephony, UDP, applications. So, low network utilization resulted in better performance for all the applications in questions. These findings mitigate the concerns outlined in [12] regarding the reliable real-time communication requirements that necessitate dedicating a standalone network to ensure packet delivery integrity for PCS applications. The 50% network utilization or lower, converged BE IP network demonstrate seamless packet delivery and can satisfy the concerns mentioned earlier in [13].

The HPAA PCS P2P application and network's delay and jitter performance had an exponential relationship with the traffic load, as presented in Figure 6.1. This is due to the compounding effect of traffic exchange between the two domains in question and the additional traffic exchange between each domain to the Master Controller. Hence, careful consideration in traffic load mix as well as regulating throughput shall be part of HPAA PCS BE CIP network design. As outlined in [42], IP networking for control functions shall adhere to stringent time delay requirements. This translated in 10ms in substation automation specifically in load shedding. However for the HPAA PCS application, a 40 ms delay is a tangible and feasible solution. This is comparable to the requirements of Emergency Shut Down systems installed at Gas well's head to prevent H_2S (lethal gas) or the electrical compressor system supporting the oil and gas separation and pipelines pumps. The PCS BE IP LAN model network delay ranged from 2 ms at 50% to 5.0 ms at 80% and up to 23.4 seconds at 100% network utilization model.

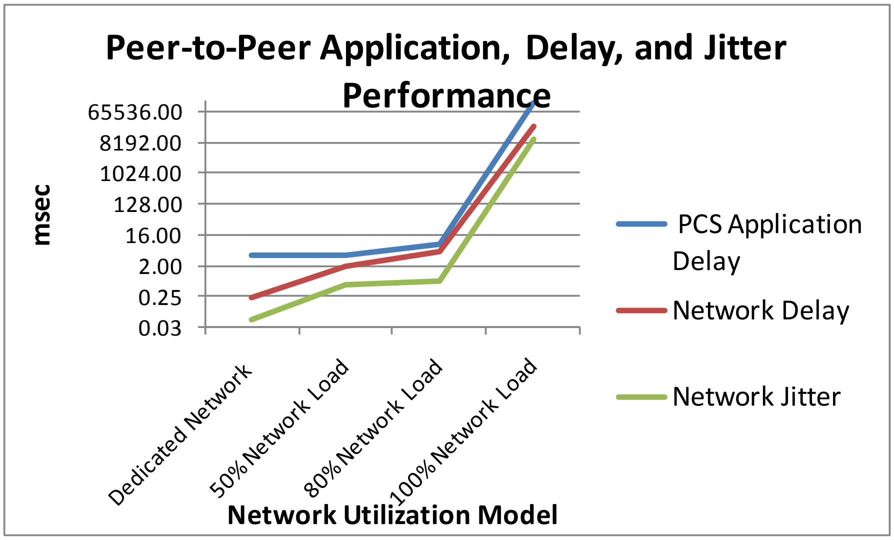


Figure 6.1 Converged Network: Peer-to-Peer Performance Non-linear Relationship

In this BE CIP simulation test case scenario, the simulation outcomes for the P2P PCS HPAA application show severe impacts at the high network loading, 100% utilization. The delay was in the order of 60 seconds, P2P jitter was not impacted, in the order of 60 µs, due to the extended delay in network and application performance. On the other hand, TCP retransmission was very high with over 40 TCP reattempts. This is In-line with what was discussed in [9], [10] and [31] regarding traffic loading impact on the performance of the carried load. The previous work highlighted the importance of balancing traffic load with network resources and showed schemes such as adding more bandwidth, altering the protocol stack and or enabling Priority based Scheduling QoS. In the BE simulated test case scenario, bandwidth regulation can be achieved by limiting the traffic source interface with a committed information rate that much less than full interface speed, 100Mbps. This task is a mundane task and labor intensive as discussed by [31].

Regarding the support services such as IP telephony and media streaming BE CIP simulation test case scenarios, their performance was impacted similar to the HPAA performance that was address earlier in this section. IP telephony encountered 60 ms delay which is acceptable for normal voice calling, at low network utilization. This is similar to the finding of [50] and [78] where voice calling in a wide area network was successfully routed through multiple network resources when links subscription is regulated to a predefined committed information rate that is lower than the link speed. Moreover, the results show the delay is lower than the expected allocated delay of the IP telephony application as defined in [51] and [52] to be 80 ms to 130 ms. However, at high network utilization (100% network loading), the voice session encountered an average delay that progressed up 38 seconds. In addition, the voice packet loss was 14%. This is due to the fact that the nature of voice UDP packet traffic defined in [8] and [62] which is datagram oriented (i.e., packet are sent and a confirmation is not required).The media streaming, at low utilization, appears to perform below the maximum required delay as discussed in [51] which is 250 ms. The delay was between 5 to 7 ms and jitter was below 6µ seconds which is transparent to the human eye. However, at high utilization of 80% and 100%, video performance was very poor, with 8 second and 38 second delays accordingly. Packet lost was in the 1% to 8% range.

6.2.3 Priority Based QoS LAN Network

The network simulation for a converged IP LAN network with Priority based Scheduling QoS settings demonstrates the performance enhancements reflected by this type of QoS setting. HPAA PCS application was assigned highest in priority, followed by voice, then media streaming, and finally large file transfer. Even though the network loading was increased from 50%, 80%, to 100%, the end-to-end application performance delay for the PCS application was consistent at all time. Master Controller to the farthest Controller delay and the cross domain, P2P Controller, delay were close to 4 ms.

The HPAA PCS packet loss was zero for the different traffic loads where the sent and received packets were equal. There was no TCP retransmission count and the TCP retransmission timeout is within the application default value of 1 second. These are very encouraging results as these performance elements are crucial for a successful and stable HPAA PCS system. This finding is very important and relates to the discussion in [30], [40], and [79] where performance parameters such as low delay, zero packet loss, and

TCP retransmission and timeout that are confined within an application are key elements that shall meet real-time applications. The previous effort highlighted these performance parameters and which were used to justify high-speed dedicated networks and in some cases separate infrastructure. So, the Priority based Scheduling QoS CIP network model provides a CIP platform that has the capability to support distributed real-time information to the different components of the PCS system. Moreover, the PCS systems will be able to interface with Ethernet Distributed Control Systems (DCS), Programmable Logic Controller (PLC), and Enterprise Resource Planning (ERP) to accomplish the convergence goals as discussed in [4], [12], [24], and [48]. These goals include having single standard network platform that can support mixed services and still comply with each application's specification. Moreover, the standard platform provides the opportunity for integrating different services, protocols, and systems.

Support services, such as voice, were assigned next in priority, priority 6; immediately after the HPAA PCS application. Then, after that, video streaming was assigned priority 5, and finally injected traffic load was assigned lowest priority; best effort (priority 0). IP telephony, voice, performance was consistent at 60 ms delay regardless of the network utilization loading of 50%, 80% and or 100%. This delay is considered acceptable since it is within the IP telephony application specification as defined in [51] and [52]; which is in the range of 80 ms to 130 ms. There was zero packet loss and this similar to [50] which define quality of IP telephony on WAN network conformance to low delay below 200 ms and with zero packet loss. Video streaming delay behavior was experienced at 100% utilization with 72 ms, but this is considered minuscule as compared with the best effort of 8 seconds and most important the delay is within the acceptable delay range as defined in [50], [51] and [52] which is 200 ms or lower. Table 6.2 provides a comparative analysis for the different simulated LAN network scenarios. From this table, it appears HPAA PCS application encountered delay for the dedicated network close to Priority based Scheduling QoS and conforming to the HPAA PCS application delay tolerance requirements, defined in Table 3.2.

On the other hand, the HPAA PCS performance in CIP BE LAN network is susceptible to more delay than Priority based Scheduling QoS setting. The BE network utilization at 50% and 80% performance fulfill HPAA PCS application delay tolerance requirements. However, at 100% utilization network model, the delay performance is not in line with the HPAA PCS Highly and Moderately demanded applications as defined in Table 3.2.The 50% network utilization network model provides ample bandwidth that can be used for unexpected traffic bursts to ensure consistent time delay during the steady-state network operation. The 80% network utilization for BE network does not leave overhead capacity that would ensure network conformance to HPAA PCS desired performance. Hence, 50% BE is more favorable as it provides ample overhead capacity that can support traffic surge resulting from application burstiness or even traffic reroute. The BE network at high utilization, 80% to 100%, do not meet the minimum HPAA PCS and other support service application delay requirements. Hence, it should not be considered as a viable option. This is in-line with previous research in [19] where application delay was correlated to link's characterization of traffic congestion by analyzing link utilization at various times. The study was able to identify traffic bursts, their duration, and delay associated with them. Moreover, the HPAA PCS BE CIP network model encountered packet loss and application stability from TCP retransmission and timeout. This is similar to the finding in [57] and [58] where the assertion and a direct relationship was established between packet loss and web page download time as the network loading progresses from 70% to 100%.

Priority based Scheduling QoS provides the ultimate objective for balancing HPAA PCS application and support service on the same network and still conform to the application delay tolerance requirements. The 100% network utilization model does not provide overhead capacity that will be needed to support traffic bursts and/or reroutes. In the same comparison, utilizing a 50% network utilization model strands network resources that may not be used for the full life-cycle of the operation. Hence, the 80% network utilization model provides excellent compromise in supporting the traffic behavior and maximizes on resource utilization in Priority based Scheduling QoS LAN network. This was demonstrated by different simulated test case scenarios and moreover the experimental test cases confirm this finding. Moreover, in [21] and [24] evaluated the effectiveness of QoS in providing the overhead capacity that can accommodate traffic surge due to burstiness or traffic reroutes driven by link failure. As explored and discussed in [9], [10], and [64], QoS priority based scheduling is a network strategy that can be used to maintain a balance of application quality of connection and still maximize the link utilization.

6.2.4 Experimental HPAA PCS IP LAN Network

The experimental results correlate to the LAN simulation test case scenarios. The three different test cases outlined in Section 4.2 clearly show that non-HPAA application such as SNMP has minimal traffic impact on the overall network in steady state operation. This is in-line with SNMP traffic behaviours as discussed in [55] and [56] where it can be efficient once confined to preset thresholds. The thresholds include update cycle and overhead messages. Otherwise, it is not very efficient and contributes in relaying unnecessary information, such as the version number, acyclic updates.

However, once the network was exposed to high traffic load, the performance of HPAA PCS and non-HPAA became a hostage of the increased traffic load. This similar to what was found in [54] and [55] relating to network monitoring via SNMP on network performance parameters under link loading. Request and predefined poll cycles were missed due to high utilization. This behavior creates unnecessary network flow alarms request addition profiling and in quickly this condition repeat itself thus saturating the network links. As depicted in Table 4.1, the network delay for both Best Effort and Priority based Scheduling were examined under different traffic loads (i.e., 50%, 80%, and 100%). The network delay for BE network was below 10 ms for the utilization of 50% and 80%. The packet error rates and discarded packets for both SNMP and HPAA were zero at low network utilization below 80%. Moreover, digital control (on/off) and continuous control were examined and tested without risking the process operation. However, at 100% network utilization, the delay was close to 4s. Moreover, the HPAA PCS application performance was adversely impacted by not processing the command within 4 to 5 seconds from being initiated. These findings are similar to what was discussed in [19] and [20] the network loading has impact on both delay and packet loss especially with applications that have large data and or frequent request and response cyclic messages. The probability of lost packet increases with the data transmission frequency as traffic burstiness has a higher opportunity to coincide with each other.

Moreover, the above findings are discussed in [24] and [31] regarding network role in shaping traffic and or filtering to balance between the impacts of traffic spikes and data transmission quality on the application performance. One aspect that was discussed is the network nodes and links in providing the platform for successful data transmission. Network utilization on the node backplane and links are key parameters that can be maintained to secure the needed bandwidth resources for vital application. In this experimental case study, the Priority based Scheduling test case scenarios shows positive results. The HPAA PCS LAN network delay was close to 10 ms independent of the network utilization model (i.e., 50%, 80%, and 100% network utilization). This is below the HPAA PCS application time delay tolerance requirements of 40 ms. Moreover, similar to BE network utilization model of 50% and 80%, there were zero packet in error or discarded. The test cases did not include actual commands from the master controller for the digital synthesis (on/off) and control of real-time traffic connected to mechanical systems such as valves and pumps, etc. Therefore, simulated control strategies were invoked utilizing personal computer connected to the IP LAN network. The HPAA PCS network performed without any impacts in Priority based Scheduling models and BE 50% and 80% network utilization models. This relates directly to what was found in [20], [21]and [22] in discussing means of overcoming Ethernet un-deterministic inherent behavior and besides altering TCP/UDP/IP protocol, the QoS protocol found to a mean that can provide quality application connection and comparable to token based master/client model. Priority based Scheduling was demonstrated to a feasible solution for substation automation local implementation where delays requirements in 10 ms.

Another important finding from this experimental test case study scenario is the test network; Gbps backbone gave an indication that with the allocated 100 Mbps bandwidth for HPAA, PCS and SNMP co-exist. The combined traffic resulted in a peak network utilization of 12%. Hence, one may deduce that even a Fast Ethernet 100 Mbps network can support the co-existence of SNMP traffic with HPAA PCS application. The effective network loading was discussed in [26] and highlights actual traffic load impacting the effective network utilization is typically much lower than the combined load which includes overhead messages, broadcast, and alarms that are used to manage either the network resources or the PCS system. Moreover, in [27] discussed HPAA application ability to adapt to low speed links provided data retransmission is not invoked due to network congestion. These where QoS priority based Scheduling can be utilized as found in this research to ensure the HPAA application is processed through the network without the need for retransmission.

This was also affirmed when Priority based Scheduling QoS, full duplex high-speed standard Ethernet trunking were invoked in the test network. This outcome lessens the overly conservative approach of utilizing a proprietary Ethernet solution as discussed in [17], [20], and [31], the use of EtherCat or PowerLink protocols which relies on alerting the data link and or TCP/UDP protocol layers by adding a special firmware stack.

6.2.5 Comparative Analysis for IP LAN Network

In this section, comparative analysis between simulation and experimental case studies for HPAA PCS in a converged IP LAN is presented. In all cases, the simulation and experimental results showed close correlation. This is very important as it reflects a validation for the simulated test case scenarios. Experimental results gave an assurance, or validation, to expand the simulated model and cover different network and application behavior instances. There was a small variance between simulated and experimental results but the trends are the same. The reason for the variance between simulated and experimental is the experimental uses large scale HPAA PCS system with vendor specific system elements i.e., instruments, controllers, servers, and network switches that were not exactly used in the simulation. The simulation, as discussed in the research design of Chapter 3, uses normalized PCS system elements to strive for a general network model that satisfies HPAA PCS applications performance requirements.

As shown in Table 6.2, the time delay for dedicated, simulated, and experimental scenarios show and validate the Priority based Scheduling QoS capability in supporting HPAA PCS in a converged IP LAN. The time delay was minimal below 5 ms and is within the HPAA PCS Application time delays characterization as defined in Table 2.2 for the low band which ranges between 10ms to 40ms. Similarly, the packet loss and TCP retransmission and timeout emphasize Priority based Scheduling QoS as the desired network model where zero packet were lost and TCP retransmission count and timeout was within the configured application window (i.e., was not immaturely triggered).

Moreover, the comparative analysis demonstrates BE QoS at low utilization of 50% or lowers to be suitable for supporting HPAA PCS application. The time delay was close to QoS Priority based Schedule but slightly higher by 11%. This finding is important as BE QoS model requires least network configuration effort as compared to Priority based Scheduling QoS as discussed in [9], [10] and [64] which requires consistent and regress settings across all the network elements and traffic sources.

Table 6.2 Comparative Analysis for LAN Simulation and Experimental Application Delay

Maximum Application Delay (milliseconds)			**Master Controller/ Subtending Controllers**		**Peer-to-Peer**	
			Request/Response	**Response**	**Request/Response**	**Response**
Dedicated Network			1.1	0.8	4.05	2
50% Network Load Model	**Simulated**	**Best Effort**	5	2	4	2.1
		Priority Based QoS	4.5	2.8	4.46	2
	Experimental	**Best Effort**	1	1	1	1
		Priority Based QoS	1	1	1	1
80% Network Load Model	**Simulated**	**Best Effort**	8	5	8	6
		Priority Based QoS	4.6	3	4.65	2.68
	Experimental	**Best Effort**	6	4	10	7
		Priority Based QoS	2	2	2	2
100% Network Load Model	**Simulated**	**Best Effort**	122000	29000	119	93
		Priority Based QoS	4.9	3.5	5.23	3.15
	Experimental	**Best Effort**	39790	26520	45000	31500
		Priority Based QoS	5	3	5	3

At high network utilization model, the BE QoS network perform poorly as delay is increased from 5ms to over 122 s. This finding provides an indication on the limited flexibility of BE QoS network model as discussed in [31] and [64] where delay and packet loss increase in direct relationship to the traffic loading. It was observed in this research that 80% BE network model loading had delay that relatively acceptable, 20% higher than 50% utilization. However, when the packet loss was examined for the 80% test case scenario, it was found at least 1 to 5% packet loss. This packet loss is undesirable as discussed in [2] and [4] relating specifically to s PCS control messages (digital or analog) that are sent with very small number of bytes. So, a packet loss may result in depriving a command from timely reaching its destination-instrumentation (i.e., actuator, shut-down, etc.).

The comparative analysis clearly highlight BE network model to perform very poorly at 100% traffic loading. The results show significant degradation in performance with respect to delay of 122 s or higher for some test cases. Moreover, packet loss was in the range of 20%. The application stability showed excessive TCP retransmission and timeout 40 s as depicted in Chapter 5, Figure 5.12. Moreover the TCP retransmission count reached over 40 counts which as shown in Figure 5.15. This illustrate the BE network shortcoming when utilization progressed from 80% to 100% loading.

This research outcome for both simulated and experimental test cases had direct correlation which provided the needed validation. The findings in this research affirm the fitness of CIP LAN network for HPAA and non-HPAA when Priority based Scheduling QoS and full duplex standard Ethernet trunking are invoked. This outcome helps in promoting a new paradigm shift on how standard Ethernet network technology is adopted and extended at lowest layers of the HPAA PCS domain.

6.3 HPAA PCS CONVERGED IP WAN NETWORK: SIMULATION CASE

The WAN network simulation shows some positive results for supporting PCS application in a Converged IP (CIP) WAN network. This is especially true when Priority based Scheduling QoS settings are invoked for all applications supported by the network.

However, there are major concerns when utilizing a WAN network with BE settings. This section discusses the WAN simulation results and deduces outcomes of this simulation for both QoS settings. Experimental case study is also discussed followed by comparative analysis and additional deduced outcomes.

6.3.1 Dedicated WAN IP Network

Even though dedicated WAN for one application, HPAA PCS, may not make economical sense as discussed in [3] and [4]; due to major capital investment in installing nodes and links just to serve one application may not be justified. Technically, dedicated IP WAN network provides impressive performance from delay, jitter, packet delivery success and TCP retransmission performance. This packet network model is almost equivalent to a long distance hardwired dedicated network as the simulation results show delay for the HPAA PCS application on the order of 40 ms. This covers most of the HPAA PCS applications with delay tolerance above 40ms as defined in Table 3.2. In addition, jitter was on the order of 300 µs. There was zero packet loss and no TCP retransmission counts. This is expected from a dedicated WAN IP network that has minimal traffic loading and fully dedicated to the HPAA PCS applications as discussed in [40] by experimenting cross traffic impacts on real time traffic for Proportional Integrator Controller (PI) loop and concluded that at steady state, PCS traffic load has minimal effect on the network resources (switches and links) due to the available bandwidth and switch CPU capacity.

However, the response time does not support the lower bound of some of the HPAA PCS applications (i.e., delay < 40 ms). As a result, additional control scheme shall be invoked locally at the controller level. This may include increasing control loop time delay. Such a step will require consistent settings across all the related components of the control loop in question [2] and [40] which include the instrument, actuator, logic solver-controller. This requires proper tracking and monitoring as addition of network elements could cause a chatter condition (i.e., sending message prematurely). Another option is adjusting the application layer to adapt to the network as a proposed solution for this constraint as it will be discussed in Section 6.4.

As discussed in [29] and [40] network cross traffic distribution shall be consistent and traffic burst kept at minimum to ensure critical data time delay is not impacted. So, the option of limiting the maximum allowable HPAA PCS traffic by altering the HPAA PCS application configuration or trigger port limiting feature on the network ports to a predetermined traffic load. The network port limitation option was successfully demonstrated in the experimental case study as discussed in Section 6.4.

6.3.2 Best Effort Converged IP WAN Network

OPNET simulations for the IP over Ethernet WAN network and HPAA PCS applications performance in CIP BE network show unfavorable results. This especially occurs at the high network utilization model. Network traffic loading and mix have an impact on the PCS application and network's performance variables such as delay, jitter, packet loss, and TCP retransmission. This is similar to the finding in [29], [40], and [58] even though the traffic mix that was addressed in their effort was different (i.e., user type service such as web browsing, email, and IP telephony) but the outcomes are the same. It was noticed that a direct correlation exists between web download, large file transfer, and media streaming. These are on applications that are much smaller in packet size and session duration such as IP telephony, and email. This re-validates the finding in this research.

Similar to LAN simulation discussed previously in Section 6.1.2, the convention of BE IP WAN network is each application will get its bandwidth appropriation based on the weighted average that is directly related to its traffic volume similar to [9], [10], [58], and [64]. The previous effort validated the concept of weighted average significance and showed direct relation between the weighted average and network resource allocation. Hence, in this research experimental and simulation test case scenarios, large file transfer will get most of the bandwidth as compared with an application on the order of 1024 bytes /second (i.e., PCS)

The delay between the PCSVC and remote sites in the WAN network at 50% network utilization was on the order of 56 ms. However, as utilization increased to 80%, the delay reached 224 ms. Finally, application behavior as traffic formation reaches maximum loading and HPAA PCS application traffic burst, the overall network delay behavior changed dramatically. This was demonstrated during the traffic increase from 80% to 100% (i.e., a 20% traffic increase) causing a step function increase in delay from 224 ms to 3.6s during a 15 minute simulated time. Moreover, packet delivery at high utilization, 100%, was a suspect. Packet drop reached the order of 14% at 80% to 15% at 100% utilization. This finding correlates with the empirical test cases where delay increased drastically when load increased from 80% to 100% traffic. The delay increased by 233% and packet loss from 14% to 15%. This is in-line with [56], [57], and [68] where previous effort showed excessive network performance degradation in a non regulated wide area network. Moreover, the concept of traffic shaping at the access layer as a means to optimize WAN was discussed and, rate limiting concept examined. HPAA PCS systems can benefit from such features especially in BE CIP model.

In addition, the TCP retransmission performance was aggravated by the high network utilization. The timeout extended for a period of 65 seconds in both network loading. As expected, the 100% loading resulted in an early retransmission rate that started five seconds earlier than the 80% loading. This is an indicator that network experienced congestion buildup at an early stage as the network loading was progressing from 80% to 100%. This behavior was discussed in [39] as part of the timeliness of message transfer for real-time automation systems. Message retransmission at the transport layer (TCP) is an early indicator for the network congestion and can be a source for increasing the traffic load by repeating the process of sending the same message.

The 50% traffic loading appears to provide a reasonable balance between delay, packet loss, and TCP retransmission performance. The delay was at 56 ms and there was zero packet loss. Moreover, the TCP retransmission performance was not impacted (i.e., zero retransmission count and timeout was 1s). However, it must be noted that for PCS HPAA applications that require stringent time delay, below 56ms, the BE effort network does not accommodate such applications. Hence, carefulness is crucial in designing

HPAA PCS application safety functions on BE WAN due to the non-guarantee time delay nature of this network model. In [2] and [39], discussed safety function and the impact of time delay on process safety control. The option of local safety function triggered when time delay is reached beyond the expected time delay window is considered part of the controller logic loop deployment.

The P2P performance was simulated. This is where two HPAA PCS areas are engaged in a control loop where one, CNT-10, in PCS Area 1 is communicating with CNT-20 in PCS Area 2. Delay, jitter, packet loss TCP retransmission count and timeout are performance indicators for the network timeliness and robustness as shown in section 5.2.2,BE Converged IP for Peer-to-Peer Controller Performance. The HPAA PCS maximum delay between CNT10 and CNT20 was close to 180 ms at 100% utilization. However, the delay at 80% and 50% were close to 20 ms and 0.21ms. The results for 50%, 80% and 100% network utilization model show correlation with the performance between the PCSVC (Master controller) and remote PCS Areas (e.g., PCS Area 1 or Area 2). In [3] and [6] discussed remote site operation and highlighted the difference in delay relating to data acquisition vs. control. The delay contributed by data acquisition is little higher than control due to the message size and the cyclic poll. Special scheme are implemented by the application layer to reduce the poll cycle once the time delay window is not met. This is an approach to reduce the traffic load especially when the network is running at 100%.

Support services such as video streaming and IP telephony were impacted by the concept of BE converged IP network. IP telephony performance degradation as the network utilization increases from 50% to 100%. The IP telephony delay performance was not tolerable at highly utilized network load as it reached 0.9s at 80% utilization and 1s at 100% utilization. However, an 8 ms delay was encountered for the IP telephony service at 50%. In-line with delay, jitter increased from 0.001 ms at 50%, 180 ms at 80%, and to 245 ms at 100%. This clearly demonstrates the lack of fitness of BE IP network for supporting IP telephony at 80% network utilization model, or higher, since IP telephony maximum tolerable delay requirements in a wide area network is 80 ms to 130 ms as discussed and validated in [49] and [50] as part of the ITU guidelines and Session

Initiation Protocol development. However, video streaming performance suffered at high network loading. Video steaming encountered a 1.8s delay at 100% loading as compared with 1s at 80% and 40 ms at 50%. Jitter was minimal but observed close to 0.010ms at 100% utilization. However, at 80% and 50% utilization was 0.001 ms. As concluded from [51] and [52], the network delay for 1 Gbps Ethernet network is acceptable for a delay bound of 200 ms or lower.

Overall, these findings provide emphasis on the challenge of utilizing CIP WAN with BE network setting at high utilization, 80% and 100%. As shown earlier, the BE CIP WAN at 50% network utilization model provides a partially feasible solution. However, this network model performance does not have the flexibility to accommodate traffic surge that may be caused by traffic bursts and/or traffic reroute due to link failure. Moreover, maintaining a WAN network to be confined to 50% utilization requires traffic engineering tools and support process. Needless to say, the stranded network (50% of the network resource will be ideal at all time) is not an encouraging proposal from an economic perspective.

6.3.3 Priority Based Scheduling Converged IP WAN Network

OPNET network simulation for a CIP network with priority based Scheduling QoS settings produced a network model that conforms to PCS HPAA application time delay requirements with delay tolerance greater than 40 ms, as defined in Table 3.2. By assigning the highest priority to the PCS application, the WAN network performance was consistent at the different network utilization, 50%, 80%, and 100% models. Similarly to BE network model, two PCS relationships were examined, the first is between the PCSVC (Master Controller) to remote PCS Areas (Area 1 and Area 2) and the second is P2P between PCS Area 1 and PCS Area 2. The PCS PCSVC performance shows an average of 61 ms, minimum of 56 ms and a maximum of 67 ms regardless of the % utilization (i.e., 50%, 80%, and 100%). The sent and received packets for PCS application had zero packet losses and this confirms the finding in [57] relating to packet loss relationship to delay. As discussed in [16], direct relationship was demonstrated between delay and packet loss under an increased traffic load. So, by confining the delay to an acceptable level, the packet loss did correlate and the outcome was zero.

Moreover, the TCP retransmission count was zero for the PCS application for all the scenarios. And, the TCP retransmission timeout is shown to be 1s reflecting the default settings for the application cyclic poll. This leads to control loop stability as discussed in [3], [28], [29], [33], and [42] which highlight message retransmission attempt or failure as a trigger for control loop activation. Safety settings such as thresholds that are lower than the optimum operation are invoked for complete systematic safe shutdown.

The HPAA PCS P2P application had similar impressive outcomes. The delay was 20 ms regardless of the % of utilization. The reason for the lessened delay behavior for the P2P as compared with the PCSVC is the P2P had direct connection between PCS Area 1 and PCS Area 2. However, PCSVC has at least one backbone node as an intermediate hop between PCSVC and PCSVC Area 2. This significantly showed contribution of the intermediate hops in between. Hence, careful consideration shall be given to the trunking plan between the backbones nodes. It is apparent as traffic tandem through more nodes; delay will accumulate resulting in extending the overall end-to-end delay. In [9] and [10], discussed the nodal traffic impacts on delay and different topologies such as Star network to minimize the compounded network delay resulted by inter-nodal. The Star network model in a WAN network is not considered an optimum solution due to the number of point to multi-point links. So, the concept of optimum links or trunks are used to establish a ring or a mesh network that can provide reliable and time delay quality. This trunk planning shall be considered as part of future research.

Support services, IP telephony and video streaming, were assigned second and third priority accordingly. The performance of these two support services provides additional important findings on the enhancement Priority based Scheduling QoS can provide for a CIP WAN network. IP Telephony had a constant delay of 87 ms regardless of % utilization, zero packet loss and no TCP retransmission count. The delay encountered with the IP telephony is way below the maximum tolerable IP telephony application delay of 150 ms – 200 ms. Video streaming had 44 ms which is also below the maximum allocated network delay of 200 ms and this reflects the finding. These findings for IP telephony and media streaming are similar to [24], [49] [50], [51] and [52] where both services were tested, best practices were developed and also fed into international guidelines.

6.3.4 Best Effort Converged IP Network for Remote Wireless Site

OPNET simulation was used to explore use of wireless backhaul link in connecting a spur remote site to the WAN network. This section summarizes the findings of this effort. Consistent with the wired WAN network links, the BE converged IP network shows degradation in PCS performance for the end-to-end delay, packet delivery, and excessive TCP retransmission. The encountered delay over a 15 minutes network simulation time was 3.9s at 100% utilization and 2.8s at 80% utilization. The delay was at 0.8s at 50% utilization. The jitter behavior was directly correlated to the traffic loading. The jitter was excessive at an average of 0.2s. The packet sent and received at 50% and 80% utilization did have no packet loss. However, the packet loss at 100% was apparent with 7% packet loss rate. Further, the TCP retransmission timeout was 2.4s. This is in-line with [38] and [46] which demonstrate wireless performance as a poor mean for communication real time data in a BE model. The wireless link performance is impacted by distance, antenna stability and the surrounding environment. Hence, special schemes as discussed in [38] and [46] which include enabling QoS Priority based Scheduling to provide the required bandwidth for the applications that are at higher value.

Delay increase beyond their defined maximum thresholds of 200ms for voice and 250ms for media can directly impact session quality and considered unbearable. This was discussed in detail in [50] and [78], discussed the support services, video streaming and IP telephony performance. In this research, similar results were reached where both voice and media had major quality challenge at 80% and 100%. IP telephony encountered over 1 second delay and video streaming was over 2.5s. This is considered excessive and not acceptable. At 50% utilization, the delay was 28 ms. However, the wireless physical link reliability and optimization for HPAA PCS was not explored in this research and this can be part of future work.

6.3.5 Priority Based QoS Converged IP for Remote Wireless Site

Priority based Quality of Service (QoS) setting for the remote wireless site. PCSVC shows impressive results. The PCS application delay was close to 40 ms and jitter was at 0.03 ms regardless of the network loading; 50%, 80%, and 100%. The packet loss for PCS application was zero as well. Moreover, the TCP retransmission count was zero at the different loading scenarios. A 1s TCP retransmission timeout was encountered during the PCS application communication. IP telephony encountered a 78 ms delay and zero lost packets. Video streaming had 0.5s delay and also zero lost packets. As discussed earlier [50] and [78], the 78ms delay for voice is below the maximum allowable delay of 150ms. However, the video streaming delay of 0.5ms is greater than maximum allowable delay of 250 ms. Hence; the performance of media streaming in wireless backhaul is suspect. This finding confirms the limited feasibility of utilizing a wireless link as backhaul link between a remote site and WAN as discussed earlier in [38] and [46] which highlights the different dependent variables of wireless coding scheme, distance, antenna stability and the surrounding environment for real-time PCS systems. These variables are out of the scope of this research and can be part of future research.

6.4 EXPERIMENTAL HPAA PCS WAN

The experimental test case were first conducted at a small scale and then later expanded to cover the different objectives of this research. The initial test cases helped in profiling the HPAA PCS Controller, HPAA application delay tolerance, and Ethernet network node QoS features. The outcomes were used and reflected in the research design, Chapter 3 as they were used as a baseline for simulation test case scenarios configuration. The simulation was then conducted and later on the experimental test cases were implemented to validate and establish a link between the experimental and simulation test case scenarios results

The experiment test case scenario displayed different results. IP over Ethernet WAN experimental Case Study has shown unique results in supporting HPAA PCS in a CIP network model. Delay and jitter were determined to be minimal, packet loss was zero, and no occurrence of TCP retransmission or timeout when the network utilization model is at 10% or below. These performance parameters start to degrade upon the utilization increase progress to 100%. In this case study, both UDP and TCP traffic were examined. The network delay was increased from 1ms to 14ms at the 100% network utilization model. Since HPAA PCS is TCP as discussed in [4], [66] the application delay reached up to 889 milliseconds at 100% network utilization model. The packet loss range is 18% to 20% at 100%.There were zero packet loss at 50% and 80% network utilization models and the delay was below 15 ms which satisfies Table 3.2; HPAA PCS application delay tolerance requirements.

The TCP traffic performance showed better results in the packet loss, estimated at 4%, when the network utilization model was at 100%. However, the network delay was increased to 17 ms, a 21% increase. This is mainly due to the behavior of TCP traffic [9] and [10] which waits on acknowledgement before sending the next packet. The HPAA PCS application delay was close to 378 ms. The network delay for 50% and 80% network utilization model was below 15 ms. Moreover, the zero packet loss and these outcomes satisfy Table 3.2; HPAA PCS applications delay tolerance requirements. Network utilization model at 80% or higher has resulted in unfavorable network jitter; on the order of 3 milliseconds or higher. And, this was discussed in [9] and [39] where an increase in network loading has direction impact on delay performance. Moreover for safety system [28] discussed the need for dedicating network to prevent competing PCS traffic with other traffic type. Hence, it is recommended keeping the network utilization at 50%, or lower, to minimize HPAA PCS traffic competing with non-HPAA applications.

Network link failure and node failure recovery have shown the level of resiliency the ring topology can provide in this test case. Link recovery is impacted by the number of switches in the ring, so for small rings below 10 switches the link recovery was 31 msec. Large rings, comprising 20 to 22 switches, may run up to 187 msec. The ring recovery due to node failure is also impacted by the number of switches on the ring due to rapid Spanning Tree recalculation. The recovery time was up to 24.85 seconds. In [23] and [27], discussed the timeliness of PCS traffic and network topology where number of intermediate nodes contributes directed in the performance of the PCS application especially if there is network reroutes caused by traffic congestion or node failures where number of intermediate nodes increased suddenly.

The industrial applications scan rate can span from 4 milliseconds to 250 milliseconds depending on the application’s process variable parameters. As such, a network delay or recovery time — for an industrial application — is on the order of 4 milliseconds; the wide area network ring topology does not fulfill the minimum time delay requirements. Applications that can survive 31 milliseconds, or higher network downtime can easily be supported. This finding is similar to what was discussed in detail in [39] regarding safety system cycle updates and the impact of missed update or extended delayed update results in an application timeout.PCS application QoAC was more impacted by the ring recovery, as compared with link failure, due to the extended time required (i.e., 24 seconds or higher) for the ring recovery. PCS application, depending on the communication channel settings, may be triggered to restart if the communication channel loss was for an extended period of time. As discussed in [27 and [39], the process of restarting the application will further increase the overall application downtime. This behavior has an impact on the overall PCS application QoAC. Additional research is required to investigate this area further.

IP telephony and media streaming were explored in the experimental test case. The delay was excessive during the BE QoS 100% network utilization model. IP telephony traffic, UDP, had an increase from 150 ms to over 400 ms. This kind of delay is not acceptable for actual users. The jitter was close to 3 ms. The packet loss was at a rate of 14% to 15%. Hence, the BE QoS 100% network utilization model is not a feasible solution at highly utilized BE network. This is in-line with [50] and [52] where voice traffic quality conforms to an acceptable delay at low network utilization as compared to highly utilized network. The BE network model had an increase of 45 ms to 50 ms that was witnessed when the network utilization model increased from 50% to 80%. However, this increase in delay is still within the acceptable IP Telephony delay of 80 ms to 130 ms.

The Priority based Scheduling QoS showed consistent network performance delay below 150 ms and jitter less than 1ms regardless of the network utilization model. Media streaming performance in this experiment case study was examined and its performance was similar to IP telephony. This application performance within its tolerance for delay and jitter at both 50% and 80% network utilization model. However, at BE 100% utilization network model the delay was excessive over 500 ms. At 50% and 80% utilization the application was within its performance tolerance. Priority based Scheduling QoS showed positive results where the network delay was below 250 ms (i.e., within tolerance). This is in-line with [9] and [10] demonstrated the QoS performance impact on the application. The outcomes of the test case similar to what discussed in [78] where real-time multimedia conformed to its performance criteria by providing an optimized network model that regulates traffic assignment to given network resources.

The above findings were crucial in supporting the initial research design assumption as defined in Chapter 3. Equally important, the experimental test case provided enough data sets to cross examine the simulation results for validation and to arrive at a linkage between network loading and HPAA PCS performance in a CIP LAN/WAN network models. The next section discusses the comparative analysis between the two research design methods and outline essential findings in support of the HPAA CIP feasible solution.

6.5 COMPARATIVE ANALYSIS FOR CONVERGED IP WAN

Simulation and experimental case study have shown systematic and correlated results for the CIP WAN, Table 6.3. The HPAA PCS application and network performance have demonstrated BE and Priority based Scheduling QoS contribution in extending HPAA

PCS application over a wide area network. The primary focus was on the PCSVC and Remote PCS areas Master/Client Controller and the PCS Areas P2P relationships. The CIP WAN network shows lack of fitness for supporting HPAA PCS applications that are below the 40 ms delay tolerance. Those applications that fall in this category require control loops and associated system component time delay adjustment to overcome this limitation, as will be discussed. For those HPAA PCS applications that can tolerate over 40 ms network delay, the CIP WAN provides an ideal multi-service platform supporting HPAA, IP telephony and media streaming.

By revisiting the result in Chapter 4 and in Chapter 5, the performance of TCP application as compared to UDP application was better in packet delivery but had more delay. HPAA PCS, TCP, traffic performance in a WAN had more delay as the network utilization model increased from 50% to 80%, and the 100% in BE QoS setting. However, with Priority based Scheduling, the HPAA PCS and support services performance were within their application delay tolerance requirements independent of the network utilization model. Experimental data correlated to the simulation scenarios which provide validation for the CIP WAN network mode as shown in Table 6.3.

Table 6.3 Comparative Analysis for Simulation and Experimental Scenarios on Application Delay Performance for WAN

Maximum Application Delay (milliseconds)			**Master Controller/ Subtending Controllers**		**Peer-to-Peer**	
			Request/Response	**Response**	**Request/Response**	**Response**
Dedicated Network			56	28	38	20
50% Network Load Model	**Simulated**	**Best Effort**	56	29	40	22
		Priority Based QoS	56	28	40	19
	Experimental	**Best Effort**	90	61	90	61
		Priority Based QoS	2	2	2	2
80% Network Load Model	**Simulated**	**Best Effort**	223	116	137	75
		Priority Based QoS	56	28	40	19
	Experimental	**Best Effort**	97	65	93	63
		Priority Based QoS	2	2	2	2
100% Network Load Model	**Simulated**	**Best Effort**	3653	3582	400	180
		Priority Based QoS	56	28	40	19
	Experimental	**Best Effort**	889	603	378	266
		Priority Based QoS	5	4	4	4

6.6 APPLICATION ADAPTATION

The WAN network round trip delays performance show inability to support HPAA PCS applications with response time requirements of below 40 ms in the simulated network models. However, the one way network delay was below 30 ms. Hence, if the application can accommodate the 30ms response time the fitness of the WAN network can be expanded to accommodate all HPAA PCS applications. This can be achieved by transferring data from the involved controller pairs when the process value has changed sufficiently. A feature that is commonly embedded in control systems and equally available in HPAA PCS applications is the event-driven data distribution [2] and [3]. This is where a process event such as an increase in temperature, pressure, etc., triggers the execution of an algorithm with associated controller to send a packet with process variables' data to the destined controller. The trigger is typically defined based on a preset threshold that the one way network delay will support. Carefulness in selecting the threshold (i.e. range sometimes referred to as deadband), as selecting non-optimal deadband may create unusable traffic, chatter, or flooding the networking. This concept was used and showed positive results as part of the United States Patent Application 20100050017 [81], inspired by this research. One drawback for this approach is the dependency between network and application increases, which could be easily impacted by changes in the network configuration, trunking plan, and the addition of new applications. Hence, this concept can be a candidate for future research.

6.7 SUMMARY

This chapter provides detailed discussion for the different simulated and experimental network models. The results show correlation between experimental and simulation test case scenario outcomes, which increases the level of confidence with the choice of technique and methodology. Moreover, the results demonstrate the interdependence between QoS models (BE and Priority based Scheduling), network utilization approaches, and application type (TCP and UDP) performance; from the aspects of delay, jitter, packet delivery and stability. Moreover, the results for Dedicated and CIP network with 50%, 80%, and 100% based on BE and Priority based Scheduling network models were entertained. A closely coupled relationship between the application, network performance, and utilization was verified for the CIP. Priority based Scheduling shows strength, from a QoS perspective, in supporting HPAA PCS in a CIP regardless of the underlying network utilization model. Support services such IP telephony and media streaming demonstrated similar outcomes in this QoS network model.

The experimental and simulation test case scenarios highlights the adopted and applied network scheduling theory by modifying the priority order defined by IEEE 802.1p, Priority based Scheduling QoS configuration model, resulting in seamless PCS HPAA application performance. Contrary to the convention of voice traffic being assigned highest priority, the HPAA PCS applications that are highest in time delay were classified with the highest priority, IP Telephony, and media steaming were second and third in priority accordingly. HPAA PCS applications that are not defiant to time delay such fluid tank gauging (i.e., typically takes minutes and sometime hours to complete the process), can be assigned lowest priority. This has contributed to reaching a feasible HPAA PCS solution for the desired CIP network model.

The BE CIP network model performance identified a uniform relationship for both HPAA PCS and support services. The relationship can be simplified as semi-proportional (i.e., non-linear) direct relationship between the network utilization and the application performance. Utilization at 80%, or higher, produced unfavorable results. The 50% utilization or lower network model for BE has showed positive results. However, the concern is this model has limited flexibility in ensuring HPAA PCS performance conformance during traffic surge that is caused by either traffic bursts or network traffic reroutes caused by link or node failure, increasing the loading suddenly over 50%.Moreover, maintaining network to be confined to 50% utilization requires traffic engineering tools and support processes. Needless to say the stranded network (50% of the network resource will be ideal at all time) is not an encouraging proposal from an economic perspective.

Moreover, application stability relating to time delay or unreachable messages by the HPAA PCS was examined and provided techniques to compensate for the network congestion. Two strategies were examined; QoS priority based scheduling and the second application adaptability as discussed earlier in this chapter; where both can help HPAA PCS application sustain expected performance.

The experimental and simulation test case scenarios have also highlighted the standard Ethernet network elements: nodes, protocol, and interfaces when configured and implemented in a consistent and uniform environment lead to positive results in minimizing the number of networks from many to one. This was attested by both experiment and simulation test cases as illustrated in Chapter 5 test results for Priority based Scheduling QoS. The results show concurrent applications can co-exist given consideration to the priority and uniformity of the interfaces. The experimental and simulated HPAA PCS Controller design reflect the evolution of the Controller from low speed with basic functionality to an advanced intelligence and distributed node based on high-speed network interface that can be extended with LAN and WAN network and support multiple and concurrent logic loops. This concept inspired patent filing, United States Patent Application 20100050017 as defined in [81] which details a new method for data acquisition and delivery from the field instrument to the enterprise system. This concept also provides data retention capabilities, Ethernet interface, and provide standard application programming interface for integration to complement the ongoing trends in the Ethernet interface penetration at lowest HPAA PCS layer (sensors, instrumentation and controller). The CIP network model fit very well with intelligent nodes that have large traffic volume and with distinct priority as was demonstrated in both experimental and simulation test case scenarios.

Another important element from this chapter is relating to the research design. The experimental and simulation test cases have provided additional validation on the effectiveness and flexibility of the OPNET simulation tool. Test case scenarios were validated and results were confirmed which provided higher creditability for this research. Finally, this chapter has shed light on new investigational opportunities that may warrant additional research, in the future. This includes formulating a network design that can support applications with a round trip time delay below 40 ms. In our present treatise, application adaptation to one way delay dynamics showed positive outcomes as evidenced by the comparative analysis involving simulation and experimentation. Another area worthy of further research is network recovery specifically impacted by the Spanning Tree recalculation, number of switches in topology, and routing protocol. Wireless backhaul link and trunking planning in a WAN network for HPAA PCS also deserve further investigation.

CHAPTER 7 CONCLUSION

7.1 Research Summary

The aim of this research is to explore, develop, and examine the Hydrocarbon Process Automation Application in a Converged Internet Protocol (HPAA CIP) network model over standard Ethernet technology. The CIP network model for HPAA Process Control Systems (HPAA PCS) was investigated in both a Local Area Network (LAN) and Wide Area Network (WAN) environments utilizing Gbps high speed Ethernet standard technology. The current best practices for HPAA networking are based on separate, dedicated, intermix interface protocols, and some proprietary solutions. This is driven by the legacy implementation and technology limitation of HPAA PCS in the field (oil and gas) and downstream processing systems (Gas and Oil Separation Plants, refineries, and distribution terminals).

The CIP network model provides an opportunity for optimizing existing HPAA networking operation and results in the reduction of concurrent networks (five or more) down to one (1) single uniform network platform. This research was motivated by the recent development in digital and packet technology that is partially infiltrating the HPAA PCS system today and projected to expand in the future. The CIP network model for HPAA is still unlocked due to lack of research in this area that would demonstrate the feasibility of collapsing the existing dedicated network model, the concurrent network implementation, and the non-standard interface protocol into a CIP over standard Ethernet. The CIP network model provides the opportunity to explore extending the PCS intelligent at the instrumentation (sensors, actuators) and be able to communicate in a distributed network intelligent where network timeliness and reliability is still conforming to the HPAA application specification. Moreover, support services such as voice and media streaming can benefit from this networking model.

This research demonstrates encouraging results for the HPAA PCS CIP network utilizing TCP/IP over high-speed standard switched Ethernet. Co-existence of HPAA PCS applications with other support services such as IP telephony, media streaming and high data packet exchange is feasible, given that traffic regulations and prioritization are invoked. Both simulation and experimental measurements have shown Converged IP LAN network can be used to achieve reliable HPAA PCS application communication with an acceptable performance; delay, jitter, packet delivery, and TCP retransmission quality. The WAN network has shown its ability to accommodate most of the HPAA application's time delay requirements (i.e., delay above 56 ms). Special adjustment for the HPAA application controller has to be invoked to accommodate those HPAA applications with time delay of 40 ms. In both network models, the support services such as IP telephony and media streaming were supported without any performance degradation. The derived HPAA PCS CIP network model from this research is expected to reduce the number of HPAA PCS networks from multiple integrated network models to a single uniformed and a standardized one. This will override current typical oil and gas HPAA operation running over such multiple networks. This includes, but is not limited to, Distributed Control System (DCS), and Emergency Shut Down (ESD) systems, Supervisory Control and Data Acquisition (SCADA) system, Media streaming, and Voice.

Chapter Two, literature review presented has uncovered gaps in the existing practices of dedicating or utilizing proprietary network solution as compared to standard TCP/IP over Ethernet network model. These gaps include the HPAA PCS controller behaviour such as high traffic density, traffic mix, and retention based capabilities that result in adapting to the standard Ethernet network solution to satisfy LAN and WAN converged IP network models. Wide Area Network based on Gigabit Switch Ethernet, (IEEE 802.3z), is a great opportunity to provide required network connectivity between different HPAA PCS systems. The Ethernet technology is fast, reliable, and provides the necessary bandwidth. The Ethernet network links connecting the controllers can be digital transmission, optical fiber, and/or wireless backhaul link. The review has shown fiber optics links are the most ideal network connectivity in the industrial domain. This is due to its resiliency against electromagnetic interference, connecting long-haul links, and providing necessary bandwidth. Wireless network connectivity for dispersed and/or remote sites present an alternative that is cost effective as compared to trenching and securing right-of way. However, wireless has its inherent signal quality issues, bandwidth capacity inverse relation with distance, and frequency licensing regulation restrictions.

The HPAA timeliness can be defined in the range of 40 ms < T_d < 200 s for HPAA from the HPAA application survey that was completed in Table 2.2. Performance of this application as part of LAN and WAN network cross traffic is mainly impacted by application specific traffic behaviour, QoS settings and available bandwidth. Bursty cross traffic has an adverse effect on the stability of the distributed process control even when the average utilization is low. This was confirmed by experiment on 10/100/1000 Mbps Ethernet network types. This has created a major challenge when we explored the CIP model for both HPAA and non-HPAA applications. The HPAA PCS related standards such as IEEE, ISA, and IEC and in their comparative analysis show no reference to Converged IP network for PCS system in general and HPAA in specific. These different standards highlight the reliability, availability, and timeliness required for PCS in general. Dedicated networks are adopted in real-time HPAA PCS running over multiple networks with limited interface-ability. A CIP network model will reduce that to a single network supporting different PCS applications, voice, and media streaming. In addition, it was found industrial networking utilizing Ethernet typically adopted based on altering the data link layer or IP layer as in the case of EtherCat, EtherNet/IP, and Modbus TCP. This is considered an unfavorable proposal due to the solution being proprietary making integration complex and at a higher support cost. However, utilizing standard Ethernet for PCS in general is now emerging as a form of dedicated network. The proposition of utilizing converged IP network was not considered for PCS. So, introducing this concept is considered a pioneering approach. Moreover, utilizing IP over Ethernet network for PCS application in an integrated form utilizing Wide Area Network is also considered a new concept. The application characterizing both HPAA and non-HPAA were identified and were part of both the simulation and the empirical study. Moreover, QoS for BE and Priority based Scheduling IP/Ethernet were explored and identified as viable options to regulate the HPAA and non-HPAA traffic in LAN and WAN network. A modification in the order of priority for Priority based Scheduling, IEEE 802.1p QoS is found to provide a CIP LAN/WAN feasible solution.

In Chapter Three, research design was developed utilizing experimental and simulation research method. The comparative analysis for the simulated scenarios and experimental test cases provides valuable findings. Experimental case study included two scenarios; HPAA & non-HPAA application co-existence on a PCS LAN. The second is converged IP for HPAA and non-HPAA applications along with support services such as IP telephony and media streaming utilizing WAN network. The experimental results are used for simulation validation. In addition, simulation scenarios and experimental test cases assumptions and requirements were formulated and defined in this chapter to facilitate the actual implementation and produces consistency throughout the phases of testing and simulation. The primary focus is on the application and the network performance; delay, jitter, packet delivery, and stability under network loadings of 50%, 80%, and 100%. And, it was understood from the research design that there will be some variance between simulated and experimental results but the trends should be the same. The reason for the variance between simulated and experimental is the experimental uses large scale HPAA PCS system with vendor specific system elements, i.e., instruments, controllers, and servers. OPNET network simulation and analysis application software tool was utilized and proved its flexibility in building HPAA PCS virtual networks. In addition, this tool has the strength in supporting different network topologies, protocols, and communication nodes configurations, and service applications such HPAA, IP telephony, and media streaming

In Chapter Four, Experimental Case Study Results, the results of this research design's experiment were presented. The primary focus was on the application and network performance which includes delay, jitter, packet lost and application stability. The test cases results are used to validate the simulation model initial configuration which leads to expanding the simulation models and later-on the results were used to validate the expanded simulation final results. The experimental case study results were approximated to averages due to the multiple and different tools that were used concurrently to trace the network and application performance. Actual tools snap shots for the test case studies were included where applicable. Experimental results show the feasibility of utilizing Best Effort CIP Ethernet standard network for HPAA and non-HPAA given careful consideration for the traffic mix and the trunk utilization. The 50% network utilization model or lower presented the balance needed between the installed network resources and the application performance. QoS activation enables HPAA and other support services to perform within their expected performance guidelines independent of the utilization model.

Chapter Five, presented the simulation results for the different network models developed in Chapter 3. This includes dedicated, BE and Priority based Scheduling QoS for 50%, 80% and 100% network utilization models. Moreover, the results address both LAN, WAN, and Wireless Remote Site with primary focus on delay, jitter, packet retransmission, and packet delivery. Support services such as IP telephony and media streaming simulated scenarios in a converged IP network were also reported. The results show the effectiveness of Priority based Scheduling QoS in enabling a converged IP network for HPAA and non-HPAA applications. This is achieved by altering the normal convention of Priority based Scheduling in a form where HPAA is the highest priority, followed by Voice, and Media Streaming. The simulation results provided an opportunity to support the intended comparative analysis and deduced results that were used in the triangulation between experimental and simulations.

Chapter Six, investigated the results of both experimental and simulation and established comparative analysis that was utilized in the triangulation synthesis of the research finding. Correlation, trended behaviour, between the experimental and simulation results relating to delay, jitter, packet loss, and TCP/IP application stability for the different network models that was observed. This finding provided necessary assurance to expand simulation models and increases the level of confidence with the choice of research design technique and methodology. Moreover, the results demonstrate the interdependence between QoS models (BE and Priority based Scheduling), network utilization model level, and application type (TCP and UDP) performance; from the aspects of delay, jitter, packet delivery and stability. Moreover, the results for Dedicated and CIP network with 50%, 80%, and 100% based on BE and Priority based Scheduling network models were entertained. A closely coupled relationship between the application, network performance, and utilization was verified for the CIP. Utilization at 80%, or higher, produced unfavorable BE network results. Priority based Scheduling shows strength, from a QoS perspective, in supporting HPAA PCS in a CIP regardless of the underlying network utilization model.

The outline outcomes above were tested in a production WAN network. The experiment results outlined in Chapter 4 and discussed in Chapter 6 provide the needed verification for both the network and application performance. The tightly coupled relationship in performance between the CIP BE network model and the network loading of 50% or lower shows positive results but has a negative attribute for the need to careful monitoring and tracking. On the other hand, the Priority based Scheduling QoS CIP network model was simulated in Chapter 5, tested and verified as outlined in Chapter 4. Priority based Scheduling governed a consistent performance for the HPAA application independent of the network utilization. Hence, it has confirmed the independence between the Priority based Scheduling and network loading.

7.2 CONTRIBUTION -THEORETICAL IMPLICATIONS

This research explored, developed, implemented, tested and verified the concept of HPAA PCS CIP network model. The CIP network model was investigated in both a Local Area Network (LAN) and Wide Area Network (WAN) environments utilizing standard Gigabit Ethernet (IEEE 802.3z). The network model were configured based on dedicated, BE QoS, and Priority based Scheduling QoS settings. The network model in both experimental and simulation were exposed to 50%, 80%, and 100% traffic loading. The experimental and simulation and test cases scenarios have demonstrated the performance of these CIP network models. The primary focus was to define the feasible network solution conforming to HPAA applications and network’s delay, jitter, packet delivery, and application stability. Moreover, support services, such as voice and media streaming (video) utilizing the same CIP network, were an integral part of this undertake. The following summarizes the key findings, theoretical implications, and contributions:

1. **Priority based Scheduling Quality of Service Network Model:** The research adopts and applies network scheduling theory by modifying the priority order defined by IEEE 802.1p, Priority based Scheduling QoS configuration model, resulting in seamless PCS HPAA application performance. The following are key guidelines to achieve intended objectives:
   - PCS applications are assigned highest priority service type. For different PCS HPAA applications that have unique stringent time delay (40 ms ≤ Delay ≤ 200 ms) requirements shall be assigned the highest priority.
   - IP telephony shall be 2nd in priority to meet the time delay requirements 100 ms ≤ Delay < 150 ms.
   - Media streaming shall be assigned 3rd in priority to meet the time delay requirements 200 ms ≤ Delay < 250 ms.
   - PCS applications with extended time delay. For those PCS applications that are with relaxed time delay requirements (i.e., 200 ms < Delay < 400 ms or higher) shall be assigned 4th in priority.
   - Other data packet communication services such as file transfer and or application with extended time delay requirements will be assigned 5th in priority.
2. **Best Effort Quality of Service Network Model:** To avoid the cumbersome requirements of priority based QoS configuration for both the application and network layers, this research produced a network model based on Best Effort Quality of Service by maintaining a 50% or below network utilization; trunks and nodes, to support seamless PCS application performance in a converged IP network. The following are key guidelines to achieve intended objectives:
   - PCS applications traffic load shall be estimated with at least 20% overhead growth factor.

- IP telephony and media streaming traffic load shall be projected. Since these services are considered support services for industrial applications, their growth is not dynamic as compared to PCS HPAA application.
- Media streaming operation is recommended to be service on demand rather than continuous streaming.
- Traffic on access and backbone trunks shall not exceed 50% network bandwidth utilization. Trunking plan shall be developed to provide observed traffic increase by either the following two approaches:
    - Optimize applications in question from data acquisition and control cycle.
    - Add more bandwidth to existing trunks or add additional trunks and maintain traffic loading at or below 50% network wide.
- Traffic management reporting and sizing shall be adopted since both simulation and empirical results show the co-existence of Simple Network Management Protocol with PCS real-time applications.

3. **Extended Intelligence over a Wide Area Network:** Priority based Scheduling QoS provides higher fitness for a converged IP network in a WAN network model. The Best Effort 50% network utilization model shows a feasible solution for a converged IP network. However, it does not provide over-head capacity flexibility in an event of a trunk and node failure. Hence, traffic burstiness cannot be accommodated at all times in a Best Effort network model. The following are key guidelines:

- The WAN network round-trip delay performance may be unable to support HPAA PCS applications with round-trip delay requirements below 40 ms. Hence, application adaptation can be invoked between the involved controller pairs. This entails event-driven data distribution generation by the Controller based on preset thresholds resulting in a one way delay from the source to destination within the expected application time delay requirements. Carefulness is recommended in selecting the thresholds, and dead-band, as selecting non-optimal dead band may create unusable traffic, chatter, or flooding the networking. This research contributed to this concept and lead to United States Patent Application # 20100050017.

- Network utilization, for both PCS HPAA applications and support services with an overhead capacity of 20%, shall be at 50% network utilization. This is necessary to absorb the total traffic load and still allocate an overhead capacity of 20% to 30% for traffic burstiness.

- Media streaming operation is to be service on demand rather than continuous streaming.

4. **High-Speed Trunks, Gbps, and Network Topology:** High-speed network links, Gbps, can form a network topology that is ideal for the co-existence of PCS HPAA and other support applications given QoS priority based scheduling model is maintained. The adoption of Gigabit Ethernet switch nodes equipped with high speed switching backplanes reduces switching delay and trunk interface queue delay.
5. **High-Speed Wireless Backhaul Link:** High-speed wireless link to connect remote spurs site is a feasible connection method as long as link traffic volume is kept at pre-defined threshold; especially in a Best Effort Network Model. These thresholds shall be defined during the site physical survey (physical spectrum signal test, antenna distance, and projected traffic load). The thresholds are utilized to shape traffic behaviour on the network resulting in a feasible network for HPAA PCS applications from time delay and packet delivery perspectives. Moreover, the bandwidth in a wireless network model has an inverse relationship to distance. Hence, compression technique can be introduced to optimize applications traffic transmission.
6. **Homogenous Network Model:** Consistent network resources network wide is desired to avoid bottleneck in network formation. This includes consistency in switch capabilities, interfaces, trunk bandwidth and configuration which will lead to a homogenous network providing a platform that can sustain expected network configuration and performance criteria; delay, jitter, packet loss, retransmission attempts, and application timeout.

7. **Simulation Verification:** Detailed simulation validated the starting hypothesis that PCS HPAA application can co-exist with non-HPAA applications such as voice, media stream, etc., on standard IP/Ethernet LAN/WAN; given regulated network behavior. The network behaviour was regulated by adopting one of the QoS network model stated above. (i.e., QoS Best Effort with 50% network utilization or adopting Priority based Scheduling QoS network model).
8. **Experimental Verification:** Detailed measurements for LAN/WAN network supporting PCS HPAA applications and non-PCS application were examined and bench-marked against their target performance criteria. Network failure analysis was also conducted to examine traffic load impact on network reroutes. Experimental data shows seamless PCS application performance at 30% or lower. However, as utilization increased to 50%, delay was also noted but still acceptable. Network utilization at above 50% utilization resulted in extended network delay and longer network recovery time. The outcomes of the experimental verification validated the simulation results and the starting hypothesis.

7.3 OTHER CONTRIBUTION - PRACTICAL IMPLICATIONS

Additional practical implication added value findings have resulted from this research. This includes optimizing the HPAA PCS application on WAN network by altering the protocol priority schemes. Moreover, the use of network virtualization provides logical traffic segregation on the same WAN network substrate by provisioning Virtual Private Network. This concept can be used in assigning priority at the application group level rather than individual basis. Also, this research introduces the concept of establishing a unified and centralized HPAA PCS solution that has the potential to contribute in increasing operation efficiency.

Moreover, the concept of application behaviour optimization by establishing thresholds and triggers to optimize message exchanged between the HPAA PCS components (instruments, actuator, and controllers) is a scheme that lessens cross network traffic resulting in improved time delay. The following provide additional details on these practical implications and contributions:

- Extended HPAA PCS application on a Wide Area Network (WAN) has seamless PCS application performance when utilizing Priority Based settings that is different than IEEE 802.1 P, Priority Queuing convention. The IEEE 802.1 P protocol assigns highest priority for voice as opposed to PCS applications. This research concludes the need for assigning the highest priority to HPAA PCS applications as stated in Section 6.2.
- To utilize a common public WAN network, there shall be a Virtual Private Network (VPN) dedicated for supporting the PCS application that has higher priority than other support services.
- PCS HPAA applications brought to a centralized location (i.e., PCS Virtual Center) optimize and concentrate vertical subject matter expertise in one location, increase effective collaboration between the oil and gas field operation (Upstream) and the refining and distribution operation (Downstream), and provides real-time virtualization.
- PCS Controller Peer-to-Peer (P2P) traffic load was simulated as continuous real time cyclic relationship. This relationship can be modified to a threshold driven traffic exchange. This implies setting dead-bands on the different process variables in question and if the thresholds are reached, the controller triggers the traffic exchange. These schemes will minimize traffic load on access and backbone trunks. Hence, resulting in only critical traffic traversing the network in steady state operation.
- Traffic confinement can be adopted as a practice by invoking rate limiting on access ports for those services that are at less priority.
- Wireless backhaul links bandwidth is susceptible to instantaneous degradations, down by over 90% , within a second which is acceptable for support services but absolutely not acceptable for HPAA. Hence, ample bandwidth has to be maintained at all times.

7.4 FUTURE WORK

In this research the focus was on converged IP network of LAN/WAN network utilizing standard Gigabit Ethernet, Layer 2 protocol with IP routing capabilities. In addition, the HPAA PCS application was supported by a TCP protocol. Fiber optic network links were used in the backbone network and wireless backhaul link was used to connect "spur" remote sites. Chapter 2 and Chapter 6 have identified new opportunities that may warrant additional research, in the future. This includes:

- Formulating a network design that can support applications with a round trip time delay below 40 ms. In our present treatise, application adaptation to one way delay dynamics showed positive outcomes as evidenced by the comparative analysis involving simulation and experimentation.

- Another area worthy of further research is network recovery specifically impacted by the Spanning Tree recalculation, number of switches in topology, and routing protocol.

- Extending this research to address IP/MPLS (Multi-label Protocol Switching) networks would open new possibilities and opportunities for Wide Area Network Models.

- PCS over UDP/IP research should help in applications that are mostly dependent in soft time.

- Wireless high-speed backhaul links as a connection method to remote spur sites provides the optimal solution. New technologies such as WiMax, IEEE 803.14n would provide additional contribution to this effort.

- Introduce a dynamic trunking plan to accommodate both HPAA and non-HPAA applications in a Best Effort Network Model.

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