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The members of the Committee approve the dissertation entitled *Data Transmission Scheduling Strategies for Distributed Simulation Environments* of Juan José Vargas-Morales, defended November 1, 2004.

Ronald F. DeMara, Chair	Avelino J. González Committee Member
Michael Georgiopoulos Committee Member	Yue Zhao Committee Member

It is recommended that this dissertation be used in partial fulfillment of the requirements for the degree of Doctor of Philosophy from the Department of Electrical and Computer Engineering in the College of Engineering and Computer Science.

Issa Batarseh, Department Head

Jamal Nayfeh, Associate Dean, Academic Affairs and Graduate Studies

Neal C. Gallagher, Dean of College

Patricia J. Bishop
Vice Provost and Dean of Graduate Studies

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Data Transmission Scheduling Strategies for Distributed Simulation Environments

by

Juan José Vargas-Morales
B.S. Universidad de Costa Rica, 1977
M.S. University of Delaware, 1991

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Ronald F. DeMara

Abstract

Communication bandwidth and latency reduction techniques are developed for Distributed Interactive Simulation (DIS) protocols. DIS Protocol Data Unit (PDU) packets are bundled together prior to transmission based on PDU type, internal structure, and content over a sliding window of up to C adjacent transmission requests, for $1 < C < 64$. At the receiving nodes, the packets are replicated as necessary to reconstruct the original packet stream. Bundling strategies including *Always-Wait*, *Always-Send*, *Type-only*, *Type-and-Length*, and *Type-Length-and-Time* predictions are developed and then evaluated using both heuristic parameters and a back propagation neural network.

Several communication case studies from the OneSAF Testbed Baseline (OTB) are assessed for multiple-platoon, company, and battalion-scale force-on-force vignettes consistent with Future Combat Systems (FCS) Operations and Organizations (O&O) scenarios. Traffic is modeled using OMNeT++ discrete event simulator models and scripts developed for a hierarchical communication architecture consisting of eight enroute C-17 aircraft each carrying three Ethernet-connected M1A2 ground vehicles, a wireless flying LAN based on Joint Forces Command's Joint Enroute Mission Planning and Rehearsal System (JEMPRS) for Near-Term (JEMPRS-NT) and follow-on bandwidth capacities. The simulation model is presented in detail, including the OMNeT characteristics necessary to understand it. The topology of the network is defined using the NED language and the behavior of each object is defined in C++ code. The simulation traffic includes Opposing Force (OPFOR) control via a CONUS-based

ground station and the corresponding satellite links. Different bandwidth capacities are simulated and analyzed. PDU travel time and slack time, router and satellite queue length, and number of packet collisions are assessed at 64 Kbps, 256 Kbps, 512 Kbps, and 1 Mbps capacities. Results indicate that a *Type-and-Length* prediction strategy is sufficient to reduce travel time up to 85%, slack time up to 97%, queue length up to 98% on bandwidth restricted channels of 64 Kbps.

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List of Acronyms

ACK	ACKnowledge
API	Application Program Interface
ARPA	Advanced Research Projects Agency
BBS	Battalion Battle Simulation
BLB	Battalion Level Behavior
bps	bits per second
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CCTT-SAF	Close Combat Tactical Trainer Semi-Automated Forces
CGF	Computer Generated Forces
CONUS	Continental United States
CSMA/CD	Carrier Sense Multiple Access / Collision Detection
DARPA	Defense Advanced Research Projects Agency
DIS	Distributed Interactive Simulation
DIS	Distributed Interactive Simulation
DDU	Differential Data Unit
DKDU	Differential Key Data Unit
DoD	Department of Defense
DPCM	Differential Pulse-Code Modulation
EMPRS	Enroute Mission Planning and Rehearsal Systems
EO	Embedded Operations

ES	Embedded Simulation
ET	Embedded Training
ESPDU	Entity State Protocol Data Unit
FCS	Future Combat System
INVEST	Inter-Vehicle Embedded Simulation Technology
HITL	Human-in-the-loop
HLA	High Level Architecture
HoL	Head of Line
JEMPRS	Joint Enroute Mission Planning and Rehearsal System
JEMPRS-NT	Joint Enroute Mission Planning and Rehearsal System Near-Term
Kbps	Kilo bits per second
LAN	Local Area Network
LBRM	Log-Based Receiver-reliable Multicast
LZ	Lempel-Ziv algorithm
MAC	Medium Access Control
Mbps	Mega bits per second
ModSAF	Modular Semi-Automated Forces
NED	Network topology Description language
NN	Neural Network
OFET	Objective Force Embedded Training
OMNeT++	Objective Modular Network Testbed in C++
OneSAF	One Semi-Automated Forces
OPFOR	Opposing Forces
OTB	OneSAF Testbed Baseline
O&O	Operations and Organizations
PDU	Protocol Data Unit
PEO-STRI	(U.S. Army) Program Executive Office for Simulation, Training, & Instrumentation
PICA	Protocol Independent Compression Algorithm

QES	Quiescent Entity Service
QoS	Quality of Service
RPC	Remote Procedure Call
SAF	Semi-Automated Forces
SIMNET	SIMulation NETwork
SMS	Switch-Memory-Switch
STOW-E AG	Synthetic Theater of War–Europe Application Gateway
STRICOM	US Army Simulation, Training and Instrumentation Command
TCP/IP	Transmission Control Protocol / Internet Protocol
TDM	Time Division Multiplexing
UA	Unit of Action
UDP	User Datagram Protocol
WAN	Wide Area Network
WGS	Wireless Ground station to Satellite link
WPP	Wireless Plane to Plane link
WSP	Wireless Satellite to Plane link

CHAPTER 1

INTRODUCTION

1.1 Overview

Computer modeling and simulation are commonly used in areas such as analysis and prediction of behavior of complex systems, training, education, games, etc., and has been applied to systems in all scientific disciplines such as Physics, Chemistry, Engineering, Psychology, Sociology, Meteorology, etc.

The U. S. Department of Defense (DoD) defines a model as a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process, and a simulation as a method for implementing a model over time [Def94].

The DoD also classifies computer simulations in three broad categories called live, virtual, and constructive simulation [US95b]. However, DoD recognizes that the categorization of simulation into live, virtual, and constructive is problematic, because there is no clear division between these categories. The degree of human participation in the simulation is infinitely variable, as is the degree of equipment realism. This categorization of simulations also suffers by excluding a category for simulated people working real equipment (e.g., smart vehicles) [US98].

According to [US95b] and [US98], each category is defined as follows:

a. Live Simulation A simulation involving real people operating real systems.

b. Virtual Simulation A simulation involving real people operating simulated systems. Virtual simulations inject human-in-the-loop (HITL) in a central role by exercising motor control skills (e.g., flying an airplane), decision skills (e.g., committing fire control resources to action), or communication skills (e.g., as members of a C4I team).

c. Constructive Model or Simulation Models and simulations that involve simulated people operating simulated systems. Real people stimulate (make inputs) to such simulations, but are not involved in determining the outcomes.

Embedded Simulation (ES) integrates simulation technology with real systems, providing the soldier with a chance to rehearse a mission in the real vehicle, interacting with the virtual world as if it were real, and enhancing training locally and in remote locations. The virtual interaction includes mission rehearsal, battlefield visualization, command coordination, and training.

Objective Force Embedded Training (OFET) methods offer several distinct advantages for 21^{st} century training environments. Benefits include the ability to perform *in-situ* exercises on actual equipment, more direct provision of support for the variety of equipment in the field, and a greater opportunity to develop new training exercises using much shorter lead times than were previously possible with stand-alone training systems [BAC97]. A fully operational OFET platform also presents several technology challenges. In particular, management of Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) resources is required for successful integration of simulation within the actual environment.

The general project proposal from which this dissertation is one of the research branches can be found in [GDD02], and the final report for its phase 2 is in [VGD03].

1.1.1 Development of OneSAF Testbed Baseline

As pointed out by McDonald [McD88], McDonald and Rullo [MR90], and McDonald and Bahr [MB98a], [MB98b], in the late 1980's Embedded Training (ET) started as an important initiative of the US Army for training army personnel. Among some of the reasons for developing ET there were budget cuts, security interests, need to train forces by practicing missions without physically disturbing cultural and environmental issues, etc. Other initiatives developed included Embedded Operations (EO) and Embedded Simulation (ES). The three initiatives had areas in common that facilitated the migration among them. The Inter-Vehicle Embedded Simulation Technology (INVEST) program was proposed by the US Army Simulation, Training and Instrumentation Command (STRICOM) in order to explore key technologies to apply ET and ES to future ground combat vehicles.

Computer Generated Forces (CGF) was a project sponsored by DOD in the 1990's. The idea behind CGF is that the trainees need opposing forces against which to rehearse, although they can also use them as friendly forces to fight along with [HGG00]. These forces are generated by one or more of the participating sites in the synthetic battlefield. Under CGF the two major efforts were Modular Semi-Automated Forces (ModSAF) and Close Combat Tactical Trainer Semi-Automated Forces (CCTT-SAF). In 1998, STRICOM started to develop a recommendation of the SAF system to be used as the baseline for integrating ModSAF and CCTT-SAF into a OneSAF Testbed Baseline (OTB). OTB was planned to be used for supporting research and development for the next generation of architecture experiments, extending toward providing a Battalion Battle Simulation (BBS) replacement capability through a Battalion Level Behavior (BLB) Application Program Interface (API), and providing the training capacity of

CCTT-SAF. Detailed information about the historic development of OTB can be found in [Cor98] and [MWH01].

1.2 Distributed Simulation Environments

As Roger Herdman explains in [Tec95], Distributed Interactive Simulation (DIS) is the linking of several military simulators like tank and aircraft in locations that can be geographically distributed throughout LANs and WANs in such a way that the crew of a given simulator can interact with crews in the other simulators playing the roles of friendly or opposing forces. The participants can cooperate with friendly forces, and shoot and destroy enemy ones. Command structures are also simulated. In this way, the participants get trained in a broad range of scenarios without risking their lives and at a fraction of the cost of a real operation.

The objective of DIS is to develop standards that provide guidelines for interoperability in military simulations. DIS is a protocol initially specified in ANSI/IEEE Std 1278-1993 Standard for Information Technology, Protocols for Distributed Interactive Simulation [IEE93]. The standard has been refined and extended in [IEE95a], [IEE95b], [IEE96], and [IEE98]. The main contribution of the DIS standards was the definition of the Protocol Data Unit (PDU).

Because DIS is a stateless system that does not utilize servers, reliable multicast communication is used to transmit information like terrain and environmental updates. A Log-Based Receiver-reliable Multicast (LBRM) communication was proposed in [HSC95] as a means to provide efficient DIS communications in high-performance simulation applications. This reliability is given by a logging server that logs all transmitted packets from the source. If a packet is lost, the corresponding receiver asks the logging server to retransmit it. Another important

fact of the logging server is that at the end of the simulation the logged PDUs are available for subsequent analysis, which is the case of the OTB logger. One successful DIS application (precursor of OTB) was ModSAF, that simulates the hierarchy of military units and their associated behaviors, combat vehicles, and weapons systems [COM96].

A drawback in DIS is its high network bandwidth requirements and the large computational loads placed on host computers. To overcome the problem, an agent based architecture together with smart networks was proposed in [SZB96]. Mobile agents consist of program scripts that are sent over the network to a remote server. They contain state information and the executable code to be run in the remote server, using the Remote Programming (RP) Paradigm. Remote programming is different form the traditional Remote Procedure Call (RPC) in the sense that not only the parameters but also the corresponding procedure is sent over the network. The mobile agent can start its execution in one server, and continue in another one by saving and attaching its state to itself. According to [SZB96], Entity State PDUs (ESPDU) account for up to 70% of the network traffic. They are used to communicate any change of state from one entity to the others, once a given threshold is achieved. Also, DIS indicates that entities must send a *heartbeat* message at specified time intervals, usually every five seconds, broadcasting their state, so that if a new entity joins the simulation, it can be informed about all the other entities already present. Also, every simulator broadcasts a *Simulator Present PDU* every 20 seconds as a heartbeat message required by the Persistent Object (PO) protocol implemented in ModSAF and OTB [Kir95]. If an entity is moving, ESPDUs are sent at a higher rate than if it is still, but even still entities have to inform its position at a given rate. Mobile agents can lower the usage of ESPDUs by maintaining the positions of the still entities, instead of constantly sending ESPDU messages.

1.3 Need for Simulation Communication Optimizations

In an embedded simulation system, the participating entities of a mission can be physically separated by long distances, possibly onboard mobile vehicles, and communicated via wireless channels. All the vehicles share a common virtual world that has to be constantly updated, which carries realtime constraints on the bandwidth, latency and connectivity of the subjacent network. OTB, for instance, communicates through the PDU messages under the DIS protocol. Every time an event occurs in a participating entity, like acceleration, firing, detonation, etc., a PDU is broadcasted, making all the other entities aware of that event. Even if nothing special is happening, the entities generate an ESPDU every five seconds as a heartbeat to inform that the entity is still up and running [SZB96, Sri96].

In distributed simulation exercises it has been found that 50% to 80% of the network traffic is originated from updates transmitted to ensure that all the simulators have consistent information about the entities participating in the simulated battlefield [CD96]. In order for the participants of the simulation to interact with the virtual world in a realistic way, they must see and communicate with each other in real time. To accomplish this, each simulator maintains dead-reckoning models of its own state and of the state of all other vehicles with which it may interact, and so the network used for embedded training must be able to transfer massive volumes of data [HGG01].

Scalability is not only desirable, but a requirement of current simulation protocols like HLA [WJ98]. Bandwidth is a scare resource, and the larger the number of participating sites, the more compromise the available bandwidth becomes. Stone [SZB96] indicates that the greatest problem currently facing the progress of distributed simulations is scalability, and that it is very difficult to scale up

beyond approximately 2000 entities due to the tremendous requirements for network bandwidth.

Several attempts have been done to overcome the bandwidth problem. The general idea relies on finding new methods or algorithms to reduce the network traffic, either by applying some lossless compression algorithms, by eliminating some redundant packets, by splitting some PDUs into static and dynamic data and sending the static data once and the dynamic data more often (delta-PDUs), by concatenating (bundling) some PDUs into a larger packet that is later split at the destinations into individual PDUs (replication), by re-scheduling some PDUs from high intensive traffic spikes to periods of lower traffic demands, by using multicasting instead of broadcasting, by applying priorities to PDUs and using Head of Line (HOL) algorithms at router queues, or by applying a mix of all these ideas.

In this dissertation some of the previous methods are investigated. Re-scheduling of the PDUs attempts to alleviate the occurrence of spikes of negative slack time when OTB timestamps PDUs at exactly the same time. The basic idea is that it is possible to slightly modify those timestamps in such a way that the overall simulation is not affected, while exploiting the time interval of positive slacks following the negative ones. The re-scheduling effect is automatically achieved by bundling those PDUs and sending a single packet at a slightly later time.

Bundling and replication deal with sequences of several consecutive PDUs timestamped at the same time or almost the same time, for instance PDUs of type *po_fire_parameters*, which are the main cause of the said negative spikes. Basically, these PDUs are copies of an initial base PDU. Then, a new method that eliminates all the duplications is proposed. Bundling occurs at the sending sites and replication is performed at the receiving ones.

1.4 Outline of This Dissertation

The rest of the document is divided in the following way. In Chapter 2, *PREVIOUS WORK*, a review of the State of the Art in bandwidth assessment for Embedded Simulations is given. The section *Bundling And Aggregation of Network Packets* deals with current techniques for bundling PDUs. The section *Data Compression* mentions some common compression techniques belonging to the *loss* and *lossless* sets. The section *Data Transmission* refers to the possibility of PDU rescheduling as a means of diminishing high traffic demands during short periods of time. The chapter ends with the section *Comparison of Techniques* that compares and contrasts the investigated techniques for making the most of the available bandwidth.

In Chapter 3, *COMMUNICATION RESOURCES AND ARCHITECTURE*, the Flying LAN is presented and serves as a framework for the rest of the document. OMNeT is introduced along with the key concepts of model design, simple and compound modules, and instantiation of the network, applied to the simulation at hands.

In Chapter 4, *ACTIVE BUNDLING STRATEGIES*, the concepts of offline and online bundling are stated, and how they relate to the algorithms proposed in this dissertation. The characteristics of embedded simulation traffic impacting bundling are exposed, and a description of the proposed offline and online algorithms is shown.

In Chapter 5, *EMBEDDED SIMULATION TRAFFIC ANALYSIS*, four experiments are described. The general format of the input data is explained, and two examples of actual PDUs are given. Simulation results are graphically presented for each one of the experiments. In each case, an independent analysis consisting of bandwidth statistics calculated before running the simulation are shown as a means of predicting and corroborating the simulation outcomes. The PDU traffic is

then analyzed considering the criteria of slack time, travel time, queue length and collision analysis. Spike analysis resulting from many observed negative spikes in the slack time of the senders is studied in one of the experiments. A sample of some negative spikes is collected, and the corresponding PDUs are identified, resulting in interesting observations about the constant appearance of *po_fire_parameters* PDUs. These observations are the key points for the proposed algorithm called PDUAlloy.

In Chapter 6, *TRAFFIC OPTIMIZATION USING PDUAlloy*, a new bundling algorithm is proposed, and its behavior is analyzed by running the simulator. Comparisons against the non-bundling algorithm are given. The conclusions indicate that PDUAlloy is a successful algorithm, much better than the non-bundling counterpart.

In Chapter 7, *CONCLUSIONS*, the results of the experiments are summarized and general conclusions about the simulation tool, the methodology employed, PDU traffic and minimum bandwidth requirements, are drawn.

In Chapter 8, *FUTURE WORK*, the continuation of the project is proposed. Several areas are proposed for further research, related to new bundling options, better prediction tools for upcoming PDUs, and the application of these techniques to other communication protocols.

1.5 Contributions of This Dissertation

A summary of the main contributions made by this dissertation follows.

1. The formalization of the independent (offline) analysis for PDU traffic based on availability of logged PDUs aimed at the assessment of minimum bandwidth requirements for the network. The independent analysis provides a first

approximation to the minimum bandwidth requirements, which is a lot cheaper than performing the actual simulation, perhaps having to run it several times under different parameter combinations. Applied to the studied vignette and without using simulation, the independent analysis estimated the required bandwidth on 200 Kbps, which was later confirmed by the simulation.

2. The formalization of selective PDU bundling, called PDUAlloy. This kind of bundling gets more active when it is needed the most: during negative spikes of the slack time, and produces new packets that preserve the internal PDU format, reason why the resulting packets can be considered a new type of PDU. Due to that characteristic, bundled PDUs are subject to further bundling and/or compression by more traditional techniques. For example, if A and B are PDUs such that $A = (a_1, a_2, a_3, a_4)$, $B = (b_1, b_2, b_3, b_4)$, and $a_2 = b_2, a_4 = b_4$, then the bundle $A\&B$ is represented as $(a_1, a_2, a_3, a_4, ((b_1, 1), (b_3, 3)))$. A simpler example could be: $(10, 8, 12, 20, 9)\&(10, 6, 12, 20, 3) = (10, 8, 12, 20, 9, ((6, 2), (3, 5)))$

3. The proposal and study of different predictive algorithms for the next PDU, three of them on-line: *neural network*, *Always-Wait* and *Always-Send*, and three off-line: *type*, *type-and-length* and *type-length-and-size*. Applying *Always-Wait* to the studied vignette and setting the wireless links to 64 Kbps, a reduction in the magnitude of negative slack time from -75 to -9 seconds for the worst spike was achieved, which represents a spike reduction of 88%. Similarly, at 64 Kbps *Always-Wait* reduced the average satellite queue length from 2963 to 327 messages for a 89% reduction.

CHAPTER 2

PREVIOUS WORK

Many different solutions aimed at decreasing the network traffic have been studied in the literature: bundling, delta-PDUs, dead-reckoning, relevance filtering, compression, multicasting, quiescent entities, and the use of unreliable transport mechanisms. Some of the most common *bundling-related* mechanisms are explained next.

2.1 Bundling And Aggregation of Network Packets

Several authors have contributed to the principle of bundling packets, not only applied to the DIS protocol, but also in other fields. In 1988 Baum and McMillan applied the concept to messages traversing an hypercube network. They investigated a mechanism for reducing the communication cost by bundling together messages sent along the same channel, and concluded that the additional overhead required to bundle the messages at the sending processor and to unbundle them at intermediate processors is not large [BM88].

Calvin and Van Hook have proposed very similar definitions of bundling. They say that bundling combines PDUs into larger packets in order to reduce packet rates. A packet is transmitted when either a timer expires or the packet reaches a maximum size. As a consequence, bit rates are reduced since fewer packet headers

are transmitted, placing multiple DIS PDUs in one single packet for transport [CST95, VCR96].

Frederiksen and Larsen introduce a new parameter to the bundling discussion: the necessary gap that must exist to separate physical packets in a communication channel. They say that if data to be sent becomes available a little at a time at irregular intervals, the sending side must decide whether to send a given piece of data immediately or to wait for the next data to become available, such that they can be sent together as a bundle [FL02]. The decision of sending is not trivial because of physical properties of the networks requiring that after sending each packet, a certain minimum amount of time (gap) must elapse before the next packet may be sent. Thus, whereas waiting for more data will certainly delay the transmission of the current data, sending immediately may delay the transmission of the next data to become available even more [FL02].

In a recent article, Ceranowicz describes the Joint Experimental Federation (JEF) and the Millennium Challenge 2002 (MC02), a simulation conducted in July and August of 2002 by 13,500 personnel at locations across the United States. In the article, he reports about the maximum limit of bytes that can be bundled. In one of the experiments, up to to 4500 bytes were bundled in each IP packet and updates were collected for up to one second. He concludes that the tradeoffs were that bundling more data together increased latency and packet loss due to transmission errors, while smaller packets increased the transmission of overhead data [CTH02].

In [BCL97] and [LCL99] consecutive PDUs are concatenated in a single packet even if their types are different, and redundancy in the fields that make up a PDU is not eliminated. Bassiouni explains that the benefit of PDU bundling comes from the fact that network routers, bridges, gateways, and computer hosts have a limited bound on the number of packets that they can process or transmit per second, and

bundling can effectively increase this bound. Bassiouni and Liang have the same formalization of PDU bundling, which follows.

Let r_s be the maximum number of PDUs of size s bytes that can be transmitted from host A to host B in one second. Suppose that host A starts bundling its transmitted PDUs, instead of sending them as individual packets, by assembling k PDUs into a larger packet that is transmitted as a single unit. Let r_{ks} be the maximum number of packets per second that can be transmitted from host A to host B if k PDUs are bundled into a single packet, where $k > 1$. In many networks under most loading conditions, the following relationship holds [BCL97, LCL99]:

$$r_s < kr_{ks} \tag{2.1}$$

and the percentage gain in the PDU peak rate is $100(kr_{ks} - r_s)/r_s$

The term ks in inequality 2.1 implies that the proposed bundling mechanism does not compress or reduce the size of the bundled PDUs. The PDUs are just concatenated regardless of their internal structure, type or redundancy.

It is also interesting to note that Bassiouni and Liang indicate that some time-critical PDUs like *fire*, *detonation* or *explosion* cannot be bundled. In this dissertation those types of PDUs are bundled, given that they are scheduled at the same time and are subject to an unavoidable delay caused by the satellite link, facts that make the incurred bundle delay negligible.

Liang also proposes bundling using Multilevel Priority Queues (MPQ) as well as Single Priority Queues (SPQ) [LCL99]. Both mechanisms are variants of the Head of Line (HoL) strategy from queue theory referenced by many authors, for instance [LS93, DGR01, Liu02, PW03, GM04]. The general idea in HoL algorithms is to assign a priority to the incoming elements (PDUs, cells, frames, etc.) and using a

priority queue, serve the higher priority elements first, possibly defining timeouts for the low priority ones so that starvation is prevented.

A delta-PDU encoding technique is mentioned in [US95a, Mac95] consisting of PDUs that carry changes respect to a reference PDU initially given. The technique exploits the fact that most information in DIS entity state PDUs is redundant from one packet to the next. The delta-PDU encoding is accomplished by splitting the DIS Entity State PDUs into static and dynamic data PDUs. The static data becomes the reference PDU, while the dynamic one carries the changes. The idea has also been studied for the HTTP protocol using intermediate proxy servers as cache memory [MDF97, MDF02, WAS96]. Wills [WMS01] describes several delta encoding and bundling techniques generally applicable to Web pages under the TCP/IP protocol suite, but none is specific to the DIS protocol.

A protocol called DIS-Lite developed by MäK Technologies [Tay95, Tay96b, Tay96a, PW98] also splits the Entity State PDU into static and dynamic data PDUs, so that the static information is sent once and the changes (dynamic PDUs) are subsequently sent as separate PDUs. DIS-Lite offers several advanced features, including packet bundling, latency compensation and enhanced dead-reckoning algorithms tailored for air vehicles [PW98]. According to [Ful96], by eliminating redundancy DIS-Lite can perform between 30% and 70% more efficiently than DIS. DIS-Lite also includes several other improvements not related to the combination of individual fields from a set of similar PDUs. These objectives complement related predictive strategies developed for conserving simulation bandwidth [BD96, HGG01].

The bundling principle is also applied to TDM (Time Division Multiplexed) networks, where a number of lower order frames are multiplexed into one higher order frame [Ber02].

2.2 Data Compression

Data compression has been long studied and many papers have been written around it. One of the goals of this dissertation is to diminish the bandwidth requirements of OTB simulations by compressing the PDUs transmitted over the network. It has been observed that in many cases the next PDUs are almost identical to previously transmitted ones. This observation leads to the conclusion that it is possible to apply one or several compression techniques to achieve better bandwidth utilization.

Generally speaking, compression algorithms can be classified in two broad categories: *loss* and *lossless* algorithms. Loss compression corresponds to algorithms that do not guarantee an exact recovery of the compressed data. In many applications like sound and video this loss is acceptable because human senses do not detect the faults in the uncompress data, or because the final quality of the uncompressed data is acceptable.

Lossless compression involves algorithms that can recover the original data without faults. Applications include the transmission of an executable binary file, or the compression/uncompression of TCP/IP packets. In this research, the lossless compression of PDUs is sought. A detailed treatment of loss and lossless compression algorithms is found in Deorowicz's PhD dissertation [Deo03].

Compression algorithms can also be classified by the method employed to compress the data. Some methods are based on dictionaries, guess tables or a mix of both [Hew95, TS02]. Methods based on dictionaries create a dictionary of strings commonly repeated in the data and corresponding keys much shorter than the strings. Then, instead of the string, the key is transmitted. Obviously, each communicating party needs to know the dictionary, which is transmitted in advance. One of the most common lossless compression algorithms based on dictionaries is

the Lempel-Ziv (LZ) algorithm [ZL77] Common compressors like *gzip*, *winzip* and *pkzip* are based on the LZ algorithm.

Guess tables are based on the idea that certain bytes can be guessed from the previous transmitted ones. Both, the sending and receiving sites maintain the same guess table. If the transmitter can guess the next byte, then that byte is not transmitted but entered into the table.

Some algorithms are based on the concept of entropy taken from the information theory to produce high compression rates. They are related to Shannon's fundamental source coding theorem [Sha48] and an example of this kind of algorithms is Huffman coding [Huf52]. In [FY94] a lossless algorithm to compress volume data based on differential pulse-code modulation (DPCM) and Huffman coding is presented.

Compression algorithms have been devised specifically to compress network packets. Dorward [DQ00] presents such an algorithm based on a variant of Lempel-Ziv's compression, and Ishac and Degermark [Ish01, DNP99] deal specifically with TCP/IP headers. If the data to be transmitted in the TCP/IP packets is too small, the transmission overhead of the headers starts to be an important factor of bandwidth waste. The header compression combined with data concatenation of several small PDU packets is then an appealing technique. According to Degermark, header compression can decrease the header overhead for IPv6/TCP from 19.5 per cent to less than 1 per cent for packets of 512 bytes.

TCP/IP compression has been researched by companies like Dataline (`http://www.dataline.com/`) that claims that by using its TCP/IP acceleration technology Joint En-route Mission Planning and Rehearsal System - Near Term (JEMPRS-NT) can deliver the functionality required by a traveling team of 12-15 users over a satellite link. Dataline affirms that by using its technology, a 64 Kbps link can give the equivalent throughput of a virtual 256 Kbps

[Fro02]. As an interesting observation, the simulations run in Chapter 6 using the proposed bundling algorithm PDUAlloy, produced results comparable to Dataline's affirmation, just by employing bundling. The usage of several compression strategies could lead to even better results.

There are two general classes of compression techniques for removing PDU redundancies: *application dependent* and *application independent*. Algorithms that fall in the first group know and take advantage of characteristics of the simulation application like encoding data based on bit strings typical of the application and sending delta PDUs. In the second group, algorithms are more general, do not know particularities of the application and work by examining and compressing the bit strings by detecting bit patterns. According to Van Hook [VCN94], application dependent techniques can achieve slightly more compression than the independent counterparts, but are a lot more complex and require much more processing power.

In 1994, Advanced Research Projects Agency (ARPA)s simulation exercise called Synthetic Theater of War–Europe Application Gateway (STOW-E AG) was conducted to test a new communication architecture. The AG was installed between each site LAN and the WAN to apply several algorithms and techniques for managing traffic flowing to and from each site, like blocking unnecessary PDUs, Protocol Independent Compression Algorithm (PICA), grid filtering, Quiescent Entity Service (QES), rethresholding, bundling, load leveling. Calvin reports that the application of all these techniques produced a reduction in network traffic by more than an order of magnitude [CST95].

PICA was originally proposed as a compression algorithm by Van Hook in 1994 to compress SIMNET PDUs [VCM94], achieving up to 76% reduction in bit rate. The SIMNET protocol and simulation was a precursor of DIS protocol developed in the late 1980's by the Defense Advanced Research Projects Agency (DARPA). PICA compresses ESPDUs by transmitting a reference ESPDU that becomes

known to the communicating entities, and subsequently sending delta-PDUs, also called Differential Data Unit (DDU), containing those bytes which differ from the reference ESPDU. Eventually, a new reference PDU, called Differential Key Data Unit (DKDU), is transmitted because at that time the compression being achieved by PICA falls below a threshold, due to increasingly larger bit pattern differences [DCV94, VCN94, Fuj95]. PICA has been reported to yield fourfold compression of entity state PDUs, although Fire, Detonation, and Collision PDUs are not compressed before bundling, due to their relatively few number and small size [VCN94]. However, in this dissertation, `po_fire` PDUs are successfully compressed because of the conditions (similar timestamps, long satellite link delays) specified for the vignette.

2.3 Data Transmission

One of the goals in this dissertation consists of rescheduling some of the PDU packets in order to better utilize the bandwidth by transferring PDUs from periods of high activity to periods of low activity. As stated in the introduction, one of the main causes of negative slack spikes is the scheduling of several PDUs at the same time, which causes a bottleneck in the transmitting sites.

Packet rescheduling is an old technique, initially developed for the Ethernet CSMA/CD protocol 802.3 [IEE85] to manage collisions during the contention period. The exponential backoff algorithm is commonly used to reschedule the collided packets, although Molle considers that the stability of the algorithm is somewhat open to debate [Mol94]. If PDUs are timestamped at the same time, they can be considered as a kind of collision that needs to be solved.

The scheduling of packet networks at the router level has been recently studied in [APR03] where a randomized parallel scheduling algorithm for scheduling packets in routers based on the Switch-Memory-Switch (SMS) architecture is developed.

Multicast routing algorithms and protocols with emphasis on QoS is addressed in [WH00]. The network is represented as a weighted digraph with one or more parameters associated to the links. Each parameter represents a characteristic of the link, like transmission and propagation delay, bandwidth, etc. The nodes also contain parameters that describe their stauts, like buffer space available, queue length, etc. The multicast routing problem consists of finding minimum spanning trees for a given objective function subject to QoS constraints. The problem is classified into several categories depending on the objective functions to be minimized and the QoS constraints. Examples of those categories are: link constrained problems, tree constrained problems, link and tree constrained problems, tree optimization problem, etc.

Packet transmission using priorities have been largely studied. The Head of Line algorithms and priority queues are examples that make use of packet priorities. A method that exploits a priority scheme to guarantee static preplanned message slots for hard real-time communication is found in [KLJ00]. The mechanism is embedded in the MAC layer. The method considers that there are highly time-critical messages that require bounded transmission times. Applied to the present simulation, these time-critical messages could be the *po_fire_parameters* PDUs involved in the negative slack spikes.

Priorities are also used in real-time applications when the traffic is shared with non real-time ones. A recent PhD dissertation by Pope addresses the issue of bounding packet delay based on various queuing disciplines under real-time constraints [Pop02].

2.4 Comparison of Bundling Techniques

The following list summarizes the most common bundling-related strategies used to conserve bandwidth over WAN networks.

1. Plain concatenation of PDUs

    - Consecutive PDUs are concatenated so that the total length of the bundle is equal to the sum of the components.
    - PDU types and timestamps are not decision variables
    - Usually applied to ESPFUs, not fire and detonation ones.
    - Each PDU conserves its own PDU header.
    - Advantages: Savings in packet headers and ACK replies at the transport layer, and separator gaps at the physical layer, by using a single header, ACK and gap instead of many ones. Fewer collisions are produced by having to acquire the channel fewer number of times, assuming a CSMA/CD link.
    - Disadvantages: Concatenation should be limited to the maximum size of a network packet, to keep the previous advantages. Redundance is not eliminated, and so fewer packets can be bundled in the same block.

2. IP header compression

    - Consecutive IP headers having high similarity are compressed by a lossless algorithm.
    - Applicable to TCP/IP packets, not to PDUs.
    - More useful if data segments are small in the packet.

- Advantages: By shortening the headers, less data is transmitted. Good for short packets.
- Disadvantages: Low compression ratio for PDUs, given that they are not compressed and in general are long. Redundancy is not eliminated.

3. Delta-PDUs

   - A reference PDU is transmitted first, followed by packets carrying the differences only.
   - Destinations must keep the reference PDU in order to extract the original PDUs from the deltas. This makes the PDUs dependent of the reference.
   - After a threshold, a new reference PDU is transmitted
   - Advantages: all the advantages of plain concatenation are applicable here, plus high compression ratio.
   - Disadvantages: delta PDUs are dependent on the reference PDU. If the reference PDU gets lost or out of sequence (assuming unreliable UDP transport), the deltas become useless and all the sequence have to be retransmitted.

4. DIS-Lite

   - Implements delta-PDUs and many other optimizations not related to bundling.
   - Terminology calls the reference and delta PDUs static and dynamic, respectively.
   - Tailored for air vehicle simulations, has been applied to video games played on the internet.

- Advantages: all the advantages of delta-PDUs are valid here, as this technique is a refinement of delta-PDUs. Involves several other compression and bandwidth-saving techniques.
- Disadvantages: Has been applied to compression of ESPDUs only. Does not examine and take advantage of the type, timestamp and internal structure of PDUs. Mainly targeted at simulations of aircraft vehicles.

CHAPTER 3

COMMUNICATION RESOURCES AND ARCHITECTURE

3.1 Simulation Vignette

A simulation environment aimed at assessing One Semi-Automated Force (OneSAF) communications bandwidth during mission rehearsal of Future Combat System (FCS) vignettes was developed at the Electrical and Computer Engineering Department of the University of Central Florida, sponsored by the U.S. Army Program Executive Office for Simulation, Training, & Instrumentation (PEO STRI), formerly STRICOM.

Activities were undertaken to understand FCS mission rehearsal operations and define a vignette to generate the simulation traffic to be modeled. The Operational and Organizational (O&O) document [For02] entitled US Army Objective Force Operational and Organizational Plan for Maneuver Unit of Action, TRADOC 525-3-90 /O&O, 22 July 2002 was obtained and reviewed for adaptation to our vignette.

Several different FCS vignettes were prepared and simulated on a Local Area Network (LAN) using the OneSAF Testbed Baseline (OTB) software, a military simulation application that implements a Joint En-route Mission Planning and Rehearsal System (JEMPRS) in an FCS environment. In [VDG04a, VDG04b],

the author describes an initial implementation of the OMNeT simulator used, and corresponding results obtained when the vignette logs were run.

Traffic logs were created from the participating sites. OTB communications are based on the Distributed Interactive Simulation (DIS) protocol defined in the IEEE Standards 1278.1 [IEE95a], 1278.2 [IEE95b], 1278.3 [IEE96] and 1278.1a [IEE98]. The fundamental communication packets under DIS are the Protocol Data Units (PDUs), which were logged including relevant PDU information used for alternative parameter variations of the model. The information logged included the type, length, and time-stamp of each PDU.

In particular, the MR1 vignette illustrating a mission rehearsal operation while en-route to deployment and reproduced in Appendix A, was used to generate the PDU traffic logs. This vignette was partly based on and extends TRADOC PAM 525-3-90 Operations & Organizations (O&O) document, "Annex F - Unit of Action Vignettes [For02]." In the section called *Statement Of Required Capabilities For Future Combat Systems* the TRADOC PAM document indicates that the Unit of Action (UA) must be able to integrate into Enroute Mission Planning and Rehearsal Systems (EMPRS) during alert, deployment and employment. FCS and Unit of Action C2 systems must access enroute mission planning, and support mission rehearsal, battle command, and ability to integrate into gaining C2 architectures during movement by air, land and sea. The document contains three vignettes including Entry Operations, Combined Arms Operations for Urban Warfare to Secure Portion of Major Urban Area, and Mounted Formation Conducts Pursuit and Exploration.

The duration of the MR1 vignette is approximately 25 minutes of simulation time. It involves Entry Operations and Maneuver to Attack of a battalion-sized unit tasked with pursuing an enemy delaying force immediately upon landing. The lead elements (Alpha company) detect a fortified position between the main elements

and the target enemy force. Four RAH-66 Comanche helicopters are deployed and follow closely. Next, the East friendly forces, begin to advance on the enemy position, however, they must traverse minefields during their pursuit. The enemy force flees southward from the North and East force. The South force engages the enemy, and is assisted by the North and East forces.

The general scenario is that a Battalion Task Force equivalent has been rapidly deployed. There are 8 aircraft, C-17 equivalent, in formation, each one carrying up to three ground vehicles. Inside each aircraft, the vehicles are connected to each other, and also to the aircraft communication resources, via a hardwired Ethernet-type network. Each ground vehicle contains a computer station running the MR1 vignette on OTB. The aircraft are in communication with each other via satellite that also provides a link to a Continental United States (CONUS) ground station. This ground station provides core exercise support including Semi-Automated Forces (SAF). Additional links are utilized directly between the aircraft to reduce demands on the satellite feed. This is based on SECOMP-1 / JEMPRS Near-Term (JEMPRS-NT) architecture as of January 2003.

Figure 1 shows the model of the flying network used for rehearsal and training on the MR1 vignette. The number of airplanes and simulation stations onboard is variable in the model. The three simulation stations onboard each airplane are connected at 100 Mbps. Connections from plane to plane are achieved via routers and wireless links. Possible values for the wireless bandwidths range from 64 Kbps to 1024 Kbps. Because the aircraft are flying in formation, the network is not considered an ad hoc network.

The main stages in the development of the model included:

1. Design, obtain approval, and using OTB construct a vignette illustrating mission rehearsal enroute to deployment.

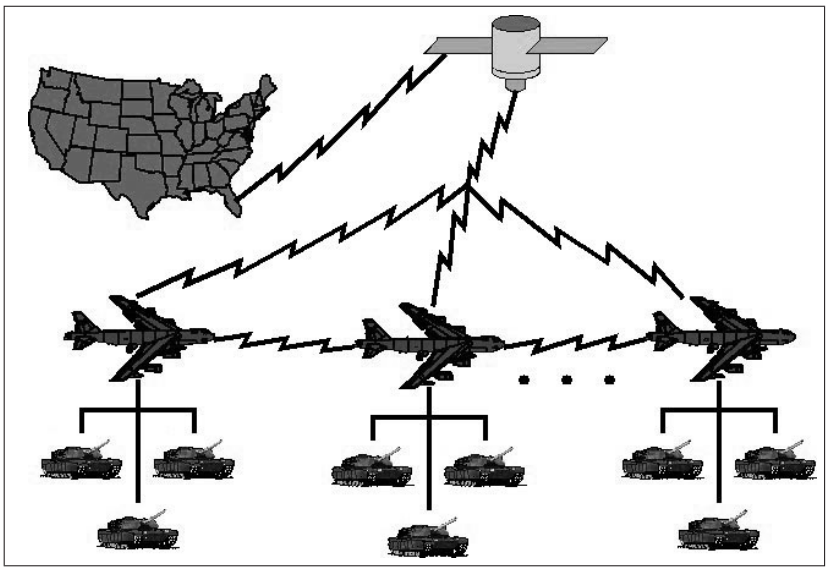


Figure 1: The Flying network

2. Analyze the steady-state and bursty traffic to determine network bandwidth requirements as a proportion of capacity in the tactical C4ISR network.

3. Assess latency and degradation of message delivery due to routing delays, queuing time, and network loading.

4. Improve the network traffic by eliminating redundancy and possibly compacting the PDUs which are the network packets used by the OTB software.

The purpose of this research is to assess the bandwidth in the wireless links and to develop improved strategies that more effectively utilize the available bandwidth.

3.2 Communication Architecture

After evaluating a number of possible configurations, a suitable communication infrastructure was defined and represented in Figure 2, which depicts the

communication architecture model used in most of the experiments performed. The simulated model consists of eight airplanes flying in formation towards deployment. Each aircraft carries three ground vehicles, and each vehicle contains a workstation running OTB. Due to the proximity of the aircraft and the fact that they are flying in a steady formation, all the planes and workstations conform a flying LAN.

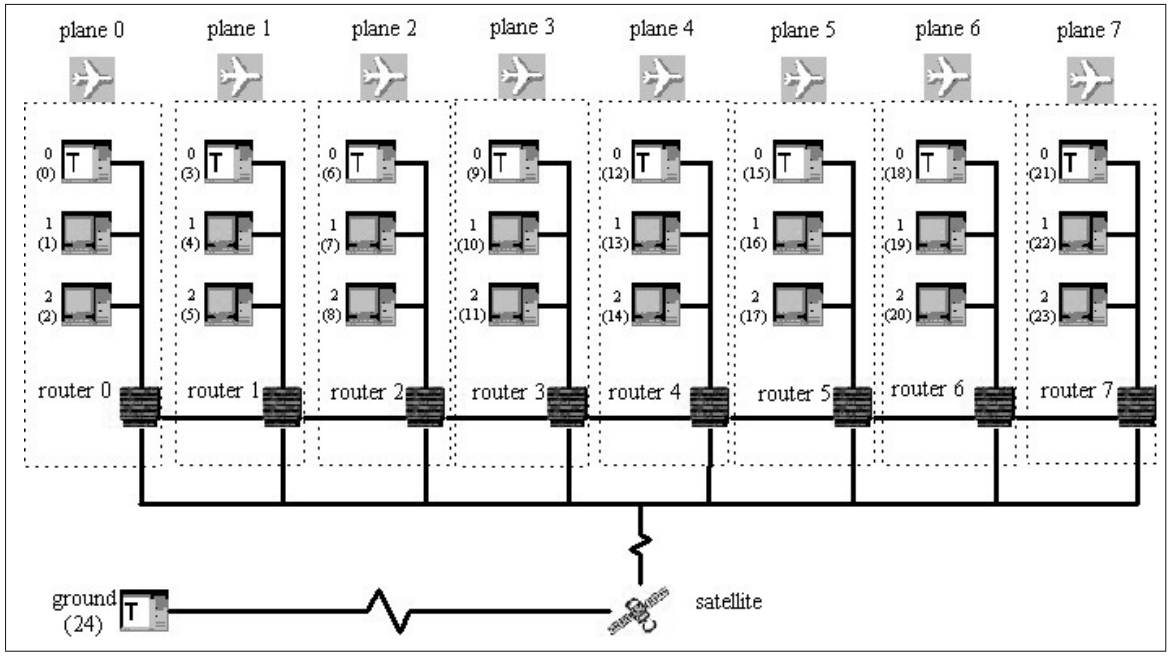


Figure 2: Communication architecture model. Sites flagged T are transmitters, the others are receivers.

Planes are numbered 0 to 7, and stations local to each plane are numbered 0 to 2, as well as 0 to 23 for the global network. The CONUS ground station is numbered 24. Routers are numbered the same as the plane they are onboard. According to the data logged form the vignette, some stations are transmitters while others are just receivers. The stations flagged "T" represent packet transmitters; the others are the receivers. But according to the DIS protocol, the transmitters broadcast their packets, and so transmitters are receivers, too.

The number of airplanes, computers onboard and channel bandwidth is not a tight restriction in the model. The three computers onboard the airplanes are

connected via Ethernet cable or similar. Connections from plane to plane are done via routers and wireless links. The bandwidth of the wireless connections is initially set to 64 Kbps, and different runs of the simulator using speeds of 128, 200, 256, 512, and 1024 Kbps are carried out. The Ethernet LAN is maintained at 100 Mbps in all cases, due to the fact that this technology is very common nowadays, and the LAN bandwidth is at least two orders of magnitude greater than the wireless bandwidth. A ground station is connected to the flying network through a satellite link. All the computers in the network use the DIS protocol to broadcast messages, as specified in [IEE95a].

An object of type *bus* models all the communication links. A bus contains input and output connectors separated by known distances. Each bus is configured to operate at a specific bandwidth and propagation delay. When a message enters through one of the input connectors, the bus delivers it to each of the output connectors at different times depending on the distance and propagation delay of the medium. The bus was programmed so that signals propagate through it in both directions. If (IC_i, OC_i) is a pair of input and output connectors located at a distance d_i from one of the bus endpoints, p is the propagation delay in the bus $(nanoseconds/meter)$, b is the bus bandwidth (bps), and a message of length n bits arrives into (IC_i at time t, then when the message reaches any other output connector OC_j the following measures hold:

$$
\begin{aligned}
Distancetraveled &= |d_i - d_j| && (3.1)\\
Propagationdelay &= Distancetraveled * p && (3.2)\\
Transmissiontime &= n/b && (3.3)\\
StarttimeatOC_j &= t + Propagationdelay \\
&= t + |d(i - d_j| * p && (3.4)\\
EndtimeatOC_j &= start + transmissiontime
\end{aligned}
$$

$$= \quad t + |d_i - d_j| * p + n/b \tag{3.5}$$

The start and end times at OC_j are useful to determine collisions. If a message has a time interval defined by start and end times overlapping the time interval defined by the start and end times at OC_j of any other message, then a collision occurs.

Generalizing, the model can be described as a collection of computer nodes and routers interconnected by different media at several bandwidths. The transmitters broadcast packets at unspecified rates. In order to generate the packets, it is possible to use a specific probability distribution over time. However, to obtain maximum accuracy, a log of the actual packets generated by OTB, including the PDU type, time-stamp, and packet length was used in place of a random distribution function, providing more realism to the results.

3.3 Transmission and Receiving Devices

The OMNeT++ discrete event simulator was used as the main tool for the model setup. OMNeT++ was designed by András Varga [Var03] at the University of Budapest. The kernel was written in C++, and the user specifies additional modules to program the behavior of the entities in the model. The model design follows a bottom-up approach for modeling the communication architecture. Simple modules are built first and compound modules are built on top of the simple ones. Figure 3 gives a general view of the simple and compound modules of the simulator connected together. It is an actual screenshot of the main OMNeT++ window. If the simulator is run with the animation option activated, each one of the traveling

messages is displayed in this window as a small circle moving across the arrow lines carrying an identification label.

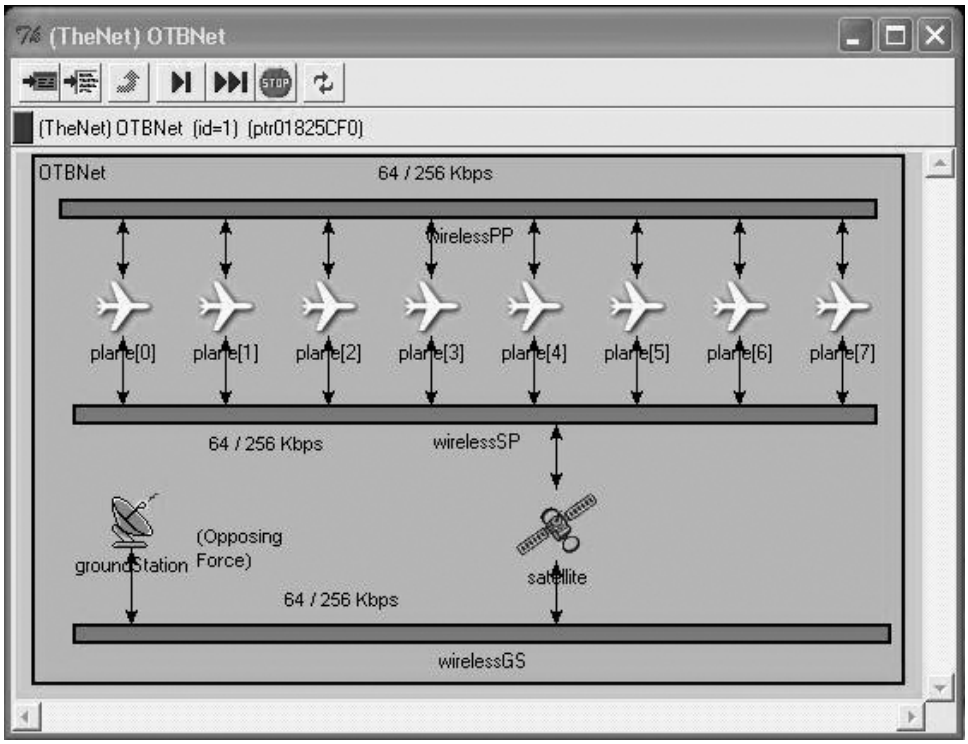


Figure 3: OMNeT screenshot of the whole network showing 8 planes, satellite ground station and 3 wireless channels.

The entities comprising the model in Figure 3 include the four communication links: LAN (not shown), Wireless Plane-to-Plane (WPP, upper horizontal bar), Wireless Satellite-to-Plane (WSP, middle bar), Wireless Ground-station-to-Satellite (WGS, bottom bar), the computer nodes containing a generator and a sink of packets (not shown), routers (not shown), the satellite, and the ground station. Each of the entities was realized as a C++ module.

3.3.1 Simple Modules in OMNeT

These are modules that contain no other modules inside them. They are used to describe the most basic elements of the simulator. Generators of messages, sinks or consumers of messages, communication channels (wireless and Ethernet buses), routers and the satellite correspond to simple modules. Each simple module is defined by two files. The first is a *.ned* file that describes input parameters to the module and the set of input and output gates or communication ports. The second is a C++ source file that defines the behavior of the module, i.e. it indicates how to process each message received through any of the input gates and which messages to send through the output gates. The simulator in this project includes the following `.ned` files of simple modules: `generator.ned, simplebus.ned, sink.ned, router.ned`, and `satellite.ned`. Figures 4 to 9 show the corresponding `ned` source codes.

3.3.1.1 The Generators

A generator is the module that produces new messages, following the instructions in the corresponding C++ file. The module reads in a sequence of PDUs from a summary file containing the *type*, *length* and *timestamp*. When the simulation time has reached the `timestamp` of a message, the generator outputs that packet to the LAN link if it is onboard an airplane, or to the WGS link if it is in the ground station.

After sending a packet, employing the transmission time corresponding to the packet length and bus bandwidth, an inter-frame space (IFS) or time gap of 50

µseconds is added, in accordance with the specifications given in ANSI/IEEE protocol 802.11 [IEE99].

The `ned` instructions declaring a generator are given in Figure 4. Due to OTB specifications, all the messages sent by one generator are broadcasted to all of the other nodes.

```
simple Generator       // Generator is a simple module
parameters:
  fromAddr: numeric,   // origin, unique ID within network
  totalNodes: numeric; // number of nodes in the network
                       // (routers not counted)
gates:
  out: out; // The only gate of a generator is called "out"
endsimple
```

Figure 4: Source file generator.ned

The `fromAddr` parameter is used to give the generator a unique identification. In this simulator, generator IDs range from 0 to 24, where 0, 1, 2 are generators onboard plane 0, 3, 4, 5 onboard plane 1, etc. up to 21, 22, 23 onboard plane 7, and generator 24 is in the ground station.

The `totalNodes` parameter represents the highest ID value assigned to a generator in the model, 24 in this case. The parameter was intended to be used in determining all the valid destination IDs of a message. However, due to the broadcasting feature of the model, the parameter is not actively used in the current version of the generators.

3.3.1.2 The Buses

A `simplebus` is the module that represents the communication links in the network. Instances of it are used to simulate both the Ethernet and the wireless links. Figure 5 shows the corresponding source code of the `ned` file.

```
simple SimpleBus
  parameters:
    busType: string,        // Types: LAN, WPP, WSP, WGS.
    numChannels,            // number of independent channels
    wantCollisionModeling, // collision modeling flag
    wantCollisionSignal,   // "send collision signals" flag
    isFullDuplex,           // channel mode
    delaySecPerMeter,       // delay of the bus
    dataRateBps,            // data rate of the bus
    gapTime;                // minimum gap between packets.
gates:
  in: in[ ];
  out: out[ ];
endsimple
```

Figure 5: File simplebus.ned

The `busType` parameter indicates the type of link. The possible values of this parameter are LAN, WPP, WSP, and WGS to represent, respectively, the Ethernet link in each airplane, the three wireless links already explained. Each link can be subdivided into several independent channels. The `numChannels` parameter indicates the number of subdivisions. Currently, the simulator is using just 1 channel per link. The module can be tailored to handle collisions and full/half duplex communications, and the next three parameters indicate this preference. The parameters `delaySecPerMeter`, `dataRateBps` and `gapTime` indicate the propagation delay in seconds per meter, the data rate in bits per second (bps) and the minimum time separation between packets for this link in microseconds, respectively. The module contains arrays of input and output gates, which sizes are specified at each instantiation of the bus. OMNeT imposes a restriction that not two modules can be connected to the same given gate. Therefore, if 3 computers plus a router are to be connected to the same Ethernet link, then the input and output gates are arrays of size 4.

3.3.1.3 The Sinks

A sink is a module that consumes packets. The sink consumes PDUs and keeps statistics about the number of frames received, the latency of each one, and number of collisions detected at the corresponding node. There is one sink per computer. The sink contains an input gate only.

```
simple Sink
gates:
  in: in;     // input gate
endsimple
```

Figure 6: File sink.ned

3.3.1.4 The Routers

Each airplane encompass three computer nodes and one router. The router is connected to the LAN, WPP and WSP links, as indicated in Figure 7.

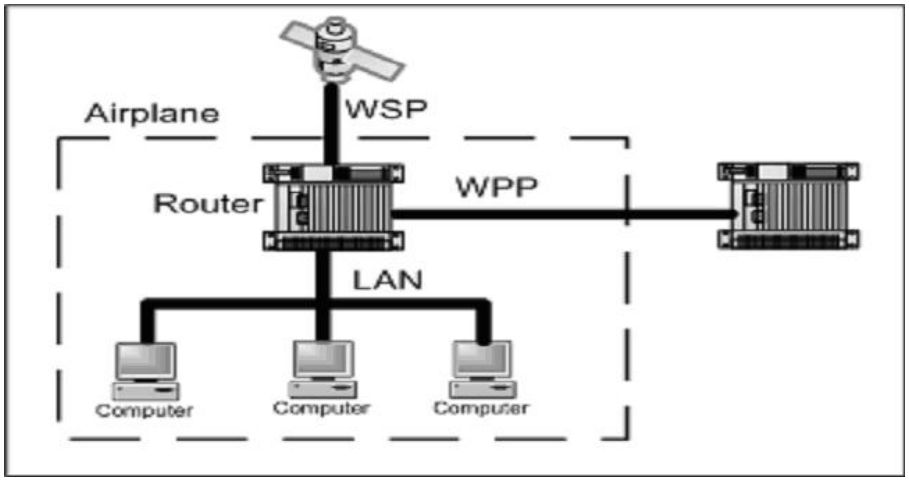


Figure 7: Router onboard a plane and its connections to the LAN, WPP and WSP links

The LAN connection is direct because the bus module and the router module are connected without requiring any intermediate object. However, the connections to the wireless channels are indirect because the router is contained in the airplane, which is the intermediate object between the router and the wireless buses. Therefore, the `ned` specifications indicate that the router is directly connected to the airplane, which in turn is directly connected to the wireless links. Each connection requires one input and one output gate. The connections are:

1. Direct connection to the local Ethernet bus (100 Mbps)
2. Indirect connection to the wireless plane-to-plane bus (64 Kbps or more)
3. Indirect connection to the wireless plane-to-satellite bus (64 Kbps or more)

Because the entire DIS traffic is broadcasted, a PDU coming from one of the input connectors is propagated to the other outputs according to Table 1. The `ned` source code defining a router is listed in Figure 8.

Table 1: Routing table in broadcast mode

Input Link	Output Link
LAN	WPP and WSP
WPP	LAN
WSP	LAN

Any device connected to a bus gate must indicate its position measured in meters from one end of the bus. This position is a parameter involved in propagation delay calculations. The router is directly connected to the local Ethernet bus. For this reason, a `LANposition` parameter is required to establish the position of the router within the bus. The other bus connections are indirect because the router is really connected to a gate in the plane that, in turn, is connected to the bus. Therefore, positions for the wireless buses are indicated as parameters of the airplane, the compound module holding the LAN.

```
simple Router
parameters:
  routerID : numeric,
  nodesPerPlane: numeric,
  totalPlanes: numeric,
  LANposition : numeric, // Local LAN position
  routerServiceTime: numeric;
gates:
  in: inFromLocal;      // gate #0
  out: outToLocal;      // gate #1
  in: inFromWirelessPP; // gate #2
  out: outToWirelessPP; // gate #3
  in: inFromWirelessSP; // gate #4
  out: outToWirelessSP; // gate #5
endsimple
```

Figure 8: File router.ned

Routers maintain an M/M/1 queue of input messages. Every time a new message arrives, the router records statistics about the number of messages in the queue at that time. The message length, the IFS gap, and the output bandwidth determine the service time, as indicated by the following formula:

$$servicetime = (messagelength\ /outputbandwidth) + IFSgap \tag{3.6}$$

3.3.1.5 The Satellite

The satellite behaves like a router with only two links attached: the WSP and the WGS links. The satellite also maintains a queue of messages and calculates statistics as any other router does. Its `ned` source code can be seen in Figure 9. The parameter descriptions are similar to the parameters of a router, and so they are omitted here.

```
simple Satellite
parameters:
  satelliteID : numeric,
  satServiceTime : numeric,
  totalNodes : numeric,
  WGSposition : numeric, // Position at wirelessGS
  WSPposition : numeric; // Position at wirelessSP
gates:
  in: inBus1;   // gate #0 (wirelessGS)
  out: outBus1; // gate #1 (wirelessGS)
  in: inBus2;   // gate #2 (wirelessSP)
  out: outBus2; // gate #3 (wirelessSP)
endsimple
```

Figure 9: File satellite.ned

3.3.2 Compound Modules

Compound modules are modules that contain other modules inside. For example, a computer onboard an airplane is a compound module because it contains a message generator and a sink. A plane is also a compound module that contains a computer, a router and an Ethernet bus. The largest compound module corresponds to the whole network that contains the airplanes, the satellite, the ground station, and the wireless buses linking these elements. Each one of these compound modules is briefly discussed in the following paragraphs.

3.3.3 The Flying Computer Nodes

Each workstation in the model consists of a computer node that contains two other submodules: the generator and the sink of PDUs. These computer nodes are directly connected to the LAN link. Figure 10 shows the OMNeT++ representation of a computer node, and Figure 11 lists its `ned` source code. The module `Node` is composed of the simple modules `gen` (generator) and `sink`. The module also contains an input (in) and an output (out) gate.

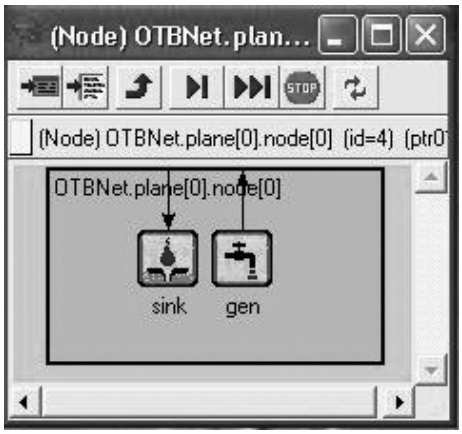


Figure 10: OMNeT representation of a computer node and its components

```
module Node
parameters:
  nodeID : numeric,
  LANposition : numeric;
gates:
  out: out;
  in: in;
submodules:
  gen: Generator;
parameters:
  fromAddr = nodeID,
  totalNodes = ancestor totalNodes;
  display: "i=gen;p=120,49;b=32,30";
  sink: Sink;
  display: "i=sink;p=81,49;b=32,30";
  connections:
  gen.out --> out;
  sink.in <-- in;
  display: "p=18,2;b=176,102";
endmodule
```

Figure 11: Ned code of a computer node

3.3.3.1 The Planes

The module `plane` is composed of the modules `router`, an array of `nodes` and the `ethernetBus`, as seen in Figure 12. The array length is one of the input parameters, set to 3 in this simulation. The corresponding `ned` file of this module is longer than the file of previous modules and is, therefore, listed in Appendix B.

The arrows in Figure 12 represent connections between modules via input and output gates. The router is also connected to the airplane input and output gates (not shown) which in turn are connected to two wireless buses.

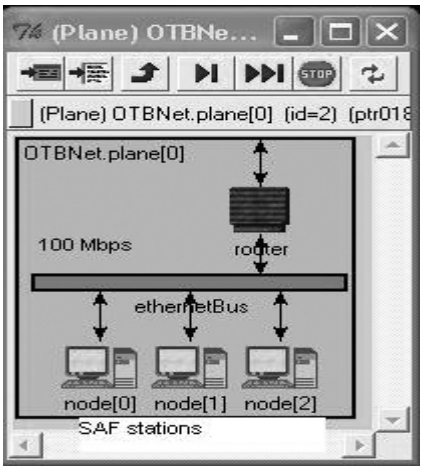


Figure 12: Airplane view showing 3 computer nodes, a bus and a router

3.3.4 The Ground Station

The ground station behaves exactly as any of the flying workstations. It is connected to the WGS link only. Figure 13 represents the ground station and Figure 14 shows its `ned` source code. This module is quite similar to the computer nodes and therefore a description is omitted. Although the CONUS ground station technically

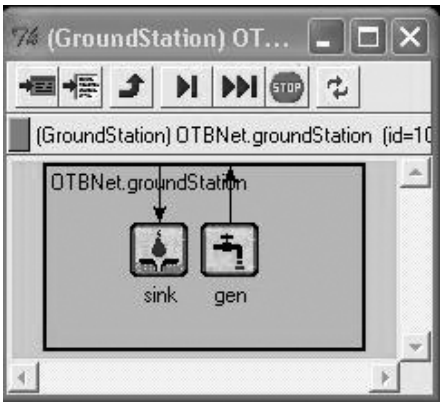


Figure 13: OMNeT view of the ground station and its components

is like any other flying workstation, it plays an important role in the simulator because it is the only station directly connected to a slow wireless link. The rest of the stations are connected to a 100 Mbps LAN link. Due to this characteristic, some of the simulations assigned the highest load in terms of number of generated PDUs to the ground station, and many statistics were collected around it.

```
module GroundStation
parameters:
  nodeID : numeric,
  WGSposition : numeric;
gates:
  out: out;
  in: in;
submodules:
  gen: Generator;
parameters:
  fromAddr = nodeID,
  totalNodes = ancestor nodesPerPlane * ancestor numPlanes;
  display: "i=gen;p=120,49;b=32,30";
  sink: Sink;
  display: "i=sink;p=81,49;b=32,30";
  connections:
  gen.out --> out;
  sink.in <-- in;
  display: "p=18,2;b=176,102";
endmodule
```

Figure 14: Ned Code of Ground Station

The parameter `fromAddr` of the generator comes from the parameter `nodeID` of the ground station. `TotalNodes` is defined as the product of `nodesPerPlane` and `numPlanes` that are defined at a higher level in the hierarchy of modules. The display feature indicates the position of this module in the graphical user interface

(GUI). Finally, the module establishes the connections between the gates from the inner (simple) modules and the container module (the ground station).

3.3.5 Instantiation of the Network

The compound module `TheNet` contains the submodules `wirelessPP`, `wirelessSP`, `wirelessGS`, `groundStation`, `satellite`, and `plane` as shown in Figure 3. Due to its length, the source code of the `ned` language for this module is found in Appendix B.

OMNeT++ uses the object programming approach. The modules as well as the whole network are considered classes that must be instantiated. In this simulation `TheNet` is the class name of the network that is instantiated as `Network OTBNet`. It includes all of the model parameters that are read from the `omnetpp.ini` file. Figure 15 shows this instantiation and the corresponding parameters.

```
network OTBNet : TheNet
parameters:
  startTime = input,    //First PDU timestamp in seconds
  nodesPerPlane = input,//Set to 3 in this simulation
  numPlanes = input,    //Set to 8 in this simulation
  LANgapTime = input,   //Minimum gap between frames in LAN
  LANbandwidth = input, //Set to 100 Mbps
  LANdelay = input,     //nanosec/meter (70% light speed)
  WPPgapTime = input,   //Minimum gap between frames in WPP
  WPPbandwidth = input, //Wireless bandwidth in WPP
  WPPdelay = input,     //nanosec/meter (light speed)
  WSPgapTime = input,   //Minimum gap between frames in WSP
  WSPbandwidth = input, //Wireless bandwidth in WSP
  WSPdelay = input,     //nanosec/meter (light speed)
  WGSgapTime = input,   //Minimum gap between frames in WGS
  WGSbandwidth = input, //Wireless bandwidth WGS
  WGSdelay = input,     //nanosec/meter (light speed)
  satServiceTime = input, //Satellite service time
  routerServiceTime = input; //Router service time
endnetwork
```

Figure 15: Instantiation of the network TheNet

The initialization file `omnetpp.ini` is shown in Figure 16 for an OMNeT model. It is used to specify input parameters to the model.

The parameter `output-vector-file` is used to specify the output file that contains all the simulation results. At the end of the simulation, this ASCII file is processed by any application capable of interpreting it and producing statistics and/or graphics. OMNeT provides the `plove` plotting tool to process this kind of vector file.

The parameter `sim-time-limit` is used to indicate an upper limit to the simulation time. Similarly, `cpu-time-limit` gives an upper limit to the CPU time used by the simulator.

The parameter `display-update` is used for the simulation with animation, and indicates the refreshing rate of the window. The section under `[Run 1]` contains all the parameters specific to a given run. It is possible to indicate several run sets with different parameters each by appending sections `[Run 2]`, `[Run 3]`, etc. A more detailed explanation of the initialization file is found in the OMNeT User Manual [Var03].

3.4 Bundling and Replication of PDUs

If several PDUs are scheduled at the same or almost the same time, and the structure of those PDUs is the same, with only small but predictable differences, then only one single PDU needs to be sent together with instructions on how to recover the other PDUs from the given one. Comparisons of `po_fire_parameters` among other PDUs involved in the same negative spike showed that the stated conditions (same timestamp, small differences) can be exploited. These PDUs differ

```
[General]
network = OTBNet
ini-warnings = no
random-seed = 1
warnings = yes
snapshot-file = planes.sna
output-vector-file = planes64repl.vec
sim-time-limit = 2550s  # simulated seconds (42:30)
cpu-time-limit = 20h    # 20 hours of real cpu time max.
total-stack-kb = 4096   # 4 MByte, increase if necessary
[Cmdenv]
module-messages = yes
verbose-simulation = yes
display-update = 0.5s
[Tkenv]
default-run=
use-mainwindow = yes
print-banners = yes
slowexec-delay = 300ms
update-freq-fast = 10
update-freq-express = 100
breakpoints-enabled = yes
[DisplayStrings]
[Parameters]
[Run 1]
OTBNet.startTime     = 1034s   # 17:14
OTBNet.nodesPerPlane = 3
OTBNet.numPlanes     = 8
OTBNet.LANgapTime    = 50us
OTBNet.LANbandwidth = 100E6    # 100 MBps
OTBNet.LANdelay      = 4.761904762ns #nsec/meter, 70% light sp
OTBNet.WPPgapTime    = 50us
OTBNet.WPPbandwidth = 64000
OTBNet.WPPdelay      = 3.333333333ns #nsec/meter, light speed
OTBNet.WSPgapTime    = 50us
OTBNet.WSPbandwidth = 64000
OTBNet.WSPdelay      = 3.333333333ns #nsec/meter, light speed
OTBNet.WGSgapTime    = 50us
OTBNet.WGSbandwidth = 64000
OTBNet.WGSdelay      = 3.333333333ns #nsec/meter, light speed
OTBNet.satServiceTime = 5us
OTBNet.routerServiceTime = 5us
OTBNet.generatorServiceTime = 5us   #PDU bundling time
OTBNet.blockWaitTime = 100ms
```

Figure 16: Initialization File Omnetpp.ini

on consecutive identification attributes (like counters), and memory addresses that change according to the PDU length.

Table 2 shows two consecutive `po_fire_parameters` PDUs, identified as PDUs #19855 and #19856 in the OMNeT simulator and captured at second 1577.697 of simulation time, which are contributors to the negative spike described in Section 61. The table is quite long, but it is included here, and not in an appendix, because the comparison showed is considered a key point in this dissertation. The bundling method called PDUAlloy described in Section 3.4.1 was proposed after analyzing this comparison. The table shows that the two PDUs are almost identical, and most of their fields are zeros. Besides the address associated with each field, only two differences were found, highlighted in grey for the second PDU. The shown PDUs are not an exceptional coincidence. In all of the negative spikes studied, the participating PDUs have similar redundancies, provided that they are of the same type and length.

Table 2: Comparison of two consecutive po_fire_parameters PDUs

<dis204 po_fire_parameters PDU>:	19855	19856
dis_header.version	= 8b3bae0 = 4 = 0x04	= 8b3bd78 = 4 = 0x04
dis_header.exercise	= 8b3bae1 = 1 = 0x01	= 8b3bd79 = 1 = 0x01
dis_header.kind	= 8b3bae2 = 236 = 0xec	= 8b3bd7a = 236 = 0xec
dis_header.family	= 8b3bae3 = 140 = 0x8c	= 8b3bd7b = 140 = 0x8c
dis_header.timestamp	= 0x70311d96 = :26:17.697 (relative)	= 0x70311d96 = :26:17.697 (relative)
dis_header.sizeof	= 8b3bae8 = 544 = 0x0220	= 8b3bd80 = 544 = 0x0220
po_header.po_version	= 8b3baec = 28 = 0x1c	= 8b3bd84 = 28 = 0x1c

po_header.po_kind	= 8b3baed = 2 = 0x02	= 8b3bd85 = 2 = 0x02
po_header.exercise _id	= 8b3baee = 1 = 0x01	= 8b3bd86 = 1 = 0x01
po_header.database _id	= 8b3baef = 1 = 0x01	= 8b3bd87 = 1 = 0x01
po_header.length	= 8b3baf0 = 528 = 0x0210	= 8b3bd88 = 528 = 0x0210
po_header.pdu_count	= 8b3baf2 = 9215 = 0x23ff	= 8b3bd8a = 9216 = 0x2400
do_header.database _sequence_number	= 8b3baf4 = 0 = 0x00000000	= 8b3bd8c = 0 = 0x00000000
do_header.object _id.simulator.site	= 8b3baf8 = 1532 = 0x05fc	= 8b3bd90 = 1532 = 0x05fc
do_header.object _id.simulator.host	= 8b3bafa = 47451 = 0xb95b	= 8b3bd92 = 47451 = 0xb95b
do_header.object _id.object	= 8b3bafc = 2898 = 0x0b52	= 8b3bd94 = 2898 = 0x0b52
do_header.world _state_id. simulator.site	= 8b3bafe = 0 = 0x0000	= 8b3bd96 = 0 = 0x0000
do_header.world _state_id. simulator.host	= 8b3bb00 = 0 = 0x0000	= 8b3bd98 = 0 = 0x0000
do_header.world _state_id.object	= 8b3bb02 = 0 = 0x0000	= 8b3bd9a = 0 = 0x0000
do_header.owner .site	= 8b3bb04 = 1532 = 0x05fc	= 8b3bd9c = 1532 = 0x05fc
do_header.owner .host	= 8b3bb06 = 47451 = 0xb95b	= 8b3bd9e = 47451 = 0xb95b
do_header.sequence _number	= 8b3bb08 = 17 = 0x0011	= 8b3bda0 = 18 = 0x0012
do_header.class	= 8b3bb0a = 19 = 0x13	= 8b3bda2 = 19 = 0x13
do_header.missing _from_world _state	= 8b3bb0b = 0 = 0x00000000	= 8b3bda3 = 0 = 0x00000000
reserved9	= 8b3bb0c = 0 = 0x00000000	= 8b3bda4 = 0 = 0x00000000

fire_parameters .unit.simulator .site	= 8b3bb10 = 1519 = 0x05ef	= 8b3bda8 = 1519 = 0x05ef
fire_parameters .unit.simulator .host	= 8b3bb12 = 47263 = 0xb89f	= 8b3bdaa = 47263 = 0xb89f
fire_parameters .unit.object	= 8b3bb14 = 2726 = 0x0aa6	= 8b3bdac = 2726 = 0x0aa6
fire_parameters .fire_zone[0] .simulator.site	= 8b3bb16 = 0 = 0x0000	= 8b3bdae = 0 = 0x0000
fire_parameters .fire_zone[0] .simulator.host	= 8b3bb18 = 0 = 0x0000	= 8b3bdb0 = 0 = 0x0000
fire_parameters .fire_zone[0] .object	= 8b3bb1a = 0 = 0x0000	= 8b3bdb2 = 0 = 0x0000
fire_parameters .fire_zone[1] .simulator.site	= 8b3bb1c = 0 = 0x0000	= 8b3bdb4 = 0 = 0x0000
fire_parameters .fire_zone[1] .simulator.host	= 8b3bb1e = 0 = 0x0000	= 8b3bdb6 = 0 = 0x0000
fire_parameters .fire_zone[1] .object	= 8b3bb20 = 0 = 0x0000	= 8b3bdb8 = 0 = 0x0000
fire_parameters .fire_zone[2] .simulator.site	= 8b3bb22 = 0 = 0x0000	= 8b3bdba = 0 = 0x0000
fire_parameters .fire_zone[2] .simulator.host	= 8b3bb24 = 0 = 0x0000	= 8b3bdbc = 0 = 0x0000
fire_parameters .fire_zone[2] .object	= 8b3bb26 = 0 = 0x0000	= 8b3bdbe = 0 = 0x0000
fire_parameters .fire_zone[3] .simulator.site	= 8b3bb28 = 0 = 0x0000	= 8b3bdc0 = 0 = 0x0000
fire_parameters .fire_zone[3] .simulator.host	= 8b3bb2a = 0 = 0x0000	= 8b3bdc2 = 0 = 0x0000
fire_parameters .fire_zone[3] .object	= 8b3bb2c = 0 = 0x0000	= 8b3bdc4 = 0 = 0x0000

fire_parameters .fire_zone[4] .simulator.site	= 8b3bb2e = 0 = 0x0000	= 8b3bdc6 = 0 = 0x0000
fire_parameters .fire_zone[4] .simulator.host	= 8b3bb30 = 0 = 0x0000	= 8b3bdc8 = 0 = 0x0000
fire_parameters .fire_zone[4] .object	= 8b3bb32 = 0 = 0x0000	= 8b3bdca = 0 = 0x0000
fire_parameters .fire_zone[5] .simulator.site	= 8b3bb34 = 0 = 0x0000	= 8b3bdcc = 0 = 0x0000
fire_parameters .fire_zone[5] .simulator.host	= 8b3bb36 = 0 = 0x0000	= 8b3bdce = 0 = 0x0000
fire_parameters .fire_zone[5] .object	= 8b3bb38 = 0 = 0x0000	= 8b3bdd0 = 0 = 0x0000
fire_parameters .fire_zone[6] .simulator.site	= 8b3bb3a = 0 = 0x0000	= 8b3bdd2 = 0 = 0x0000
fire_parameters .fire_zone[6] .simulator.host	= 8b3bb3c = 0 = 0x0000	= 8b3bdd4 = 0 = 0x0000
fire_parameters .fire_zone[6] .object	= 8b3bb3e = 0 = 0x0000	= 8b3bdd6 = 0 = 0x0000
fire_parameters .fire_zone[7] .simulator.site	= 8b3bb40 = 0 = 0x0000	= 8b3bdd8 = 0 = 0x0000
fire_parameters .fire_zone[7] .simulator.host	= 8b3bb42 = 0 = 0x0000	= 8b3bdda = 0 = 0x0000
fire_parameters .fire_zone[7] .object	= 8b3bb44 = 0 = 0x0000	= 8b3bddc = 0 = 0x0000
fire_parameters .no_fire_zone[0] .simulator.site	= 8b3bb46 = 0 = 0x0000	= 8b3bdde = 0 = 0x0000
fire_parameters .no_fire_zone[0] .simulator.host	= 8b3bb48 = 0 = 0x0000	= 8b3bde0 = 0 = 0x0000

fire_parameters .no_fire_zone[0] .object	= 8b3bb4a = 0 = 0x0000	= 8b3bde2 = 0 = 0x0000
fire_parameters .no_fire_zone[1] .simulator.site	= 8b3bb4c = 0 = 0x0000	= 8b3bde4 = 0 = 0x0000
fire_parameters .no_fire_zone[1] .simulator.host	= 8b3bb4e = 0 = 0x0000	= 8b3bde6 = 0 = 0x0000
fire_parameters .no_fire_zone[1] .object	= 8b3bb50 = 0 = 0x0000	= 8b3bde8 = 0 = 0x0000
fire_parameters .no_fire_zone[2] .simulator.site	= 8b3bb52 = 0 = 0x0000	= 8b3bdea = 0 = 0x0000
fire_parameters .no_fire_zone[2] .simulator.host	= 8b3bb54 = 0 = 0x0000	= 8b3bdec = 0 = 0x0000
fire_parameters .no_fire_zone[2] .object	= 8b3bb56 = 0 = 0x0000	= 8b3bdee = 0 = 0x0000
fire_parameters .no_fire_zone[3] .simulator.site	= 8b3bb58 = 0 = 0x0000	= 8b3bdf0 = 0 = 0x0000
fire_parameters .no_fire_zone[3] .simulator.host	= 8b3bb5a = 0 = 0x0000	= 8b3bdf2 = 0 = 0x0000
fire_parameters .no_fire_zone[3] .object	= 8b3bb5c = 0 = 0x0000	= 8b3bdf4 = 0 = 0x0000
fire_parameters .no_fire_zone[4] .simulator.site	= 8b3bb5e = 0 = 0x0000	= 8b3bdf6 = 0 = 0x0000
fire_parameters .no_fire_zone[4] .simulator.host	= 8b3bb60 = 0 = 0x0000	= 8b3bdf8 = 0 = 0x0000
fire_parameters .no_fire_zone[4] .object	= 8b3bb62 = 0 = 0x0000	= 8b3bdfa = 0 = 0x0000

fire_parameters .no_fire_zone[5] .simulator.site	= 8b3bb64 = 0 = 0x0000	= 8b3bdfc = 0 = 0x0000
fire_parameters .no_fire_zone[5] .simulator.host	= 8b3bb66 = 0 = 0x0000	= 8b3bdfe = 0 = 0x0000
fire_parameters .no_fire_zone[5] .object	= 8b3bb68 = 0 = 0x0000	= 8b3be00 = 0 = 0x0000
fire_parameters .no_fire_zone[6] .simulator.site	= 8b3bb6a = 0 = 0x0000	= 8b3be02 = 0 = 0x0000
fire_parameters .no_fire_zone[6] .simulator.host	= 8b3bb6c = 0 = 0x0000	= 8b3be04 = 0 = 0x0000
fire_parameters .no_fire_zone[6] .object	= 8b3bb6e = 0 = 0x0000	= 8b3be06 = 0 = 0x0000
fire_parameters .no_fire_zone[7] .simulator.site	= 8b3bb70 = 0 = 0x0000	= 8b3be08 = 0 = 0x0000
fire_parameters .no_fire_zone[7] .simulator.host	= 8b3bb72 = 0 = 0x0000	= 8b3be0a = 0 = 0x0000
fire_parameters .no_fire_zone[7] .object	= 8b3bb74 = 0 = 0x0000	= 8b3be0c = 0 = 0x0000
fire_parameters .fire_cnt	= 8b3bb76 = 0 = 0x0000	= 8b3be0e = 0 = 0x0000
fire_parameters .no_fire_cnt	= 8b3bb78 = 0 = 0x0000	= 8b3be10 = 0 = 0x0000
fire_parameters .method	= 8b3bb7a = 0 = 0x00	= 8b3be12 = 0 = 0x00
fire_parameters .technique	= 8b3bb7b = 0 = 0x00	= 8b3be13 = 0 = 0x00
fire_parameters .permission	= 8b3bb7c = 0 = 0x00	= 8b3be14 = 0 = 0x00

fire_parameters .enemytype	= 8b3bb7d = 0 = 0x00	= 8b3be15 = 0 = 0x00
fire_parameters .launchtype	= 8b3bb7e = 0 = 0x00	= 8b3be16 = 0 = 0x00
fire_parameters .fire_unknown	= 8b3bb7f = 0 = 0x00	= 8b3be17 = 0 = 0x00
fire_parameters .vehicle_def[0] .engagement_range	= 8b3bb80 = 0 = 0x00000000	= 8b3be18 = 0 = 0x00000000
fire_parameters .vehicle_def[0] .ignore_after	= 8b3bb84 = 0 = 0x00000000	= 8b3be1c = 0 = 0x00000000
fire_parameters .vehicle_def[0] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[1] .engagement_range	= 8b3bb98 = 0 = 0x00000000	= 8b3be30 = 0 = 0x00000000
fire_parameters .vehicle_def[1] .ignore_after	= 8b3bb9c = 0 = 0x00000000	= 8b3be34 = 0 = 0x00000000
fire_parameters .vehicle_def[1] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[2] .engagement_range	= 8b3bbb0 = 0 = 0x00000000	= 8b3be48 = 0 = 0x00000000
fire_parameters .vehicle_def[2] .ignore_after	= 8b3bbb4 = 0 = 0x00000000	= 8b3be4c = 0 = 0x00000000
fire_parameters .vehicle_def[2] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[3] .engagement_range	= 8b3bbc8 = 0 = 0x00000000	= 8b3be60 = 0 = 0x00000000
fire_parameters .vehicle_def[3] .ignore_after	= 8b3bbcc = 0 = 0x00000000	= 8b3be64 = 0 = 0x00000000

fire_parameters .vehicle_def[3] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[4] .engagement_range	= 8b3bbe0 = 0 = 0x00000000	= 8b3be78 = 0 = 0x00000000
fire_parameters .vehicle_def[4] .ignore_after	= 8b3bbe4 = 0 = 0x00000000	= 8b3be7c = 0 = 0x00000000
fire_parameters .vehicle_def[4] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[5] .engagement_range	= 8b3bbf8 = 0 = 0x00000000	= 8b3be90 = 0 = 0x00000000
fire_parameters .vehicle_def[5] .ignore_after	= 8b3bbfc = 0 = 0x00000000	= 8b3be94 = 0 = 0x00000000
fire_parameters .vehicle_def[5] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[6] .engagement_range	= 8b3bc10 = 0 = 0x00000000	= 8b3bea8 = 0 = 0x00000000
fire_parameters .vehicle_def[6] .ignore_after	= 8b3bc14 = 0 = 0x00000000	= 8b3beac = 0 = 0x00000000
fire_parameters .vehicle_def[6] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[7] .engagement_range	= 8b3bc28 = 0 = 0x00000000	= 8b3bec0 = 0 = 0x00000000
fire_parameters .vehicle_def[7] .ignore_after	= 8b3bc2c = 0 = 0x00000000	= 8b3bec4 = 0 = 0x00000000
fire_parameters .vehicle_def[7] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000

fire_parameters .vehicle_def[8] .engagement_range	= 8b3bc40 = 0 = 0x00000000	= 8b3bed8 = 0 = 0x00000000
fire_parameters .vehicle_def[8] .ignore_after	= 8b3bc44 = 0 = 0x00000000	= 8b3bedc = 0 = 0x00000000
fire_parameters .vehicle_def[8] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[9] .engagement_range	= 8b3bc58 = 0 = 0x00000000	= 8b3bef0 = 0 = 0x00000000
fire_parameters .vehicle_def[9] .ignore_after	= 8b3bc5c = 0 = 0x00000000	= 8b3bef4 = 0 = 0x00000000
fire_parameters .vehicle_def[9] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[10] .engagement_range	= 8b3bc70 = 0 = 0x00000000	= 8b3bf08 = 0 = 0x00000000
fire_parameters .vehicle_def[10] .ignore_after	= 8b3bc74 = 0 = 0x00000000	= 8b3bf0c = 0 = 0x00000000
fire_parameters .vehicle_def[10] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[11] .engagement_range	= 8b3bc88 = 0 = 0x00000000	= 8b3bf20 = 0 = 0x00000000
fire_parameters .vehicle_def[11] .ignore_after	= 8b3bc8c = 0 = 0x00000000	= 8b3bf24 = 0 = 0x00000000
fire_parameters .vehicle_def[11] .priority	= " " = 0x0000000000000000 0000000000000000	= " " = 0x0000000000000000 0000000000000000
fire_parameters .vehicle_def[12] .engagement_range	= 8b3bca0 = 0 = 0x00000000	= 8b3bf38 = 0 = 0x00000000

fire_parameters .vehicle_def[12] .ignore_after	= 8b3bca4 = 0 = 0x00000000	= 8b3bf3c = 0 = 0x00000000
fire_parameters .vehicle_def[12] .priority	= " " = 0x0000000000000000 00000000000000000	= " " = 0x0000000000000000 00000000000000000
fire_parameters .vehicle_def[13] .engagement_range	= 8b3bcb8 = 0 = 0x00000000	= 8b3bf50 = 0 = 0x00000000
fire_parameters .vehicle_def[13] .ignore_after	= 8b3bcbc = 0 = 0x00000000	= 8b3bf54 = 0 = 0x00000000
fire_parameters .vehicle_def[13] .priority	= " " = 0x0000000000000000 00000000000000000	= " " = 0x0000000000000000 00000000000000000
fire_parameters .vehicle_def[14] .engagement_range	= 8b3bcd0 = 0 = 0x00000000	= 8b3bf68 = 0 = 0x00000000
fire_parameters .vehicle_def[14] .ignore_after	= 8b3bcd4 = 0 = 0x00000000	= 8b3bf6c = 0 = 0x00000000
fire_parameters .vehicle_def[14] .priority	= " " = 0x0000000000000000 00000000000000000	= " " = 0x0000000000000000 00000000000000000
fire_parameters .vehicle_def[15] .engagement_range	= 8b3bce8 = 0 = 0x00000000	= 8b3bf80 = 0 = 0x00000000
fire_parameters .vehicle_def[15] .ignore_after	= 8b3bcec = 0 = 0x00000000	= 8b3bf84 = 0 = 0x00000000
fire_parameters .vehicle_def[15] .priority	= " " = 0x0000000000000000 00000000000000000	= " " = 0x0000000000000000 00000000000000000

The observations and analysis of those PDUs participating in negative spikes lead to the proposal of PDUAlloy, a new way of bundling PDUs that can be seen as a kind of high level of compression because the resulting block still conserves the

characteristics of a PDU, perhaps of a different type, and so it is subject to further compressions. In fact, the proposed bundling does not remove the redundancy within the same PDU: the fields filled with zeros in the basic (reference) PDU will continue being the same length of zeros. Only the redundancy resulting from the similarities between consecutive PDUs is removed. Therefore, other traditional compression mechanisms are recommended after the bundling.

Replication is the converse procedure of bundling. Given a bundled block that arrived to a destination, the individual PDUs have to be extracted or replicated from it. Replication is independent of other data compression techniques because it is targeted at the PDU level and the resulting traffic is of PDU type. Therefore, even if there are no plans to modify the transport protocol in effect (by compressing TCP/IP headers, for instance), the reduction of PDU packets to increment the bandwidth availability by using replication is still applicable.

After running the simulator without using bundling, and collecting performance statistics, it was observed that at 64 Kbps the generator in ground station could not cope with the demanding traffic, and an increasing delay in timeliness to send PDUs at the indicated timestamp started to build up. The proposed solution was to bundle PDUs of the same type and length into longer ones, eliminating redundancy in similar fields, as explained in the following section.

3.4.1 Mathematical Description of Bundling: PDUAlloy

The following definition is named *PDUAlloy Bundling* in this dissertation, and is the base for the PDUAlloy algorithm of Section 4.4.

Given a set $N = \{1, 2, \ldots, n\}$ of indexes and two consecutive PDUs $A = (a_1, a_2, \ldots, a_n)$ and $B = (b_1, b_2, \ldots, b_n)$, where A and B are of the same type

and the a_i and b_i represent PDU fields, and a subset $S \subseteq N$ such that $a_i = b_i$ for all $i \in S$, then the bundle of A and B is defined as the PDU $A\&B = (a_1, a_2, \ldots, a_n, ((b_j, j)_{j \in N \setminus S}))$. A is called the *base* PDU in the bundle. The definition can be extended to any number of PDUs.

Example:

Given the PDUs: $A = (a_1, a_2, a_3, a_4)$, $B = (b_1, b_2, b_3, b_4)$, and $C = (c_1, c_2, c_3, c_4)$, such that $a_2 = b_2 = c_2$, $a_3 = b_3, a_4 = c_4$, then the bundle $A\&B\&C$ is the new PDU

$A\&B\&C = (a_1, a_2, a_3, a_4, ((b_1, 1), (b_4, 4)), ((c_1, 1), (c_3, 3)))$

From the information contained in the shown n-tuple it is possible to reconstruct the original PDUs A, B and C. Each component (b_j, j) indicates that the value b_j replaces the field j in the base PDU. In a practical implementation, j could be a pointer or an offset into the base PDU.

The above bundle will be called PDUAlloy because it acts like a metal alloy, bundling PDUs based on their internal structure. It differs from other proposals in several ways. First, the resulting bundle conserves the basic characteristics of any other PDU and therefore, can be considered a new type of PDU subject to further bundling and/or compression algorithms. In [BCL97] consecutive PDUs are concatenated in a single packet even if their types are different, and field redundancy is not eliminated. A delta-PDU encoding technique is mentioned in [US95a] consisting of PDUs that carry changes respect to a reference PDU initially given. In [WMS01] several bundling techniques generally applicable to Web pages under the TCP/IP protocol suite are described, but none is specific to the DIS protocol. A protocol called DIS-Lite developed by MäK Technologies [Tay95, Tay96b, Tay96a, PW98] splits the Entity State PDU into static and dynamic data PDUs, so that the static information is sent once and the changes (dynamic

PDUs) are subsequently sent as separate PDUs. According to [Ful96] by eliminating redundancy, DIS-Lite can perform between 30 % and 70 % more efficiently than DIS. DIS-Lite includes also several other improvements not related to the combination of individual fields from a set of similar PDUs.

3.4.2 Implementation of PDU Bundling in the Simulator

After analyzing all of the PDUs in the log file for a given vignette, it was observed that the type and the size of a PDU completely determine its internal field structure. In other words, if PDUs $A = (a_1, a_2, a_3, \ldots, a_n)$ and $B = (b_1, b_2, \ldots, b_m)$ are such that $type(A) = type(B)$ and $length(A) = length(B)$, then $n = m$ and $field\_type(a_i) = field\_type(b_i)$ for all $1 \leq i \leq n$, assuming that *type*, *length* and *field_type* are functions that return the type, the length in bytes, and the field type of a PDU, respectively. If two PDUs are of the same type and length, they are called *compatibles* and are candidates to be bundled.

The basic idea behind PDU bundling is that if consecutive PDUs of the same type and length are scheduled within a predefined short time interval, then they can be bundled and delivered as a single packet.

The pseudo-algorithm of PDU bundling is described as follows:

1. Wait until next PDU is ready for delivery. Let A be that PDU.
2. $bundling = A$. This is the first PDU (called base PDU) in the bundling.
3. Set $timeout$ = maximum time A will wait in the bundle.
4. While ($timeout$ not expired){

   If next PDU is ready for delivery, let B be that PDU,
   otherwise repeat the while-loop;

If A and B are compatible PDUs

$\{bundling = bundling \,\&\, B;\ B = \emptyset;\}$

else break the while-loop$\}$

5. Send *bundling* PDUs through the network as a single packet.

6. If $B = \emptyset$ then repeat from step 1) else $A = B$ and repeat from step 2).

This algorithm is called the *Always-Wait* algorithm because after processing a PDU, the algorithm waits for the next one unless a timeout is detected. When the next PDU is obtained, its type is checked and if it is different from the type of the base PDU, the base PDU is sent and the time waited was wasted. It seems that if there were a way to predict the type and length, or at least the type, of the next PDU and the prediction indicates a type different form the type of the current base PDU, then the current bundle could be sent immediately, saving the waiting time. So, in the next paragraphs a variation of the above algorithm is introduced.

3.4.2.1 PDU Type prediction using a Neural Network

One way to predict the next PDU based on the recent history is by using a neural network (NN) approach. A NN can learn sequences of PDU patterns and use them as a basis for predicting the incoming type. In this research, we set up a gradient descent NN that predicts the next type based on the types of the previous 48 PDUs. Inorder not to complicate the simulator logic, the NN procedure was run offline, and the results were incorporated into the PDU summary file. The NN predicted the next PDU type with a certainty of near 70 %. Considering that there are near 27 different PDU types, the percentage is meaningful. If the NN prediction indicates that the next PDU type is the same as the current one, a w (for *wait*) character is appended offline to the summary file, otherwise an s (for *send*) is appended.

Due to the fact that the summary PDU files do not include the actual PDU fields, it is impossible to determine the bundling resulting from two PDUs of the same type and length because their fields cannot be compared and their differences cannot be established. In this research, the comparison took place offline in the pre-process stage using actual PDU fields, which resulted in three *perfect prediction* offline methods, additionally to the in line neural network prediction. The perfect prediction methods calculate the next PDU type with 100 % certainty because they know all the sequence of PDUs in advance.

The first perfect prediction method considers the PDU *type* only, the second one considers the *type-and-length*, and the last one considers the *type-length-and-time*. Given any PDU, if the next one can be bundled to it because its type (method 1), and length (method 2), and timestamp (method 3) are equal, a W character (meaning *wait*) is appended to the description of the current PDU in the summary file, otherwise an S (*send*) is appended.

Figure 19 in Chapter 5 shows four characters at the end of each line containing the S and W letters. The first character corresponds to the neural network prediction and the rest correspond to each one of the perfect prediction methods. Only one character is processed per run by the simulator and the `omnetpp.ini` file has been set up to include the prediction method desired in each run.

Additionally to the four predictive methods already described, there are two other ones called *Always-Wait* and *Always-Send*, obtained by assuming that one column is filled all with either w or s characters, respectively.

Figure 17 shows the general algorithm used by each generator for sending PDUs to the network. The abbreviations used in the figure are:

EOF end of file

bwt block waiting time, delayed incurred due to bundling

gt gap time, minimum separation between packets

rts ready-to-send message (future OMNeT event)

tt transmission time

$\emptyset$ empty set

The generator is activated when it receives one of two possible messages from the OMNeT kernel:

BlockTimeout: indicates that the oldest PDU in the current bundle has timed out (bwt has elapsed), and therefore the generator must send it as soon as possible, which means that if the generator is idle, the bundle can be sent immediately, but if it is busy transmitting an older packet, then the current bundle has to wait for the end of that transmission plus the gap time.

ReadyToSend (rts): indicates that the generator is not transmitting and is ready to send a block that has timed out, or to get the next PDU from the summary file. If during reading the next PDU the EOF condition arises, The the current block of bundled PDUs is examined. If the block is empty, the generator stops, otherwise it sets the conditions to proceed to send the bundle.

If a new PDU is successfully retrieved form the summary file, the generator calculates its slack time. If the slack is positive, the generator schedules an rts to be awaken at the PDU timestamp. If the slack is negative, the generator is behind the schedule and proceeds to bundle the PDU to previous PDUs already bundled, or to initiate a new bundle, or to send the current bundle which is not compatible with this PDU and create a new bundle starting with this PDU. In any case, the prediction character (W or S) is read and the generator acts accordingly, either keeping the bundle in case of W, or sending it in case of S.

If a bundle is performed, some time should be spent in the bundle operation itself. In other words, it is not possible to process a PDU (read it and bundle it) in zero time. Each *schedule ready-to-send* operation (`Sched rts`) includes some minimum time ($5\mu s$) for the bundle operation. This time could be considered as *generator service time*. The busy time is then computed as the transmission time(tt), plus the gap time (gt), plus any generator service time if a bundling operation is carried out.

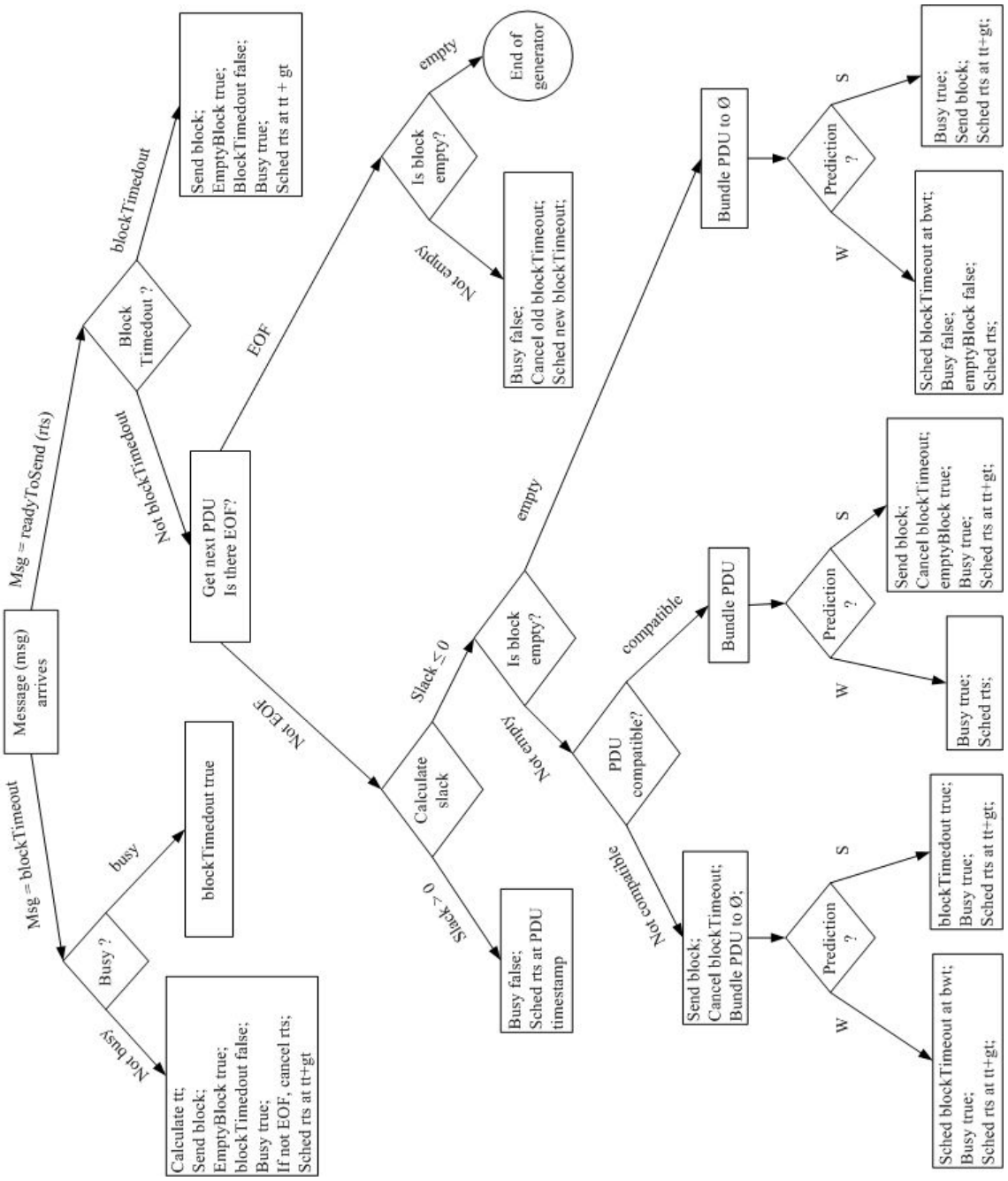


Figure 17: Decision tree of the algorithm used by generators for sending PDUs to the network

CHAPTER 4

ACTIVE BUNDLING STRATEGIES

Bundling strategies are confronted with the decision of waiting for the next packet to arrive and bundle it to the current block, or sending the current block and start a new collection of packets from scratch. This type of decisions are typical of online and offline algorithms.

4.1 Offline Bundling

Given a sequence σ of input data, in which the decision of processing each individual data element applying one of several possible actions is taken with complete knowledge of the whole sequence σ, constitutes an offline algorithm. Applied to the network packets, each frame, message or PDU is an element of the sequence, and the possible actions are bundling the incoming packet to the current block, or sending the current block and start a new block. Because offline algorithms know the complete packet sequence at the decision time, including the future packet sequence, the best offline algorithm must take the optimal decision. A decision is optimal if it minimizes some cost function. In the transmission of network packets, the cost function could be the total latency time incurred by all the packets sent from the origin to the final destination. Another cost function could be the absolute value of the sum of all negative slack times when the PDUs are sent.

Symbolically, given a sequence $\sigma = \{PDU_i\}_{i=1,\ldots,n}$ of PDUs, where each packet i is released and stamped at time $Tstamp_i$, and arrives at the final destination at time $Tarr_i$, then the cost function for the total latency of the travel time is:

$$C_{Ttrav}(\sigma) = \sum_{i=1}^{n} (Tarr_i - Tstamp_i) \tag{4.1}$$

Similarly, if the simulator is reading PDUs from a summary log file, and each PDU_i is read for the first time at time $Tread_i$, the cost function that measures the absolute value of the total negative slack time is:

$$C_{Tslack}(\sigma) = \sum_{i=1}^{n} H(Tread_i - Tstamp_i)(Tstamp_i - Tread_i) \tag{4.2}$$

where H represents the Heaviside step function, $H(x) = 1$ if $x > 0,\ 0$ otherwise, used to select only the negative slacks.

Offline algorithms are useful in many other computer-related areas. Most of the database algorithms like sorting and searching files are offline. A recent example of an offline algorithm for compressing data is given by Turpin in [TS02].

Offline algorithms are not supposed to be implemented in an actual real-time simulation because obviously the messages to be produced in future times are not known at the present simulation time. In simulation, the main application of offline algorithms lies in the possibility of comparing them to the corresponding online counterparts, with the purpose of asses online performances. A measure of comparison of performance for online algorithms is the *competitive ratio*. A competitive ratio of $t > 0$ means that the performance of an online algorithm is at least a factor of $1/t$ of the performance achieved by the best offline algorithm. This will be expanded in the next section.

Offline bundling is the process of taking decisions about to bundle or not consecutive packets. Considering that after one packet has been sent, a certain

minimum time gap must elapse before sending the next packet, then the decision is not trivial. If the first packet is sent immediately, the second one could be delayed more than if the two packets are sent in a single bundle. This decisions are referred to as the *Packet Bundling Problem* [FL02].

In the case of the OTB simulation, the offline bundling is carried out taking as input the PDU log files produced by the OTB simulator, and not only the time gaps, but also the type and the length of the PDUs are considered.

4.2 Online Bundling

General online and offline algorithms have been studied in the literature for a long time [Kar92, FL02, FLN03, GHP03]. Karp defines these algorithms in the following way.

> An on-line algorithm is one that receives a sequence of requests and performs an immediate action in response to each request. On-line algorithms arise in any situation where decisions must be made and resources allocated without knowledge of the future. The effectiveness of an on-line algorithm may be measured by its *competitive ratio*, defined as the worst-case ratio between its cost and that of a hypothetical off-line algorithm which knows the entire sequence of requests in advance and chooses its actions optimally (with minimum cost)[Kar92].

Online algorithms are characterized by a lack of knowledge about the future. Phillips [PW99] indicates that the online algorithm receives each input and must process it immediately, serving the sequence of requests one item at a time without having explicit knowledge of the following inputs.

The performance of online deterministic algorithms is measured by its competitive ratio when compared with the optimal offline algorithm. Ambühl [AGS01] defines this ratio in the following way. If σ is any input sequence, $A(\sigma)$ represents the cost function of an online algorithm A, and $OPT(\sigma)$ is the corresponding cost function of the optimal offline algorithm OPT, then A is called c-competitive for a constant c if there exists a real number a such that for all input sequences σ, it is true that:

$$A(\sigma) \leq c \cdot OPT(\sigma) + a \tag{4.3}$$

If $a = 0$, then A is called strictly c-competitive. If A is a randomized algorithm, equation 4.4 becomes:

$$E[A(\sigma)] \leq c \cdot OPT(\sigma) + a \tag{4.4}$$

where $E[A(\sigma)]$ represents the expected cost of algorithm A on the sequence σ.

The competitive ratio of an algorithm is defined as the infimum over all real numbers c such that the algorithm is c-competitive [FLN03, GIS03].

4.3 Characteristics of Embedded Simulation Traffic Impacting Bundling

Several characteristics of the Embedded Simulation traffic are to be considered for bundling purposes. The discussion here applies to PDUs generated under the DIS protocol, although many of them are general enough to be valid under other protocols as well.

4.3.1 The Simulation is a Real-Time Application

During the Embedded Simulation, the participants interact with each other in real time. If one tank fires, or starts moving, or decelerates, all the other entities should be informed of the event as soon as possible. This characteristic impacts bundling in several aspects. First, the time a PDU waits for the upcoming PDU creates a delay against the meaning of real time. Therefore, a small timeout should be introduce to limit that waiting time. Second, not bundling PDUs could cause that the following PDU will be delayed even more, due to the gap time that must separate frames. Also, not bundling produces more traffic and longer router queues, which finally goes in detriment of the real time properties.

The decision of bundling PDUs must consider the pros and cons of each alternative. It is possible that for some environments bundling is not a necessity, for example a scenario in which few sites are simulating a simple vignette, connected in a LAN, not requiring a router.

4.3.2 There Is a High Percentage of ESPDUs

It is well documented that ES traffic contains 70% or more of Entity State PDUs. Usually these ESPDUs are redundant and not urgent. For example, if a vehicle is not moving, it still needs to send heartbeat ESPDUs at regular intervals. ESPDUs are less harmed by waiting to be bundled than other PDUs of higher priority. Because they are so abundant, bundling and compressing ESPDUs have a major impact on the overall traffic decrease. However, in this research ESPDUs were not bundled in the majority of cases because they did not participated in negative spikes as bursts of consecutive ones, as `po_fire_parameters` did.

4.3.3 There Is a Low Percentage of High Priority PDUs

Some high priority PDUs like fire and detonation occur in short bursts, but they are usually sent at the same time, creating negative slack spikes that attempt against the real time approach. If the bundling operation is not time-consuming and the waiting timeout is selected appropriately, bundling a sequence of consecutive PDU and sending a single block could take less time than sending the individual PDUs without bundling them. For instance, if a PDU is 512 bytes long and the bandwidth is 64 Kbps, the transmission time of one single PDU is 64 milliseconds, while bundling several PDUs could take less than one millisecond.

4.3.4 High Levels of Redundancy

PDUs contain lots of redundancy, both inside each PDU and across PDUs. As a sample, the PDUs listed in Table 2 contain zeroes in the majority of fields, and just two differences from one PDU to the other. Bundling and compression can take advantage of this high redundancy. For example, the proposed algorithm PDUAlloy would append only the two fields containing the differences in the second PDU of the table to the first one. Other bundling algorithms also profit from this redundancy, like those based on sending delta PDUs.

4.3.5 PDU Internal Structure

PDUs have a definite structure made up of fields of different sizes, that are determined by the type and length of the PDUs. This characteristic allows the comparison of PDUs at the field level, which facilitates the extraction of the

differences. Determination of the PDU structure based on the type and the length allows a fast comparison among PDUs for algorithms like PDUAlloy.,

4.3.6 PDUs Are Broadcasted

In the DIS protocol, PDUs are broadcasted. This characteristic simplifies the PDU header since a particular destination is not needed. All the PDUs in a bundle are to be delivered to the same recipients.

4.3.7 Slow Connections Favor Bundling

The slower the connections, the better the bundling. If a connection is slow, bundling and compression becomes more necessary. In slow connections, gap times are larger, and so the penalty for not bundling the next PDU. Also, a slow bandwidth shows more negative slack times during transmission, causing bottlenecks and long queues. As an example, in the MR1 vignette the satellite connection introduces a propagation delay of about 0.25 seconds, much higher than the time gap required to separate frames during transmission. Therefore, bundling of high priority PDUs like `po_fire_parameters` is worth.

4.3.8 PDU Bursts Scheduled at Once

Bursts of PDUs timestamped at the same or almost the same time encourages bundling, because not doing it causes a large negative slack spike, or bottleneck, at the transmitting site that delays the following PDUs.

4.4 PDUAlloy Bundling Model

The proposal of the algorithm PDUAlloy involves decisions about to bundle or not two consecutive PDUs. Three variables can be considered in this algorithm: the type, the length and the timestamp of each PDU. Observations taken from PDUs participating in negative spikes indicate that if the type and the length of consecutive PDUs are the same, they are compatible and can be bundled according to the definition in Section 3.4.1.

4.4.1 Overview

The online algorithms proposed try to identify compatible PDUs P_1 and P_2 that can be bundled in a block $B = P_1 \& P_2$. A requirement is that the two PDUs should have the same type and length. But because P_2 has not arrived by the time P_1 is being processed, the generating site must decide whether it will send P_1 immediately, or wait for P_2. Chances are that P_2 will not be compatible with P_1. If the generator could predict the type and the length of P_2, then the prediction could be used in the decision process. It is more difficult to predict both, type and length, than only one variable. For decisions based on one variable only, the type is preferred because it discriminates better among PDUs.

A neural network approach was used to predict the type only, as indicated in Section 3.4.2.1. Besides that, other non-predictive online algorithms were proposed: *Always-Wait* and *Always-Send*. The former takes the decision of wait all the time, using a timeout of 100 milliseconds, much less than the 0.25 second delay of the satellite link. The latter never waits. It sends the PDU as soon as the time gap has elapsed, actually not bundling PDUs.

Considering the functions:

$$\begin{aligned} &type(PDU) \\ &length(PDU) \\ &timestamp(PDU) \\ &compatible(PDU_1, PDU_2) \end{aligned} \tag{4.5}$$

that return the type, length and timestamp of any PDU, as well as the true value of PDU compatibility, respectively, then three offline bundling algorithms can be defined: *Type*, *Type+Length* and *Type+Length+Time*, as explained next.

4.4.2 Type

If $(P_i)_{i=1...n}$ is the sequence of PDUs to be transmitted from some site, then the *Type* offline algorithm takes its bundling decision based on the type of the PDUs. Using the notation of Section 3.4.1, if the block B already contains some PDUs, being P_k the first one (base PDU), then P_j will be bundled: $B = B\&P_j$ if $type(P_j) = type(P_k)$ and $compatible(P_j, P_k)$ is true.

In words, if the two PDUs bear the same type, then their compatibility is analyzed, and if a successful comparison results, they are bundled.

4.4.3 Type+Length

The *Type+Length* offline algorithm takes its bundling decision based on the type and length of the PDUs. Given the sequence $(P_i)_{i=1...n}$ of PDUs, and assuming the the block B contains the base PDU P_k, then a new PDU P_j will be bundled in

the sense of $B = B\&P_j$ if $type(P_j) = type(P_k)$, and $length(P_j) = length(P_k)$ and $compatible(P_j, P_k)$ is true.

In words, if the two PDUs bear the same type and length, then their compatibility is analyzed, and if a successful comparison results, they are bundled.

4.4.4 Type+Length+Time

This last algorithm called *Type+Length+Time* is similar to the previous ones, except that it includes an extra condition for bundling: $timestamp(P_j) = timestamp(P_k)$. The condition looks very restrictive because it asks for an exact match of timestamp in both PDUs. If two PDUs were scheduled with a time difference of one single nanosecond, the offline algorithm will not bundle them. In practice, it has been observed hundreds of PDUs scheduled exactly at the same time. Therefore, the purpose of this algorithm is to evaluate the impact of bundling just those PDUs.

CHAPTER 5

EMBEDDED SIMULATION TRAFFIC ANALYSIS

5.1 Processing Flow and Sequencing

The simulator was run on data collected from several vignettes. Initially, a vignette developed by Hubert Bahr for his PhD research under the advice of Dr. Ronald DeMara was used. This vignette contained PDUs sent by one single entity.

A second simulation was run on a vignette containing two senders. Because of its simplicity, this vignette, as well as the previous one, were used mainly to test the simulator and to have some insight about the preprocessing that had to be performed on the input data previous to the simulation phase.

The most important results in this research come from the MR1 vignette described in Appendix A, which includes 6 senders. Four sets of simulations were performed on it, varying the assignment of senders to computer nodes. Additionally, simulations were run to observe the effect of applying PDU bundling, as well as the usage of the Head of Line (HOL) priority in router queues.

5.2 Input Data and AWK preprocessing

The input data to this model comes from the OTB logger. After setting up a particular vignette, OTB runs it and the logger records all the Protocol Data

Units into an output file that is later converted to ASCII text. OTB does not generate regular PDUs, but Persistent Object PDUs (PO_PDUs) that are a subclass of the general category of PDUs. PDU formats are defined in the IEEE Standards [IEE95a], [IEE95b], [IEE96] and [IEE98]. Although PO_PDUs have a somewhat different format as compared to regular PDUs, a considerable degree of similarity exists that allows the application of the IEEE standards to PO_PDUs in order to extract information about the type, length and timestamp of each message.

The raw data collected by the OTB logger is not directly used as input to the simulator due to the large size of the file (265 Mb for the MR1 vignette) and to the amounts of data stored therein, which are unnecessary for the simulation. The log is an ASCII file containing the descriptions of all the transmitted PO_PDUs. Figures 20 and 21 display samples of the raw log.

When OTB ends processing the vignette, an awk program (see Appendix C) parses the ASCII file and collects only those PDU variables required during the simulation (type, length and timestamp) into a summary PDU file, along with two newly created counters. One counter represents a local PDU ID for the generating site, and the other is a global ID from among all the participating sites.

The OTB logger does not save PDUs in strict ascending order of timestamp within the input files. In the logged files collected from running the vignettes there were found sequences of 40 or more PDUs bearing exactly the same timestamp, as well as cases of PDUs stored in reverse chronological order. Due to these anomalies, the PDU files are sorted chronologically previous to running the awk program that assigns the local and global IDs, keeping the original relative order for records having the same timestamp. Figure 18 depicts a general view of the steps involved in the simulation process.

The awk parser creates a separate file for each different transmitting site found, and names it `data`n`.txt`, where n is the site ID. Each `data`n`.txt` file contains

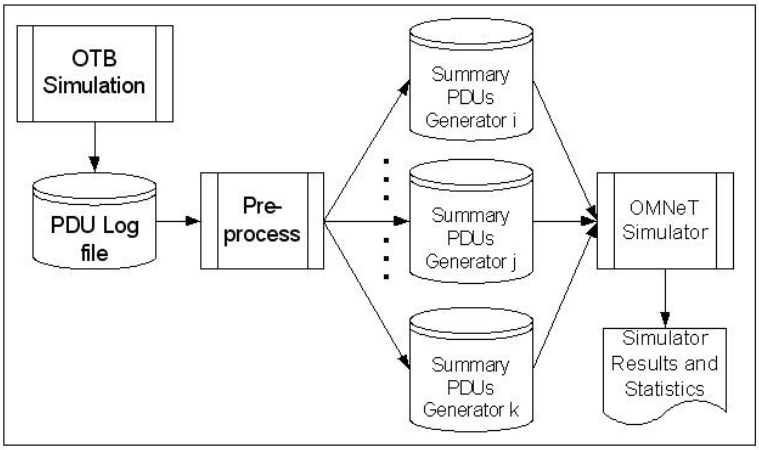


Figure 18: Overview of the simulation process

summaries of all the PDUs generated by site n. Then, during the simulation, each generator n reads in the corresponding PDU summary file `data`n`.txt` created out of OTB logged data. A sample of the resulting files `data`n`.txt` is shown in Figure 19.

The information listed in Figure 19 is interpreted as follows from left to right: hexadecimal timestamp, PDU length in bytes, separator "—", decimal timestamp, local PDU ID equivalent to the current position of the PDU within the file, PDU type surrounded by angle brackets, global PDU ID, and the four letters S and W already explained in Section 3.4.2.1.

In the DIS protocol timestamps are stored in 32 bits. In order to convert timestamps into decimal, each unit of the unsigned integer value stored in the leftmost 31 bits represents $1/(2^{31}-1)$ of an hour, giving the timestamp a resolution of less than 0.5 nanoseconds. The rightmost bit of the timestamp is a flag that indicates whether the time is relative to an arbitrary initial time, or absolute (UTC time). For example, the value in the hex timestamp 0x4f690c7a corresponds to $4f690c7a/2 = 27B4863D = 666142269$ units in decimal, and $666142269/(2^{31}-1) = 0.31019666$ hours $=: 18 : 36.707$, as indicated in the sample file of Figure 19.

```
0x4f690c7a  32|:18:36.707  1 <dis204 acknowledge PDU>:             41 s W W S
0x4f7ab058  32|:18:37.676  2 <dis204 acknowledge PDU>:             73 s W W S
0x4f8ca818  32|:18:38.663  3 <dis204 acknowledge PDU>:            112 s S S S
0x4ffc8a88  92|:18:44.809  4 <dis204 po_simulator_present PDU>:  310 s S S S
0x513da63a 100|:19:02.448  5 <dis204 po_objects_present PDU>:    977 s S S S
0x51752798  92|:19:05.497  6 <dis204 po_simulator_present PDU>: 1084 s W W S
0x531629f4  92|:19:28.404  7 <dis204 po_simulator_present PDU>: 1687 s S S S
0x53617074 100|:19:32.539  8 <dis204 po_objects_present PDU>:   1868 s S S S
0x548db8ba  92|:19:49.034  9 <dis204 po_simulator_present PDU>: 2365 s S S S
0x558cfbfa 100|:20:03.056 10 <dis204 po_objects_present PDU>:   2805 s S S S
0x55fe2df6  92|:20:09.274 11 <dis204 po_simulator_present PDU>: 3000 s W W S
0x57a315a2  92|:20:32.395 12 <dis204 po_simulator_present PDU>: 3717 s S S S
0x57b565ee 100|:20:33.401 13 <dis204 po_objects_present PDU>:   3768 s S S S
0x5917877a  92|:20:52.854 14 <dis204 po_simulator_present PDU>: 4393 s S S S
0x59e1a736 100|:21:03.957 15 <dis204 po_objects_present PDU>:   4721 s S S S
0x5a8738fc  92|:21:13.052 16 <dis204 po_simulator_present PDU>: 5039 s W W S
0x5c357768  92|:21:36.686 17 <dis204 po_simulator_present PDU>: 5728 s S S S
0x5c357768 100|:21:36.686 18 <dis204 po_objects_present PDU>:   5729 s S S S
0x5ca513f0  84|:21:42.817 19 <dis204 po_point PDU>:             5972 w W W W
0x5ca513f0  84|:21:42.817 20 <dis204 po_point PDU>:             5973 w W W W
0x5ca513f0  84|:21:42.817 21 <dis204 po_point PDU>:             5974 w W W W
0x5ca513f0  84|:21:42.817 22 <dis204 po_point PDU>:             5975 w S S S
```

Figure 19: Sample of the contents of files `data`*n*`.txt`

PDU lengths vary widely, as seen in the sample of Figure 19. In the studied vignettes, the minimum PDU length found is 26 bytes, the maximum is 1368, with an average of 211 bytes. The sample also shows the last four PDUs bearing the same timestamp and type, which makes them compatible for bundling.

5.2.1 Example PDU 1

As a first example of a complete PDU, Figure 20 lists the ASCII equivalent of the fields in a `po_variable` PDU. From among all the fields, the most important to the simulator are those containing the site identification, the length in bytes and the timestamp. The example shows `do_header.object_id.simulator.site = 1082`, `po_header.length = 147` bytes, and `dis_header.timestamp = :01:33.432` (1 minute, 33 seconds and 432 milliseconds). The timestamp represents the time the entity generated this PDU and put it on the output queue.

```
<dis204 po_variable PDU>:
dis_header.version = 853cfb0 = 4 = 0x04
dis_header.exercise = 853cfb1 = 1 = 0x01
dis_header.kind = 853cfb2 = 250 = 0xfa
dis_header.family = 853cfb3 = 140 = 0x8c
dis_header.timestamp = 0x6a4e556 = :01:33.432 (relative)
dis_header.sizeof = 853cfb8 = 196 = 0x00c4
po_header.po_version = 853cfbc = 28 = 0x1c
po_header.po_kind = 853cfbd = 2 = 0x02
po_header.exercise_id = 853cfbe = 1 = 0x01
po_header.database_id = 853cfbf = 1 = 0x01
po_header.length = 853cfc0 = 147 = 0x0093
po_header.pdu_count = 853cfc2 = 7905 = 0x1ee1
do_header.database_sequence_number = 853cfc4 = 0 = 0x00000000
do_header.object_id.simulator.site = 853cfc8 = 1082 = 0x043a
do_header.object_id.simulator.host = 853cfca = 23825 = 0x5d11
do_header.object_id.object = 853cfcc = 685 = 0x02ad
do_header.world_state_id.simulator.site = 853cfce = 0 = 0x0000
do_header.world_state_id.simulator.host = 853cfd0 = 0 = 0x0000
do_header.world_state_id.object = 853cfd2 = 0 = 0x0000
do_header.owner.site = 853cfd4 = 1082 = 0x043a
do_header.owner.host = 853cfd6 = 23825 = 0x5d11
do_header.sequence_number = 853cfd8 = 1 = 0x0001
do_header.class = 853cfda = 11 = 0x0b
do_header.missing_from_world_state = 853cfdb = 0 = 0x00000000
reserved9 = 853cfdc = 0 = 0x00000000
variable.total_length = 853cfe0 = 132 = 0x00000084
variable.expanded_length = 853cfe4 = 7812 = 0x00001e84
variable.offset = 853cfe8 = 0 = 0x00000000
variable.length = 853cfec = 132 = 0x0084
variable.obj_class = 853cfee = 8 = 0x08
variable.data = "Mine Pallet US M75"
```

Figure 20: Complete PDU of type `po_variable`

Obviously, the actual PDUs transmitted by OTB are not in ASCII code, but in binary format. This research had no access to the binary data because all material related to PO_PDUs is classified. Therefore, some internal aspects of the PO_PDU format were assumed as being similar to the PDUs described in the IEEE standards. For example, the type of PDU displayed in this example is `po_variable`, as seen in its first line. It is not displayed in the usual format `field = value`, but the IEEE standard 1278.1 [IEE95a] indicates that the binary format is prefixed by a PDU header containing its type, among other variables, and so it was assumed by the awk parser that this first line represents a field in the header containing the PDU type.

Other assumptions include the length and format of some variable fields, which are undocumented in the IEEE standards and whose length in ASCII characters differs from their length in hexadecimal representation. A C++ parser written

specifically to compare PDUs and calculate their differences, listed in Appendix C, assumed the hexadecimal length in this situation.

5.2.2 Example PDU 2

The second example of a short PDU is shown in Figure 21. As before, the parameters `originating_id.site = 1086, header.sizeof = 32`, and `header.timestamp = :00:35.003` are extracted by the awk parser and stored in the summary file. As an observation, this is an acknowledge PDU, which does not contain the `length` keyword, but the `sizeof` keyword.

```
<dis204 acknowledge PDU>:
header.version = 8576c78 = 4 = 0x04
header.exercise = 8576c79 = 1 = 0x01
header.kind = 8576c7a = 15 = 0x0f
header.family = 8576c7b = 5 = 0x05
header.timestamp = 0x27d3a76 = :00:35.003 (relative)
header.sizeof = 8576c80 = 32 = 0x0020
originating_id.site = 8576c84 = 1086 = 0x043e
originating_id.application = 8576c86 = 23825 = 0x5d11
originating_id.entity = 8576c88 = 65535 = 0xffff
receiving_id.site = 8576c8a = 1086 = 0x043e
receiving_id.application = 8576c8c = 23825 = 0x5d11
receiving_id.entity = 8576c8e = 65535 = 0xffff
ack_flag = 8576c90 = 3 = 0x0003
response_flag = 8576c92 = 0 = 0x0000
request_id = 8576c94 = 3 = 0x00000003
```

Figure 21: Short PDU of type *acknowledge*

The entries in the summary file corresponding to the PDUs shown in Figures 20 and 21 are:

1. `0x6a4e556 147 | :01:33.432 1 <dis204 po_variable PDU>:  1`

2. `0x27d3a76 32 | :00:35.003 122 <dis204 acknowledge PDU>:  344`

5.3 Parameters Analyzed

For each experiment, two types of analyses were performed. The first one can be called *independent* or *offline* because it takes place before running the simulator. The second one corresponds to the results obtained by running the simulator.

5.3.1 Independent Analysis

This analysis is subdivided into 2 categories: distribution and assignment of PDUs, and minimum bandwidth requirements.

5.3.1.1 Distribution and Assignment of PDUs

This is a frequency distribution of all the types of PDUs involved in the experiment, as well as the assignment of computer sites mentioned in the PDUs to simulated generators in computer nodes. The distribution gives information about the sites with more activity that can be taken into account for a better strategic assignment to computer nodes.

5.3.1.2 Minimum Bandwidth Requirements

An awk program was written to merge the PDUs of all the sites in one single stream of data sorted according to their timestamps. Then, another program calculates the required bandwidth at specific time intervals (2 seconds) without performing any simulation. Computing the bandwidth based on a single data stream is justified by the fact that all PDUs are broadcasted, and so any listening site will

have to receive the PDUs from all the generating sites as one single stream of data. Due to traffic changes in time, different minimum *instant* bandwidths over time are required. Instant bandwidth is computed as the ratio of volume of data transmitted to the time interval allotted among consecutive PDUs. No overheads like retransmissions, packet losses, or collisions are considered in the calculation of the bandwidth. However, a time gap separation of 50 microseconds between consecutive PDUs was included in accordance with the IEEE Std. 802.11 [IEE97]. Therefore, the resulting minimum bandwidth should be seen as an absolute lower bound for the actual bandwidth. The awk script in Section C.2 of Appendix C calculates the bandwidth for each set of PDUs.

The mathematical definition of the minimum instant bandwidth concept follows. Let all the PDUs in the simulation be sorted in ascending order of timestamp and numbered PDU_1, ..., PDU_n. The length in bytes and the timestamp in seconds of PDU_i are represented, respectively, by L_i and T_i. Let g be the minimum separating time gap between PDUs. The minimum instant bandwidth is defined for those time intervals of minimum length greater than or equal to S seconds, delimited by timestamps T_i that meet some conditions. Specifically, given a pair of timestamps T_a and T_b as close as possible to each other such that the following conditions hold:

$$T_b - T_a \geq S \tag{5.1}$$

$$T_b - T_i - (b-i)g > 0, \qquad \forall\, i:\ a \leq i < b \tag{5.2}$$

then, the average bandwidth B_i for the time subinterval $[T_i - T_b)$ is calculated as:

$$B_i = \frac{\sum_{j=i}^{b-1} 8L_j}{T_b - T_i - (b-i)g} \tag{5.3}$$

and the minimum instant bandwidth for the interval $[T_a, T_b]$ is given by:

$$B = \max_{a \leq i < b} \{B_i\} \tag{5.4}$$

It should be noted that the time interval $[T_i - T_b)$ includes PDU_i and does not include PDU_b. Equation 5.1 indicates that the time interval must have a minimum length of S seconds, for a given constant S selected a priori. Equation 5.2 says that the remaining time from T_i to T_b should be enough to accommodate all the gaps between PDUs and still have some room for the transmission of bytes. The average bandwidth for the interval $[T_i - T_b)$ is the ratio of the total number of bits transmitted to the remaining time in the interval once the gaps have been deducted, as stated in Equation 5.3. Finally, given that the bandwidth for the whole interval $[T_a, T_b]$ is constant, it should not be less than any individual average bandwidth B_i. Therefore, Equation 5.4 takes the maximum of all the B_i and considers it the minimum bandwidth required.

5.3.2 Analysis of Simulation Results

This analysis is subdivided into 4 categories:

a) Slack Time Analysis. Statistics about the slack time of all the PDUs generated at a particular site are graphed and discussed. The slack time *Tslack* of a given PDU is defined as the difference between its timestamp and the current simulator time at the moment the PDU is read from the summary input file. In symbols, if *Tstamp* represents the timestamp of a PDU and *Tread* represents the time when the PDU was read, then

$$Tslack = Tstamp - Tread \tag{5.5}$$

If the difference is positive ($Tslack > 0$), then the generator is ahead of the planned schedule, otherwise it is behind it. Thus, a negative slack time indicates that the channel bandwidth is not enough to transmit the required PDUs without incurring in delays. If several PDUs are scheduled for transmission at the same timestamp, then they will necessarily produce a negative slack, no matter the bandwidth used. However, the greater the bandwidth, the smaller the magnitude of the negative slack.

b) Travel Time Analysis. Statistics about the travel time of all the PDUs collected at a particular sink are graphed and discussed. The travel time is the difference between the sending time of a PDU from a computer node generator and the arrival time to a node sink. All the transmission times, propagation times and waiting times in router queues are part of the travel time. If $Tstamp$, $Tarr$ and $Ttrav$ represent the release time (timestamp), the arrival time and the travel time of a given PDU, then

$$Ttrav = Tarr - Tstamp \tag{5.6}$$

c) Queue Length Analysis. There is a message queue at the satellite and another at each router to store incoming PDUs pending of service. Every time a PDU arrives to the satellite or a router, the number of other messages in the system is counted, including the PDUs already in the queue, plus any one being serviced. This counter along with the arrival time of the incoming PDU is recorder in an OMNeT statistics file. When the simulation ends, a separate program processes the file and gets the statistics about the number of messages in that system.

d) Collision Analysis. The satellite and routers keep separate counters of collisions received from each of the links they are connected to. The satellite is

connected to the wireless links WSP and WGS and the routers are connected to the LAN, WSP and WPP links (see Figure 7). Each time a collision is detected, the corresponding counter is incremented and its new value along with the current simulation time is recorder for future processing.

5.4 Simulation 1: Vignette With One Sender

The vignette of this first simulation produced a log file of 28 Mb of PDU data. The simulation time spanned from 00:14.341 to 07:22.446, for a time period of 7 minutes and 08.105 seconds. A total of 5940 PDUs were generated by one single site.

5.4.1 Independent Analysis of Logged PDUs

5.4.1.1 Analysis of PDUs and Assignment

Figure 22 shows the distribution and the relative proportion of PDUs according to their types. All the PDUs were generated by the site identified in OTB as 1013. During the simulation, this site was assigned to node 0 onboard plane 0. It can be noted that `entity_state`, `po_task_state` and `transmitter` PDUs are the three most frequent types of PDUs in this simulation, which agree with observations that have been pointed out by several authors (e.g. [Mac95], [SZB96], [BCL97], and [HIL98]).

```
<dis204 stop_freeze PDU>:              6
<dis204 start_resume PDU>:             6
<dis204 po_delete_objects PDU>:        8
<dis204 acknowledge PDU>:             12
<dis204 fire PDU>:                    17
<dis204 detonation PDU>:              17
<dis204 signal PDU>:                  20
<dis204 po_simulator_present PDU>:    22
<dis204 aggregate_state PDU>:         30
<dis204 po_task_frame PDU>:           31
<dis204 po_line PDU>:                 74
<dis204 po_objects_present PDU>:     105
<dis204 po_fire_parameters PDU>:     115
<dis204 po_point PDU>:               140
<dis204 po_parametric_input PDU>:    186
<dis204 po_unit PDU>:                241
<dis204 emissions PDU>:              340
<dis204 po_task PDU>:                374
<dis204 transmitter PDU>:            878
<dis204 po_task_state PDU>:         1417
<dis204 entity_state PDU>:          1901
Total PDUs =                        5940
```

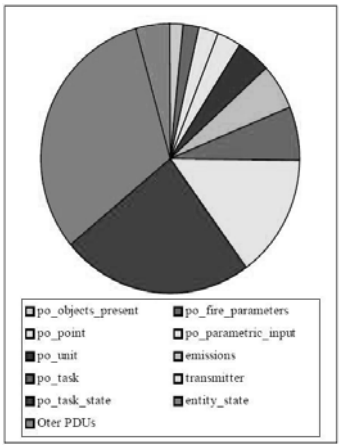
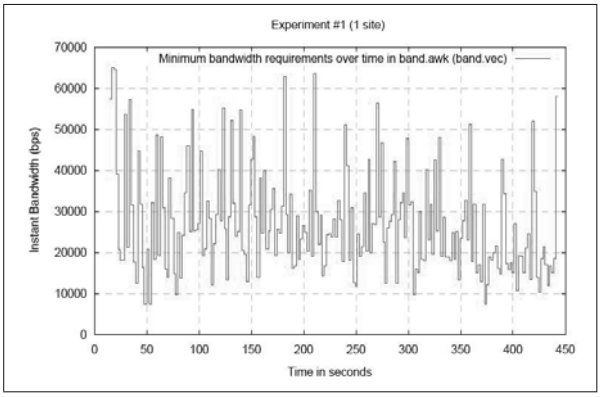


Figure 22: PDU Type Distribution Generated in Simulation 1

5.4.1.2 Minimum Bandwidth Requirements

Figure 23 shows the minimum instant bandwidth required at each interval of 2 seconds. The graph is typical of a burst transmission, having instants of heavy traffic followed by others of low usage. According to the results, all the instant bandwidths lie in the range of 7.3 Kbps to 65 Kbps, with an average of 27 Kbps. Therefore, a standard value of 64 Kbps in the wireless channels should be enough to handle all the traffic in this simulation.




```
Samples = 206
Init time = 14.341000
Final time = 442.446000
Minimum bandwidth = 7337.8
Maximum bandwidth = 65065.5
Average bandwidth = 26907.5
Std deviation = 12630.6
```

Figure 23: Minimum Bandwidth Requirements

5.4.2 Slack Time

Figure 24 shows that negative slacks are not detected. There are some, but they are not visible at the graph scale. Occurrences of negative slacks also depend on the node assignment of site 1013. If the site had been assigned to the ground station, probably more negative slacks had appeared. The reason is that the generators onboard planes are directly connected to the Ethernet bus running at 100 Mbps. From the generator point of view, the network is very fast and it is almost always ahead of schedule. However, the ground station is directly connected to the slow 64 Kbps wireless channel, what promotes more negative slacks.

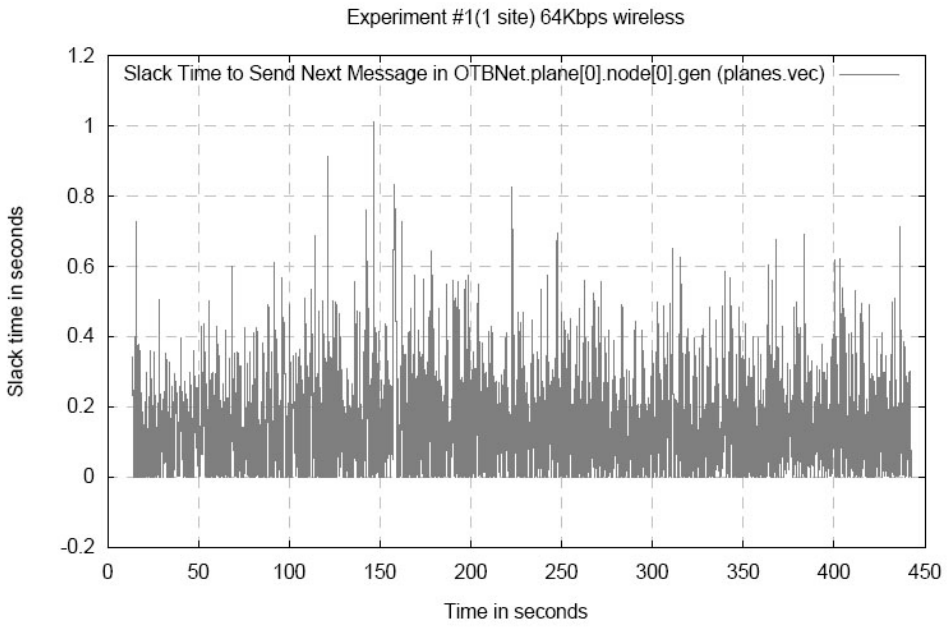


Figure 24: Slack Time at Generator 0

5.4.3 Travel Time

As depicted in Figure 25, the travel times of PDUs seen by the ground station show that most PDUs took less than 0.6 seconds to arrive at the destination. The minimum travel time is close to 0.255 seconds that correspond to the time needed by a signal to travel from Earth to the satellite and back to Earth ($38300Km \times 2$) at the speed of light.

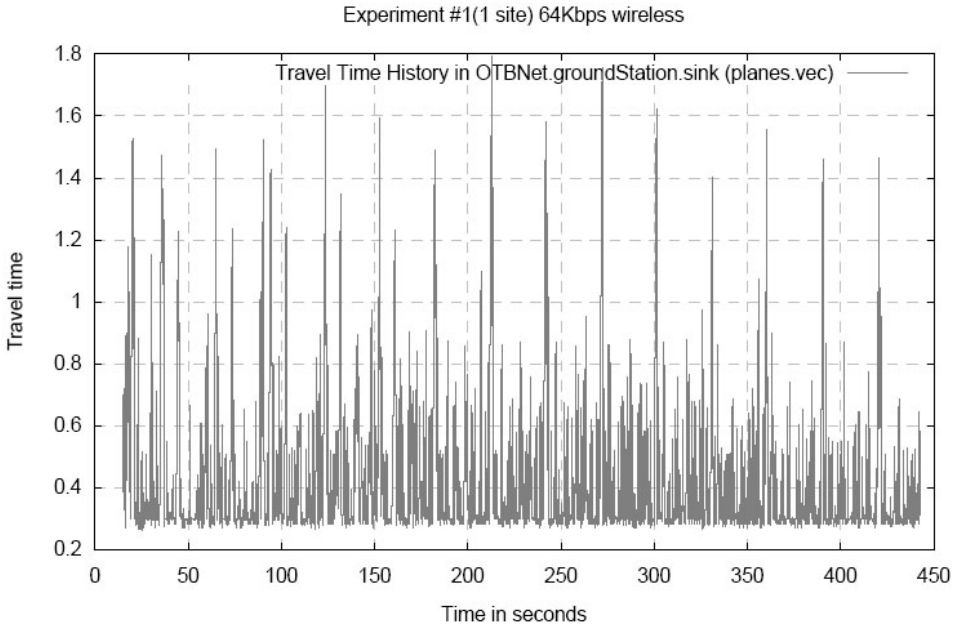


Figure 25: Travel Time as Sensed by the Ground Station

5.4.4 Queue Length

Figure 26 shows the number of messages at the router of plane 0. The maximum value is less than 45, which is quite acceptable for a router. In Figure 27, the satellite shows even better results with maximum queue less than 16 messages. In

both instances, the queue usage has similar characteristics throughout the simulation time, showing peaks of all sizes evenly distributed along the time.

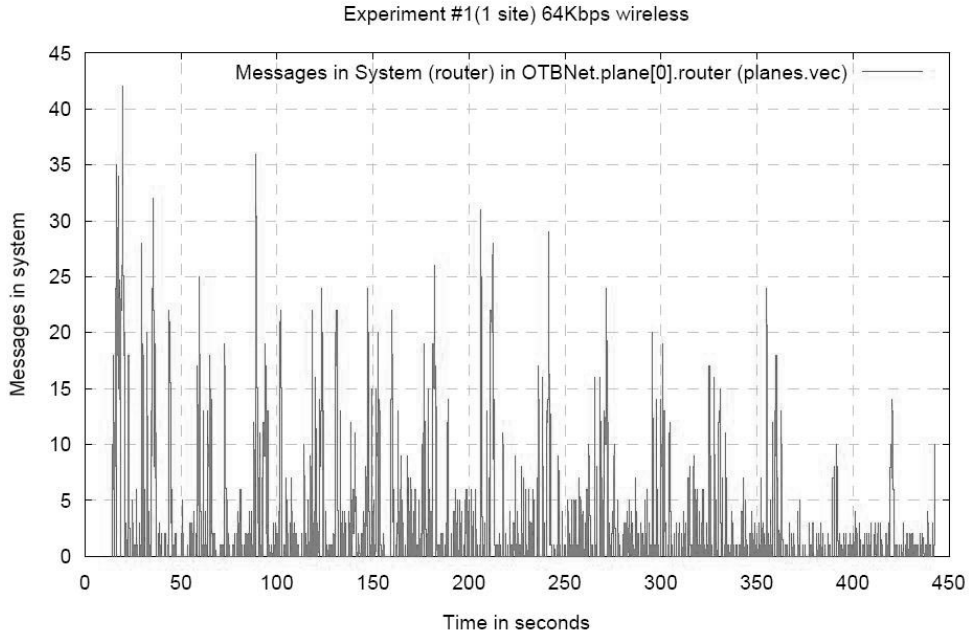


Figure 26: Messages in Router 0 (plane 0)

5.4.5 Collisions

No collisions were detected. This is understandable due to the fact that only one site is transmitting.

5.4.6 Conclusions of Simulation 1

This first simulation was based on a simple vignette. The main purpose was really to test the simulator itself. All the wireless links were set to a bandwidth of 64 Kbps. The results are congruent with the expected values for such a simulation.

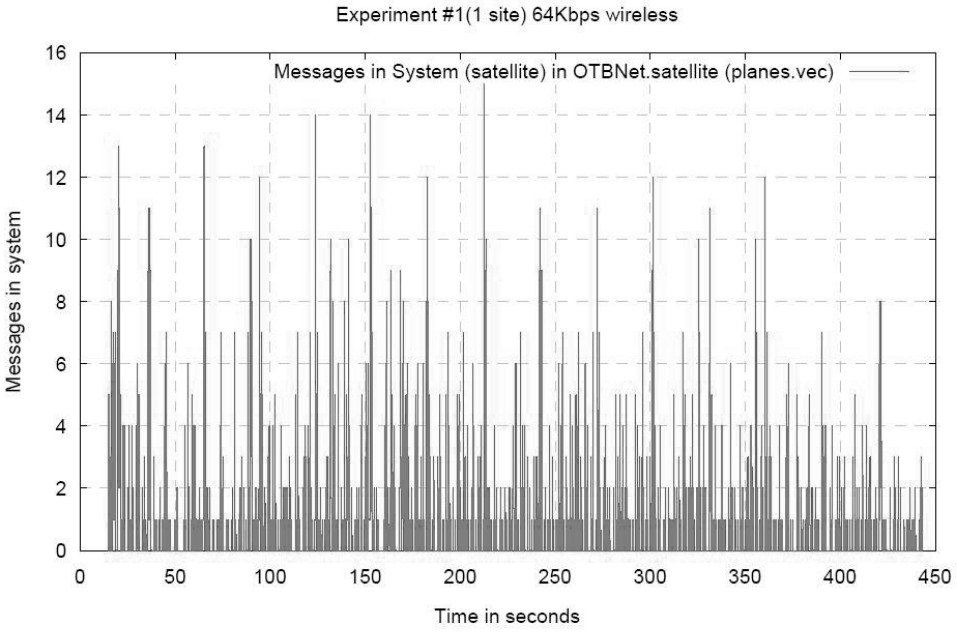


Figure 27: Messages in the Satellite

The behavior of the PDU traffic is typical of that of a computer network using the DIS protocol, as has been reported by other authors. For example, in [MZP94] there are graphs of time vs. PDU/second showing similar PDU activity as in Figures 26 and 27.

It is interesting to note that the simulator calculates the PDU travel time to the ground station with a lower bound of near 0.25 seconds, based solely on the parameters given, as propagation time of each communication link and distance between sites, which gives another indication of its reliability.

As a conclusion, it can be stated that the OMNeT simulator works accordingly with the expected results for this simulation, which gives some degree of confidence in its accuracy. The traffic is perfectly handled at 100 Mbps in the Ethernet link and 64 Kbps in the wireless.

From the simulation data, it can be concluded that negative slack at the generator is negligible, the queue lengths in the routers and satellite were less than 45 and 16 messages, respectively, and collisions were not detected. Therefore,64 Kbps in the wireless channels is enough bandwidth for this simulation. It should be noted that the conclusion agrees with the results of the independent analysis, which gives support to the idea that the independent analysis is a valuable tool in the bandwidth analysis of a network.

5.5 Simulation 2: Vignette with Two Senders

The vignette in this second simulation produced a log file of 22 Mb of PDU data. The simulation time spanned from :00:35.003 to :05:50.574, for a time period of 5 minutes and 15.571 seconds. A total of 5430 PDUs were generated by 2 sites identified in OTB as 1082 and 1086.

5.5.1 Independent Analysis of Logged PDUs

5.5.1.1 Analysis of PDUs and Assignment

Figure 28 shows the distribution and the relative proportion of PDUs for each type. Sites 1082 and 1086 generated 926 and 4504 PDUs (17% and 83%) respectively, which indicates that in the vignette one site is much more active than the other.

During the simulation, site 1082 was assigned to ground station (node 24) and site 1086 was assigned to node 0 onboard plane 0. As in the first simulation, PDUs of types `entity_state` and `po_task_state` are among the most frequent.

```
<dis204 stop_freeze PDU>:                    3
<dis204 start_resume PDU>:                   3
<dis204 po_delete_objects PDU>:              7
<dis204 acknowledge PDU>:                   12
<dis204 po_link PDU>:                       12
<dis204 aggregate_state PDU>:               18
<dis204 fire PDU>:                          24
<dis204 detonation PDU>:                    24
<dis204 po_simulator_present PDU>:          26
<dis204 signal PDU>:                        27
<dis204 po_parametric_input_holder PDU>:    40
<dis204 po_objects_present PDU>:            52
<dis204 po_overlay PDU>:                    64
<dis204 po_line PDU>:                       65
<dis204 po_fire_parameters PDU>:            65
<dis204 po_point PDU>:                      80
<dis204 po_task_frame PDU>:                 85
<dis204 po_parametric_input PDU>:          165
<dis204 po_unit PDU>:                      186
<dis204 emissions PDU>:                    204
<dis204 transmitter PDU>:                  547
<dis204 po_variable PDU>:                  760
<dis204 po_task PDU>:                      835
<dis204 entity_state PDU>:                1021
<dis204 po_task_state PDU>:               1105
Total PDUs =                              5430
```

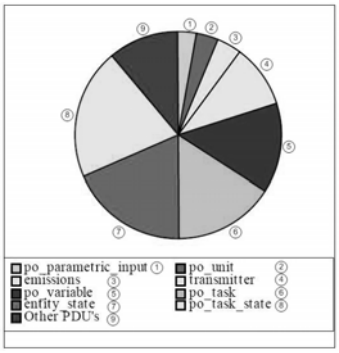


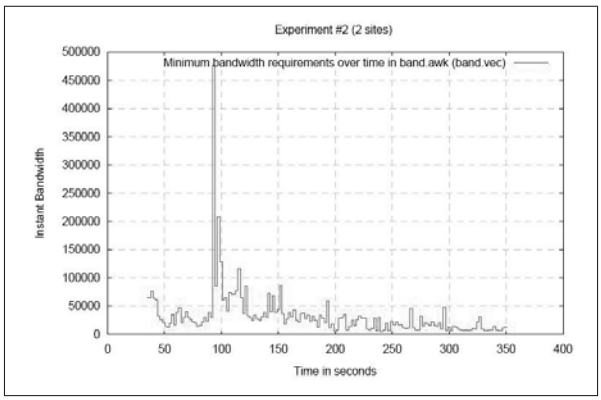
Figure 28: PDU Type Distribution Generated in Simulation 2

5.5.1.2 Minimum Bandwidth Requirements

Figure 29 shows a high bandwidth spike near the second 95. The reason is that lots of PDUs are scheduled to be sent at times close to second 95. A close look at the data shows that during the time interval [92.463000, 94.484000], 310 PDUs totaling 957 K bits are being scheduled. This volume of data requires approximately 474 Kbps to be sent on time. After the second 100, the remaining PDUs can be handled at 64 Kbps, as Figure 29 indicates. Because the bandwidth is considered constant in the actual links, 64 Kpbs will be insufficient to fulfill the needs of this second vignette.

5.5.2 Slack Time

Figure sim2:slack1 shows the slack time as seen by computer node 0 (line labeled 1) and the ground station (line labeled 2), setting the wireless bandwidth to 64 Kbps.




```
Init time = 35.003 sec.
Final time = 350.574 sec.
Minimum bandwidth = 5153.6 bps
Maximum bandwidth = 477404.0 bps
Average = 32401.2 bps
Std deviation = 44953.7 bps
```

Figure 29: Minimum Bandwidth Requirements

It is clear that in the approximate time interval [90, 120] the ground station suffered from high negative slacks. This is due to the impossibility to handle the data volume at 64 Kbps. After the second 120 the ground station gets recovered from the delay. Figure sim2:slack2 represents a zoom in of Y axis in Figure sim2:slack1 Even at this scale, there are no visible negative slacks in plane 0, mainly due to the high bandwidth of the LAN link.

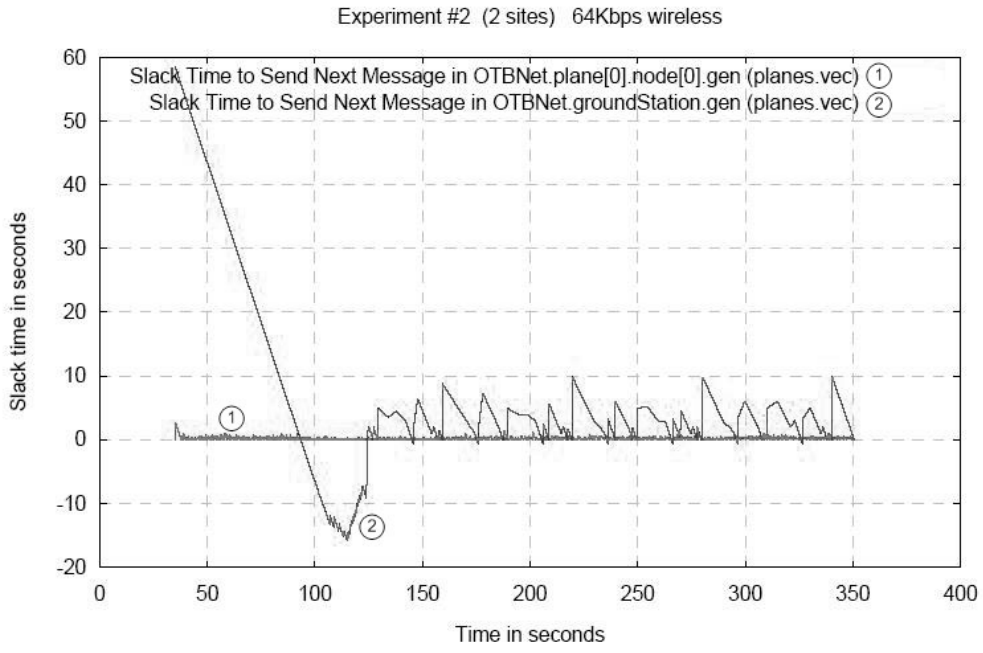


Figure 30: Slack time to send next message at plane 0 and ground station (64 Kbps)

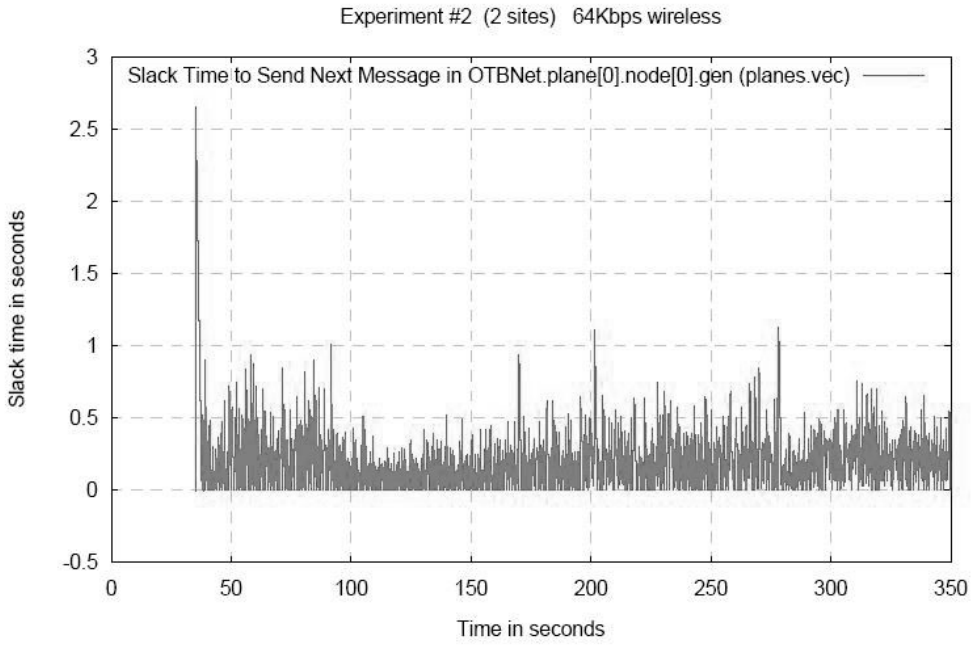


Figure 31: Slack time to send next message by plane 0 (64 Kbps)

Figure sim2:slack3 shows both, the slack time at the ground station (blue) and the slack at plane 0 (red) for a wireless bandwidth of 400 Kbps. This non standard bandwidth was chosen based on the results of the independent analysis. As seen, the slack at the ground station is greatly reduced but it is still negative before second 100. However, the positive slacks were almost unaffected by the bandwidth increase.

5.5.3 Travel Time

Figure 33 represents the travel time as seen by node 0 (line labeled 1) and the ground station (line labeled 2) at 64 Kbps in the wireless channels. Both graphs are quite similar, showing a big delay during the interval from second 90 to second 170.

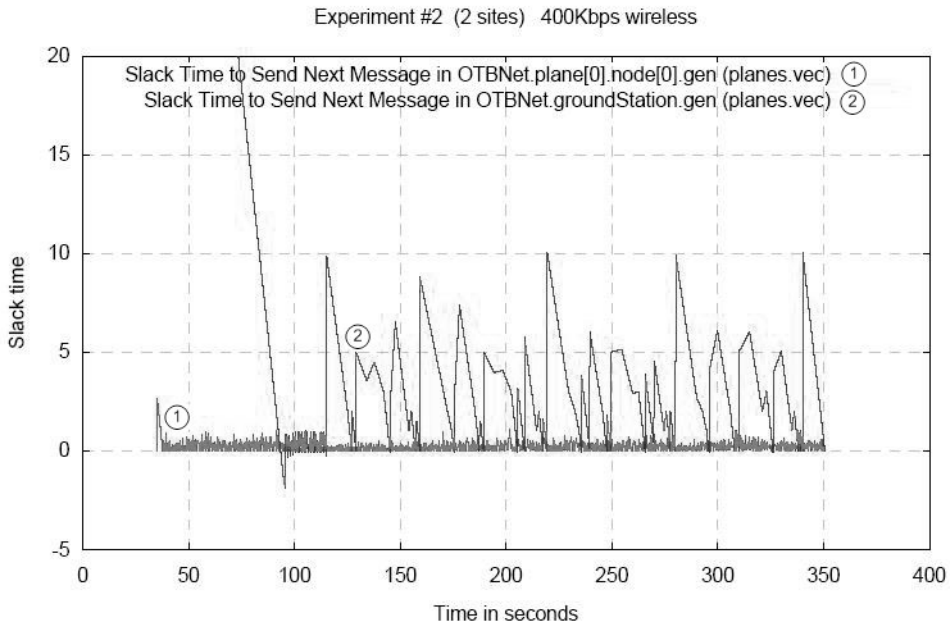


Figure 32: Slack time to send next message by plane 0 and ground station (400 Kbps)

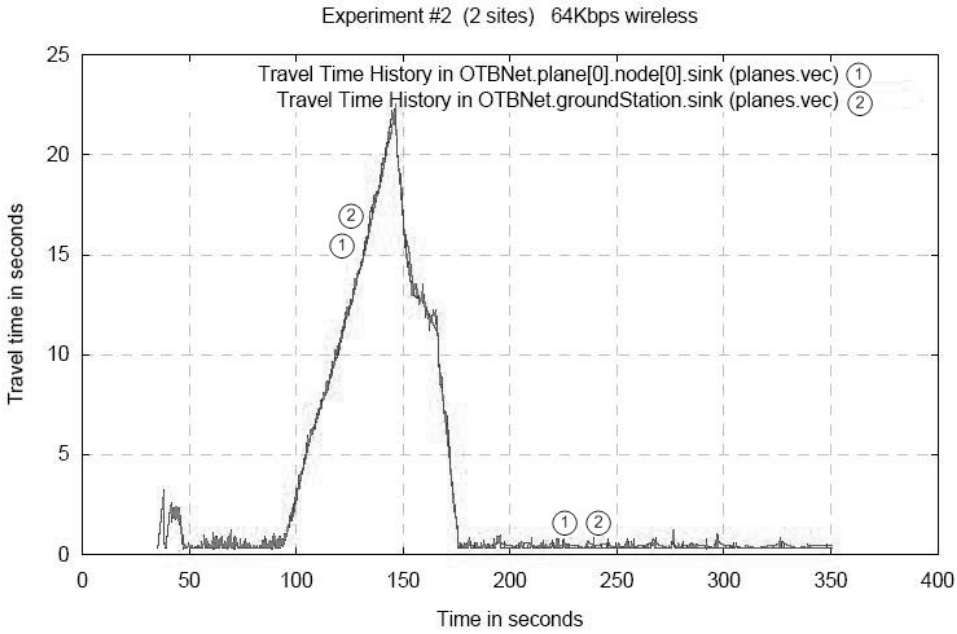


Figure 33: Travel times at plane 0 and ground station (64 Kbps)

Node 23 (plane 7, node 2) produces the graph shown in Figure 34, which was drawn using lines to connect consecutive observations. The graph shows two sets of PDUs. The PDUs coming from ground station suffer from high delays, while PDUs coming from plane 0 have short delays. The reason is that PDUs coming from plane 0 do not wait at the satellite queue and are not affected by the propagation delay of satellite signals.

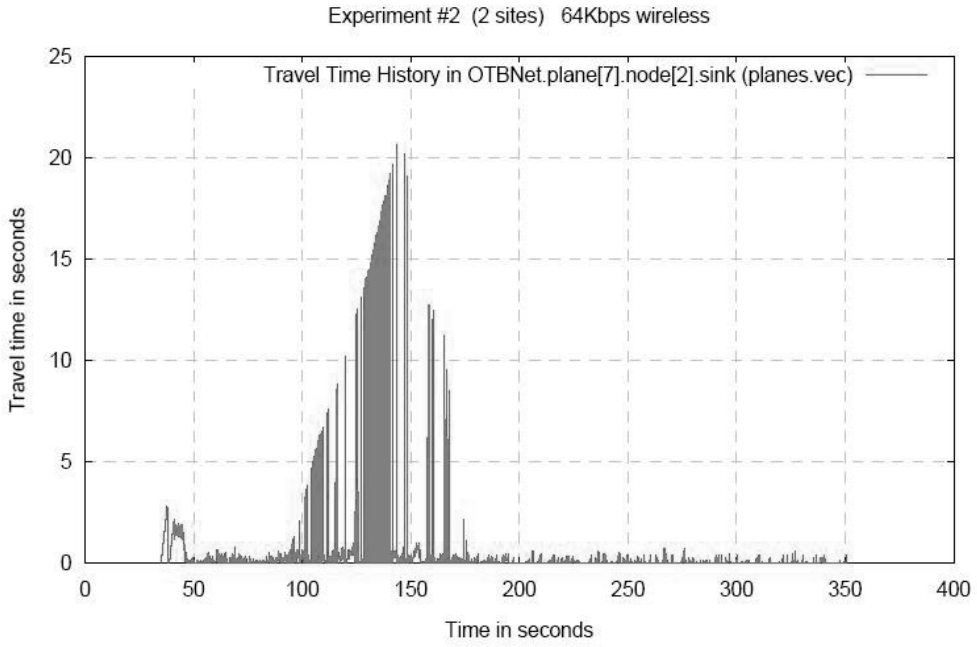


Figure 34: Travel times at plane 7 (64 Kbps)

Figure 35 shows travel times seen by node 21 (plane 7, node 0) when the wireless bandwidth is increased to 400 Kbps. It is more clear now that this node receives two types of PDUs, being the satellite PDUs delayed by approximate 0.25 more seconds.

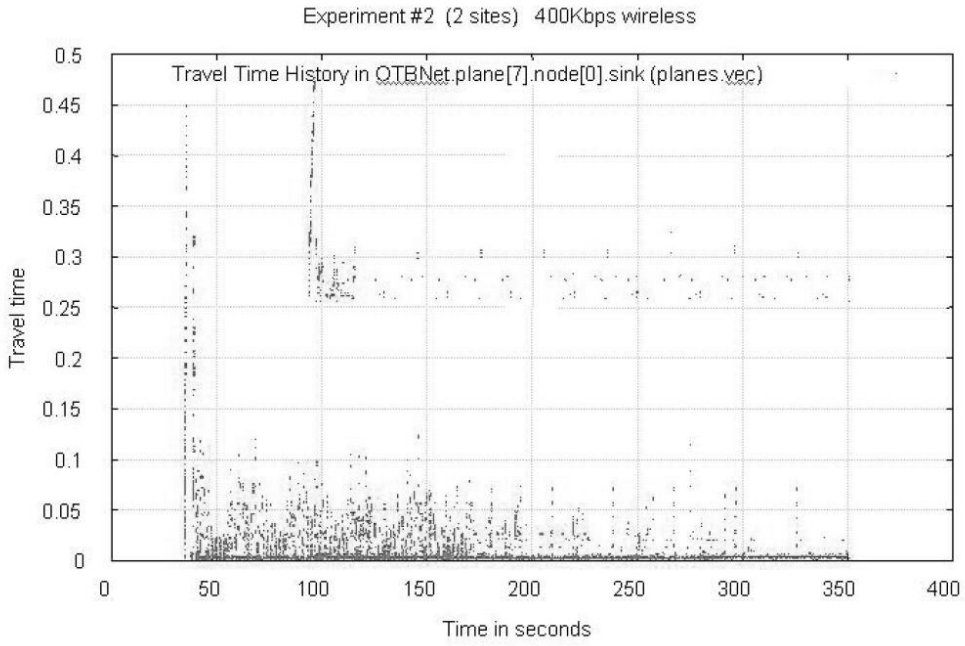


Figure 35: Travel times at plane 7 zoomed in (400 Kbps)

5.5.4 Queue Length

Figure 36 clearly shows that at 64 Kbps in the wireless, the satellite suffers from a big queue delay during the time interval [100, 170]. This is a strong indication that 64 Kbps are not enough to handle the traffic at the satellite. On the other side, the traffic at the router onboard plane 0 seems capable of handling its corresponding traffic.

Increasing the bandwidth to 400 Kbps greatly improves the satellite queue, as indicated in Figure 37. At 400 Kbps, the satellite maintains a queue length fewer than 20 PDUs most of the time. The router onboard plane 0 still shows an initial queue length of 120 messages which does not impact its performance.

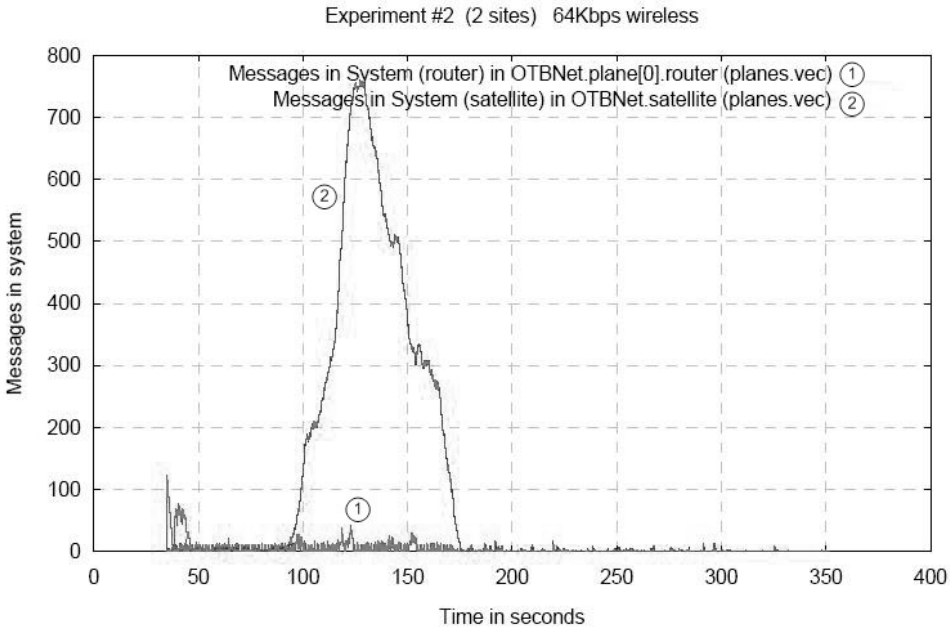


Figure 36: Comparison of queue lengths of plane 0 and satellite (64 Kbps)

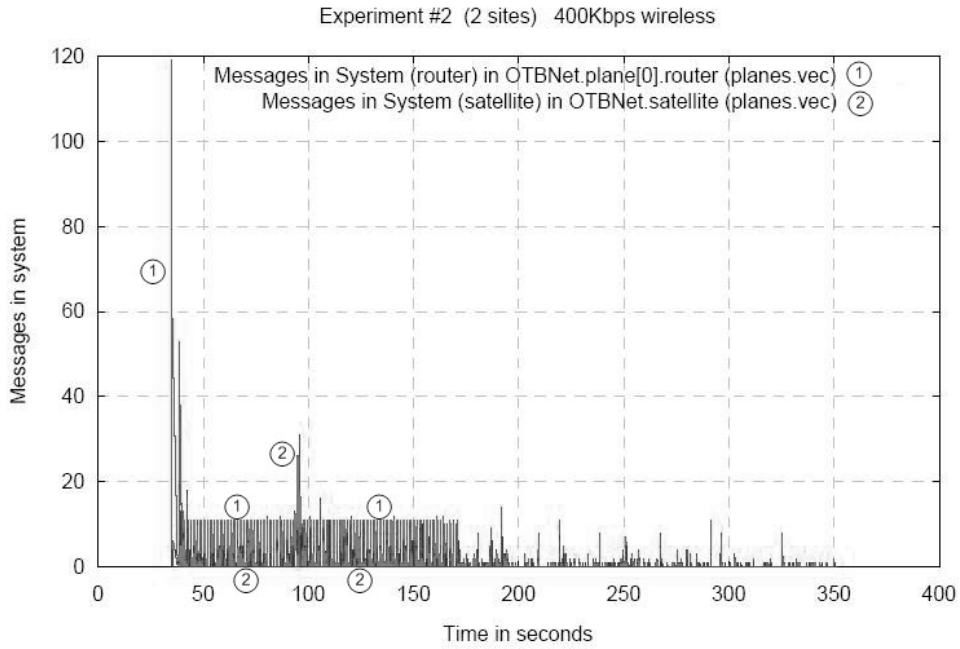


Figure 37: Comparison of queue lengths of plane 0 and satellite (400 Kbps)

5.5.5 Collisions

At 64 Kbps in the wireless channels, Figure 38 shows that some collisions were detected in the WSP channel that connects the satellite to the planes. The other channels do not show collision activity. The above graph represents the number of collisions detected per second by the router at plane 1.

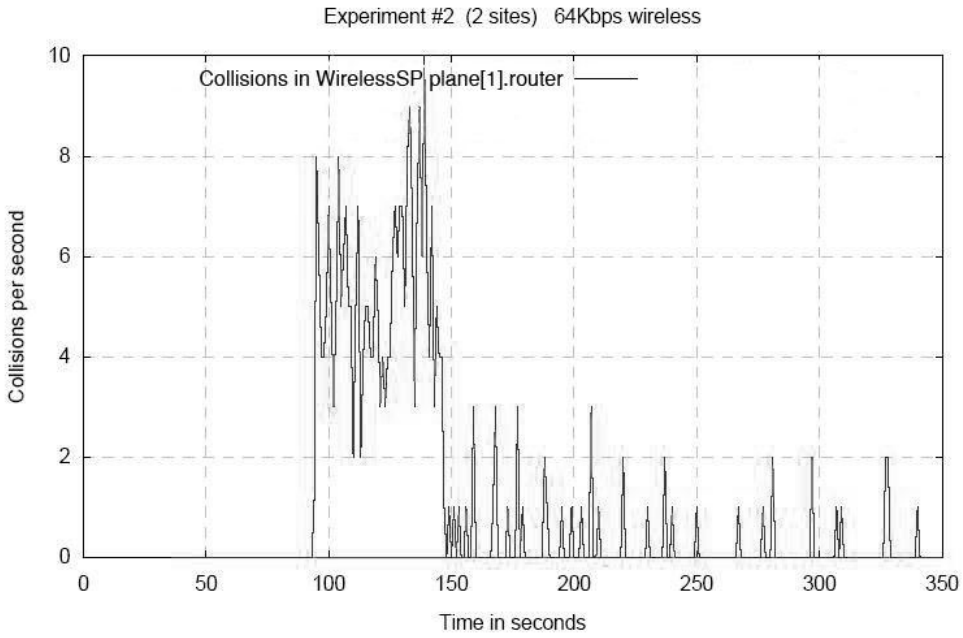


Figure 38: Collisions per second detected at plane 1 (64 Kbps)

Figure 39 gives the number of collisions accumulated along the time, as seen by the router at plane 7. The maximum collision rate occurs in the range [90, 140], totaling near 280 collisions. Afterwards, the rate evidently decreases, and at the end of the experiment the collision counter reaches approximately 325. Considering that the total number of PDUs sent is 5430, the collisions represent near 6% of the total number of packets.

The current simulator does not include a special treatment for collisions, like retransmissions using exponential backoff algorithms [Mol94] [IEE97] [FZ02].

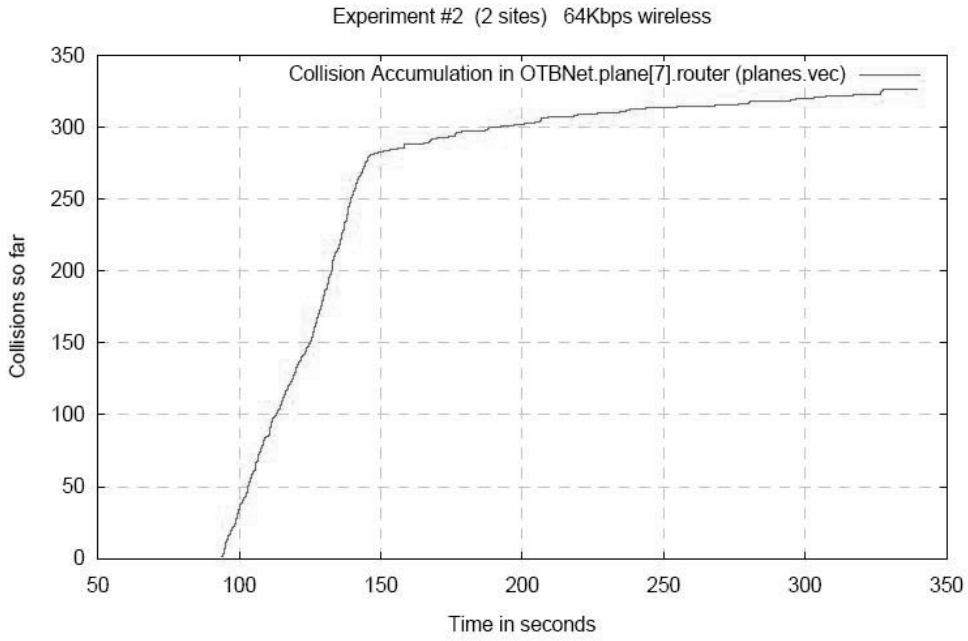


Figure 39: Collision Accumulation over time at plane 7 (64 Kbps)

However, the small percentage of collisions leads to conclude that a more sophisticated simulator including exponential backoff will produce results very similar to the ones produced by the current one.

The simulator was run setting the wireless channels to 400 Kbps. At this bandwidth, collisions in the WSP link are significantly reduced, totaling fewer than 60 at the end of the experiment. Near the second 92 a peak of 8 collisions per second occurs immediately decreasing to 3 or fewer collisions per second during the rest of the simulation time.

5.5.6 Conclusions of Simulation 2

As indicated at the beginning of the chapter, the two first simulations were used mainly to test the logic and general behavior of the OMNeT simulator, as well as for taking a closer look at the PDUs, their distribution and initial statistics.

As predicted in the independent analysis, 64 Kbps in the wireless channels is insufficient bandwidth to handle traffic near the interval [90, 175] seconds. After second 175 the traffic becomes less intense and can be handled. Based on the independent analysis, increasing the bandwidth to 400 Kbps in wireless channels produce much better results, with travel times less than 0.5 seconds for all packets. Collisions were detected in the WSP link only, but at 400 Kbps, the total number is less than 60. At 64 Kbps, the queue length was close to 750 PDUs in the satellite, number that decreases under 30 PDUs at 400 Kbps. Assuming the worst case length in the satellite queue, 750 PDUs of 1368 bytes each would require near 1 Mb of memory, which does not impose a tight restriction.

5.6 Simulation 3: Vignette MR1 with Six Senders

Simulation 3, as well as the remaining ones, is based on the MR1 vignette described in Appendix A. The log file for this simulation is 265 Mb long. The simulation time spanned from :17:14.447 to :42:27.808, for a time period of 25 minutes and 13.361 seconds. A total of 60341 PDUs were generated by 6 sites identified in OTB as 1519, 1526, 1529, 1532, 1533, and 1538. The simulation is not using the bundling technique. Bundling simulations are covered in Chapter 6.

5.6.1 Independent Analysis of Logged PDUs

5.6.1.1 Analysis of PDUs and Assignment

There are 27 different types of PDUs in the OTB simulation of the MR1 vignette. Figure 3 shows the distribution, the volume of bytes and the relative proportion of PDUs for each type, and Figure 40 depicts the corresponding pie charts. The most frequent type of PDU is `entity_state` with 28569 PDUs, (47%), followed by `po_task_state` with 11960 PDUs, (nearly 20%).

Table 3: Types of PDUs and volume of bytes transmitted for each type

PDU Type	#PDUs	# Bytes	% # PDUs	% # Bytes
Laser	3	264	0.005	0.002
start_resume	3	132	0.005	0.001
stop_freeze	3	120	0.005	0.001
po_task_authorization	6	388	0.010	0.003
po_minefield	14	5384	0.023	0.043
fire	23	2208	0.038	0.018
detonation	25	2550	0.041	0.021
acknowledge	36	1152	0.060	0.009
po_delete_objects	110	4216	0.182	0.034
minefield	117	42120	0.194	0.339
po_message	119	69020	0.197	0.556
signal	237	19896	0.393	0.160
aggregate_state	256	37888	0.424	0.305
po_simulator_present	370	34040	0.613	0.274
po_task_frame	382	87984	0.633	0.709
mines	386	396088	0.640	3.19
po_point	659	55356	1.09	0.45
po_objects_present	682	577952	1.13	4.65
po_fire_parameters	713	376464	1.18	3.03
iff	851	51060	1.41	0.41
po_line	912	115524	1.51	0.93
po_parametric_input	1196	165440	1.98	1.33
po_unit	1793	1161864	2.97	9.36
po_task	2274	399744	3.77	3.22
transmitter	8642	898768	14.3	7.24
po_task_state	11960	3052824	19.8	24.6
entity_state	28569	4857328	47.3	39.1
Totals	60341	12415774	100%	100%

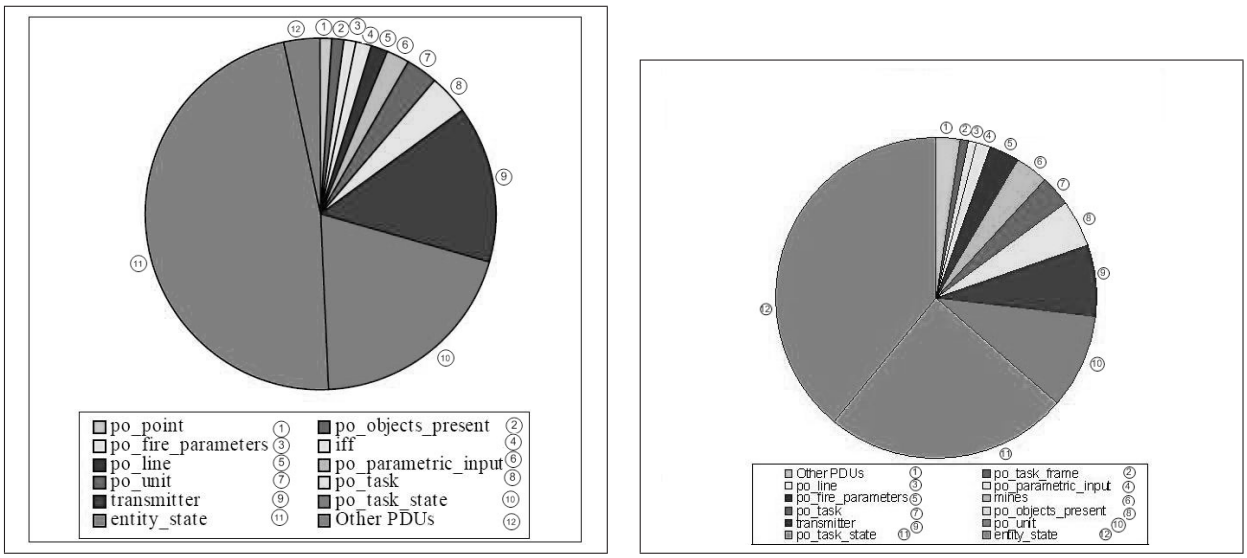


Figure 40: Distribution of types and volumes of PDUs produced in the simulation of MR1 vignette

It is interesting to note that the percentage of PDU types does not necessarily agree with the percentage of byte volume for the same type. For example, `transmitter` PDUs represent the 14.3% of the total number of PDUs, but only the 7.24% of total byte volume, and `po_unit` PDUs are the 2.97% of type frequency, but the 9.36% of total byte volume.

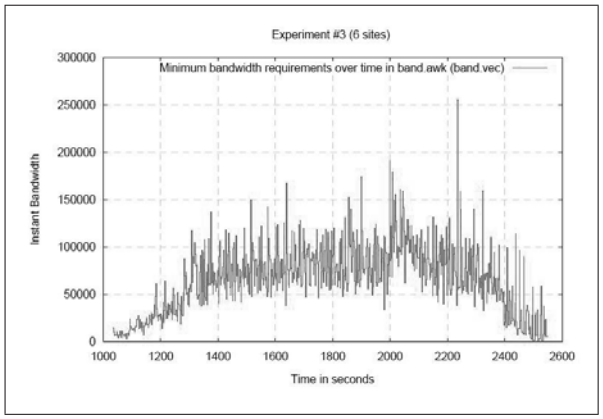
The assignment of OTB sites to computer nodes in this simulation is as follows.

- Site 1519 (0): 50230 PDUs assigned to plane 0, node 0 (computer node 0)
- Site 1526 (3): 1056 PDUs assigned to plane 1, node 0 (computer node 3)
- Site 1529 (6): 483 PDUs assigned to plane 2, node 0 (computer node 6)
- Site 1532 (24): 7382 PDUs assigned to ground station (computer node 24)
- Site 1533 (9): 553 PDUs assigned to plane 3, node 0 (computer node 9)
- Site 1538 (12): 637 PDUs assigned to plane 4, node 0 (computer node 12)

Site 1519 generated 50230 PDUs (83%), being it the most preponderant one. The assignment was made such that the site with the highest rate of PDUs belongs to an aircraft, and the second one in importance goes to the CONUS ground station.

5.6.1.2 Minimum Bandwidth Requirements

Figure 41 shows a more uniform bandwidth requirements than in previous vignettes, but this is mostly caused by the larger number of PDUs in the vignette. As seen, the static analysis indicates that the maximum bandwidth required is near 256 Kbps, but the majority of the time the bandwidth required is less than 200 Kbps. With an average of near 67 Kbps, it seems that 64 Kbps would be completely insufficient for this vignette, fact that will be acknowledge during the simulation.




```
Init time          = 1034.447
Final time         = 2549.808
Minimum bandwidth  = 773.2
Maximum bandwidth  = 255745.3
Average            = 66756.4
Std deviation      = 35082.2
```

Figure 41: Minimum Bandwidth Requirements in Simulation 3

5.6.2 Slack Time

Figure 42 shows the slack time for all the units (routers and ground station) at 64 Kbps in the wireless channels. The second graph was plotted by dots instead of lines and was zoomed in to the Y axis to show that the ground station carries the

majority of the negative slacks. This is explained by the fact that the generators onboard the planes are directly connected to high speed Ethernet buses, while in the ground station the generator is connected to a low speed wireless channel.

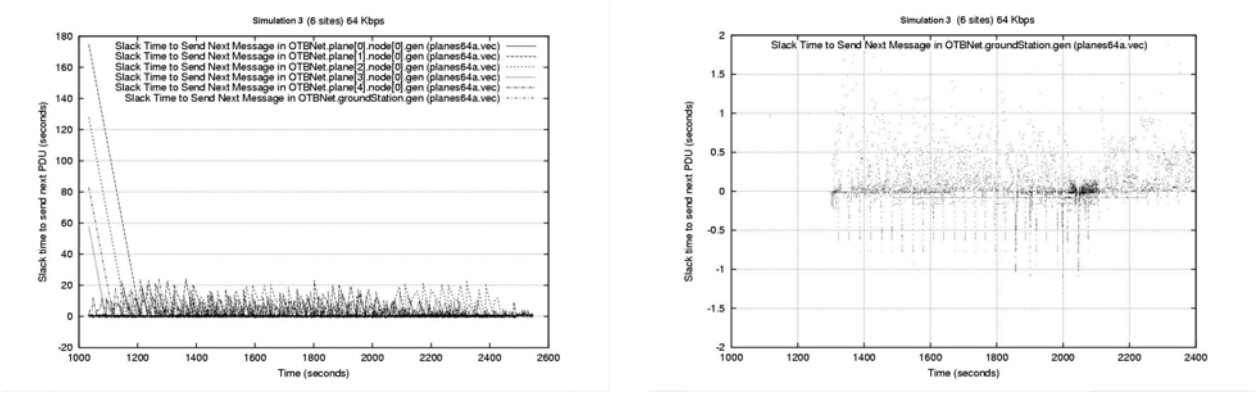


Figure 42: Slack time to send next message by different generators at 64 Kbps, and zoom in showing details of ground station only.

Table 4 displays the percentage of packets with positive slack by site. A separate program was used to calculate them.

Table 4: Percentage of packets with positive slack at sending sites

```
Site 0, positive slack frames= 39656 (78.95%), total frames sent= 50230
Site 3, positive slack frames= 519 (49.15%), total frames sent= 1056
Site 6, positive slack frames= 236 (48.86%), total frames sent= 483
Site 9, positive slack frames= 340 (61.48%), total frames sent= 553
Site 12, positive slack frames= 394 (61.85%), total frames sent= 637
Site 24, positive slack frames= 4182 (56.65%), total frames sent= 7382
Total # of PDUs delivered on time: 45327 out of 60341 = 75.11%
```

It calls to the attention the low percentages of positive slacks observed at airplane nodes. At 100 Mbps in the LAN, it is expected to have positive slacks in 95% or more of the PDUs. The percentage of negative slacks is considerable. However, those negative slacks are not observed in Figure 42. The reason is that at 100 Mbps in the LAN buses, the negative slacks are almost negligible to be seen in the graph, but they are still present. The cause of negative spikes is mainly due to the fact that OTB schedules several PDUs at exactly the same time, at least to the resolution of

the OTB clock. These negative slacks will not completely disappear by increasing the network bandwidth. The only way to eliminate them is by bundling and/or rescheduling the PDUs so that they do not occur at the same time.

Figure 43 shows the effect of increasing the wireless bandwidth to 1024 Kbps in the ground station channel. Although experiments with intermediate values of 128, 200, 256, and 512 Kpbs were carried out, it is difficult to visualize them in one single black and white figure. Nevertheless, the consequences of a bandwidth increase are evident: at 1024 Kbps negative spikes are still present, even though the spike magnitude decreases. The experiments showed that for the other intermediate bandwidths the results are in between, as expected. The more the bandwidth is increased, the less the negative slack is detected.

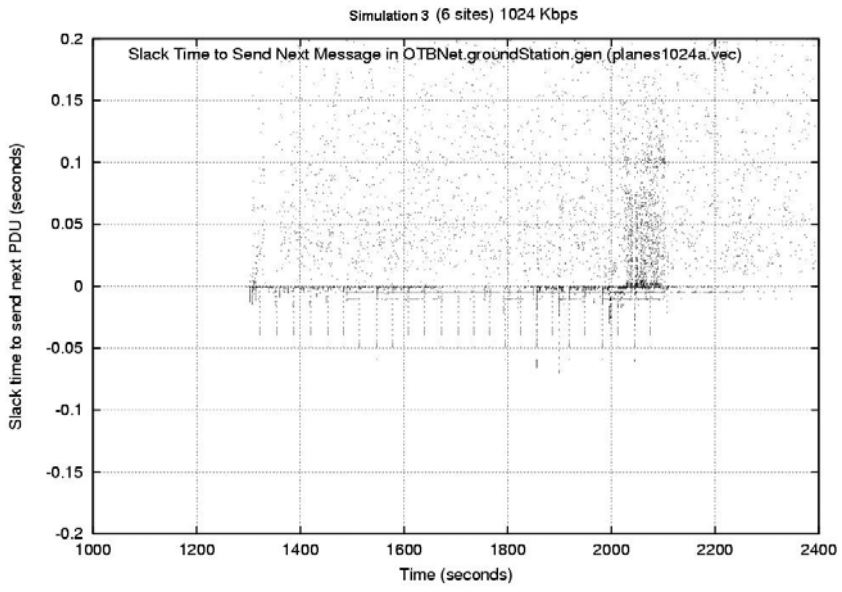


Figure 43: Zoom in of slack time to send next message by ground station (1024 Kbps). Negative spikes are still observed.

5.6.3 Travel Time

Figures 44 and 45 show the travel time of PDUs measured by the sinks at node 2 and ground station, respectively, using 64 Kbps on the wireless links. At node 2 the graph clearly shows two traces corresponding to two sources of PDUs.

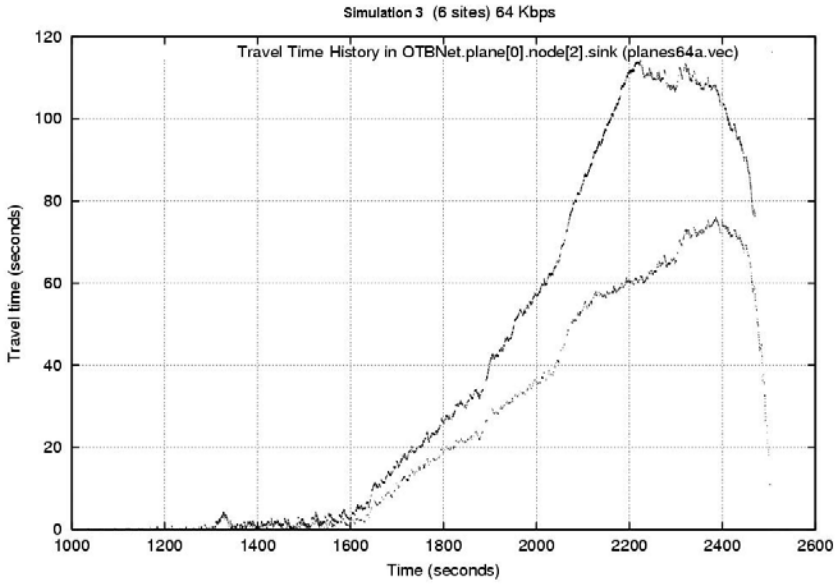


Figure 44: Travel time at node 2 in plane 0 (64 Kbps)

The PDUs that take longer to arrive come from the ground station. These PDUs had to wait on the satellite queue as well as on the router queue. On the other hand, the PDUs coming from computers onboard the other planes had to wait on the router queue only. This produces the two traces shown. There are no messages coming from nodes within the same plane 0 because of the assignment given. However, if they had been issued their trace would not be seen because the LAN at 100 Mbps would render them near zero at the scale used. The graph was drawn using dots instead of lines to better observe the traces.

Obviously, at 64 Kbps the travel times of most PDUs is completely unacceptable. Some PDUs took more than 100 seconds since the time they were sent to the time

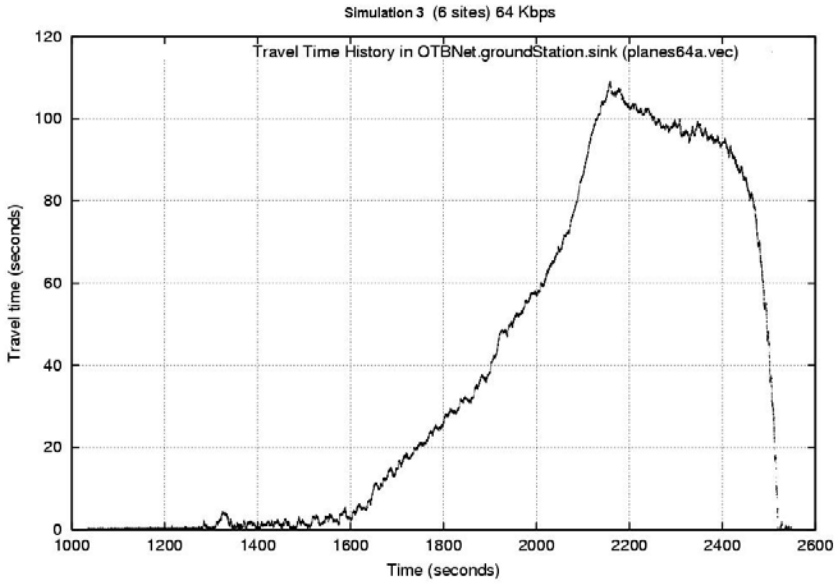


Figure 45: Travel time at ground station (64 Kbps)

they arrived. The ground station presents a similar behavior due to the long queue times at the satellite.

Figure 46 shows travel times measured at the ground station for bandwidths of 64 and 256 Kbps. The graph was zoomed in to the Y axis to show the details in the neighborhood of 0 to 2 seconds. The spots at the left side having travel times over 1 second correspond to 64 Kpbs, while the other spots that almost do not reach the 1 second limit correspond to 256 Kpbs. It is worth noting the enormous difference between these two bandwidths. At 256 Kbps in the wireless channels, the travel times to the ground station are less than 1 second in the majority of cases. Considering that the minimum travel time is about 0.25 seconds, latencies less than 1 second can be acceptable, especially if OTB could deliver the PDUs in a not-so-bursting mode.

At 256 Kbps Figure 46 shows many discrete positive peaks separated at regular intervals that could be diminish by a better scheduling policy. The positive travel

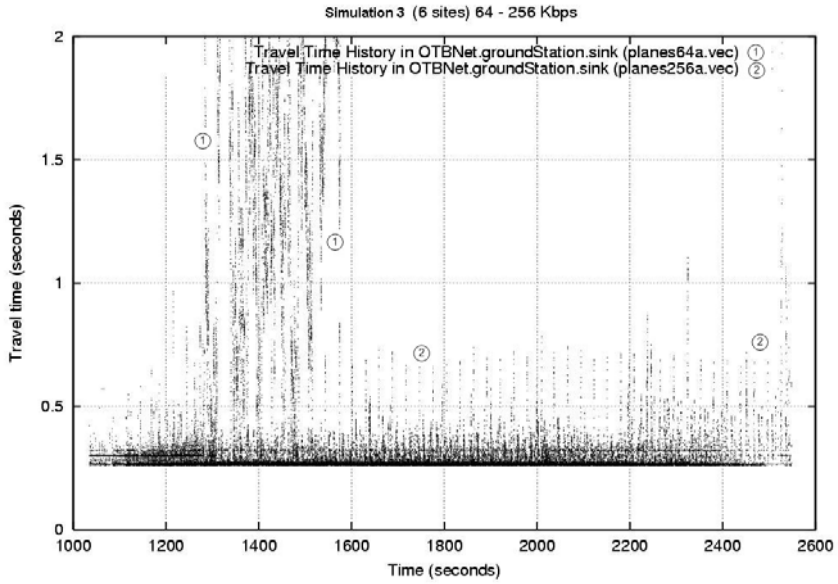


Figure 46: Zoom in of travel times at ground station (64, 256 Kps)

time spikes and the negative slack time spikes shown in Figures 42 and 43 are correlated because the more time the sending site is behind the timestamped schedule, the more heavy the network traffic is and the packets will have to wait more time in router queues. Both measures are good indicators of the network performance. If some PDUs at the spikes of negative slack could be moved to time intervals of positive slack, the network traffic would become less bursty.

5.6.4 Queue Length

The two most important queues to analyze are the queue at the router onboard plane 0 and the queue at the satellite, because these routers are the most heavily loaded in the simulation. The router at plane 0 connects a high speed link of 100 Mbps to a slow link of 64/256 Kbps. Therefore, messages coming from plane 0 will wait at the router queue for a chance to be transmitted. The satellite receives

and transmits all the messages at low speeds, which constitutes a bottleneck in the system. The routers at other planes not heavily transmitting PDUs take packets from a slow wireless channel and pass them to a fast Ethernet link, resulting in almost no queue waiting time. Nevertheless, the queue at another router is shown as a sample of the behavior of the other routers.

Figure 47 represents the number of messages in the router at node 0, using 64 Kbps in the wireless channels. The queue length becomes really unacceptable, reaching more than 3000 messages during some periods.

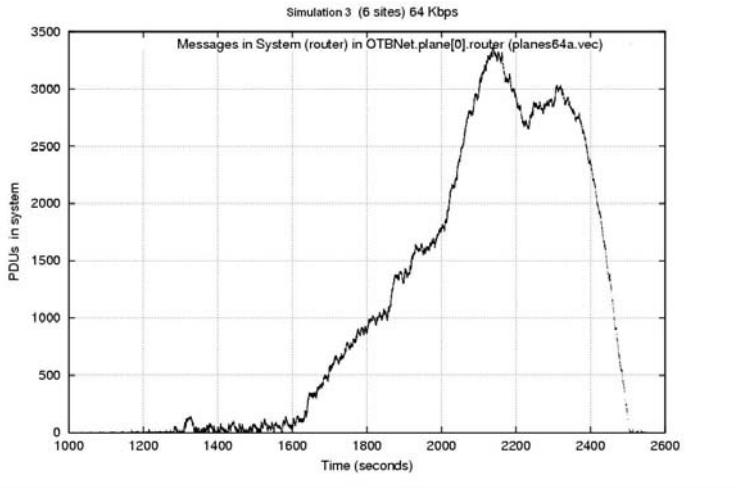


Figure 47: Messages in system at plane 0 (64 Kbps)

On the contrary, Figure 48 shows that the router at plane 3 has a normal queue with a maximum of 23 messages. The reason for the short queue is that the corresponding node 9 transmits only 553 PDUs, which are easily handled by the router.

Figure 49 shows that the queue at the satellite (64 Kbps) has an unacceptable behavior with a peak of more than 2200 messages.

Figure 50 shows the effect on the queue length of the router onboard plane 0 when the bandwidth increases from 64 to 256 Kbps. As a result, the queue length

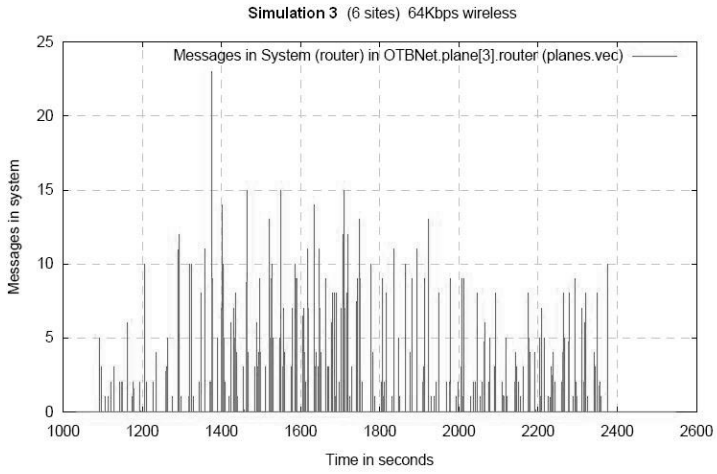


Figure 48: Messages in system at plane 3 (64 Kbps)

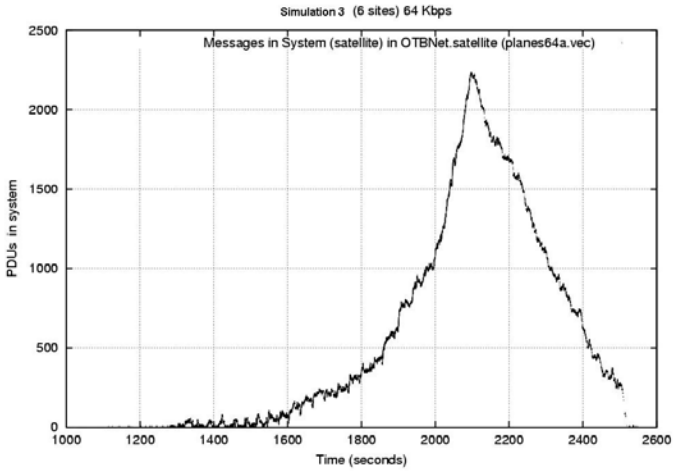


Figure 49: Messages in system at satellite (64 Kbps)

decreases to less than 50 messages in its highest peak. Therefore, the change of speed greatly reduces the router queue.

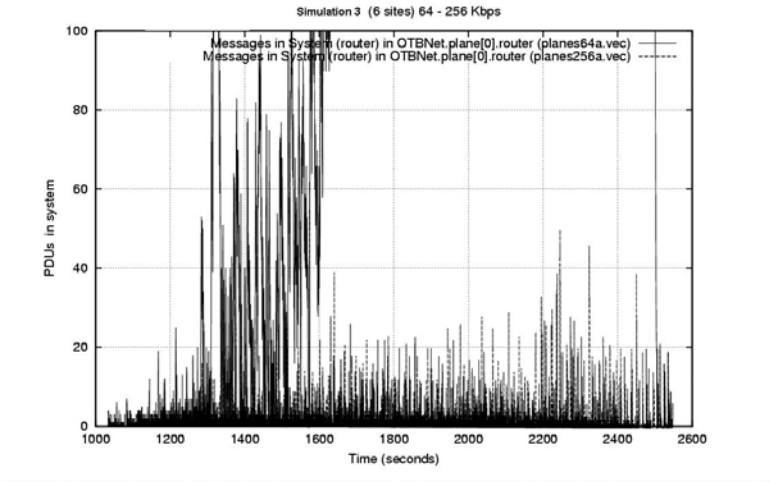


Figure 50: Zoom in of messages in system at plane 0 (64 and 256 Kbps)

At the satellite, the change in the queue length is also noticeable, as shown in Figure 51. At 256 Kbps, less than 25 messages are held in the satellite during the highest peak.

5.6.5 Collisions

There are two factors that influence the way collisions are detected and analyzed in the OMNeT simulator.

First, the simulator considers the transmission media as an ideal bus in the sense that a wave does not become weaker by traveling long distances. As a result, two waves coming form opposite directions can collide in the middle of the bus, but they will continue their ways without being destroyed. Therefore, only a listener located at the collision point can detect the collision. In other words, it is perfectly possible for a collision to be detected at some point of the bus and not at others. Due to

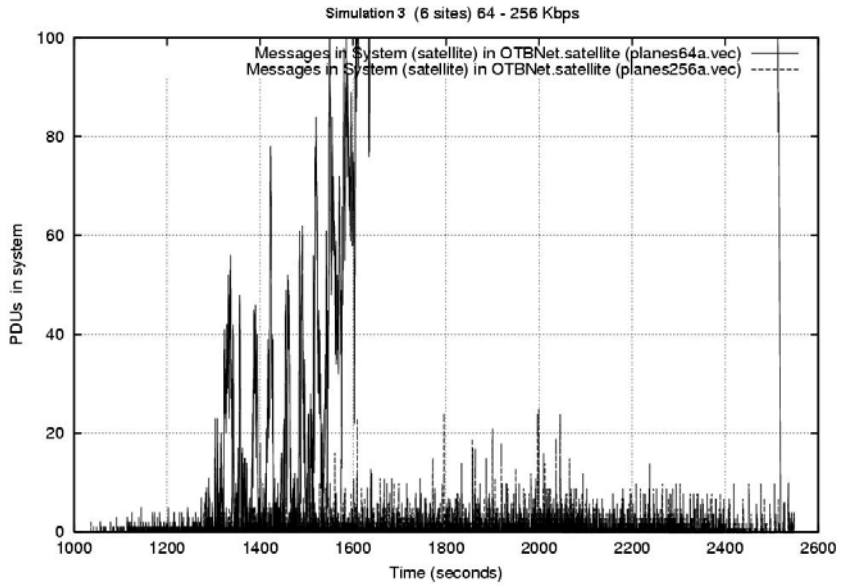


Figure 51: Zoom in of messages in system at satellite (64 and 256 Kbps)

the high propagation speed of the bus, for short distances between nodes, like in the LAN bus or the WPP bus, this behavior is irrelevant. However, for the WSP channel, it has to be taken into account.

Second, the bus was programmed such that a message delivered at some bus gate is not returned back to the sending entity, even if it collided. Therefore, in order to detect collisions, a plain listener node (sentinel) should be chosen, as the router at plane 7 in this simulation.

Figure 52 shows the collision accumulation sensed at planes 1, 2 and 7. Planes 1 and 2 are transmitters and receivers, while plane 7 is a receiver only. A few more than 6000 collisions were detected at 64 Kbps in plane 7, which represents approximately 10% of the total number of PDUs. The statistics are very similar in the three cases, but plane 7 detects more collisions because the other planes cannot detect collisions caused by the sending of their own messages.

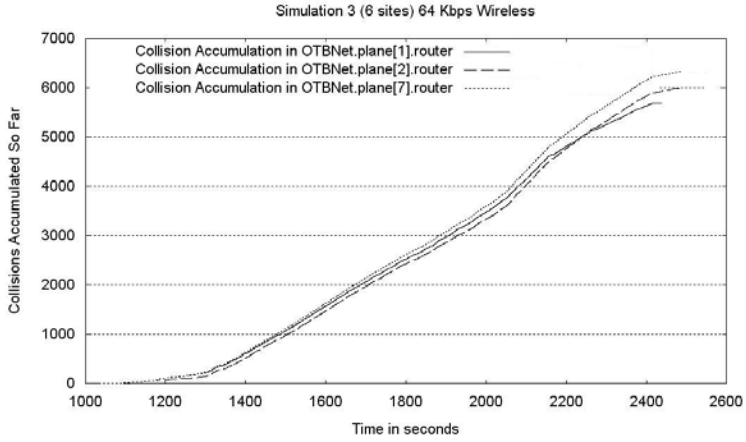


Figure 52: Collision accumulation at planes 1, 2, 7 (64 Kbps)

Figure 53 shows the collisions per second in the WSP wireless channel. The other two links are not displayed because the LAN bus has no observable collisions and the WPP link exhibits just a few ones. The WSP channel gets most of the collisions. At 64 Kbps, the highest rates are close to 13 collisions per second in this channel, near the second 2100, with an average of approximately 4 collisions per second for the whole simulation.

Simulations performed using combinations of 64, 200, 256, 512 and 1024 Kbps in wireless channels showed that the number of collisions decrease when the bandwidth increases, as expected. Collision accumulation statistics viewed from plane 7 are given in Figure 54. At 256 Kbps the total number of collisions is near 3800 that represents about 6% of all the PDUs.

5.6.6 Spike Analysis of Slack Time

Figure 55 shows a zoom in sample of the slack time at the ground station when the model is run at 64 Kbps on wireless channels. Some negative spikes are visible

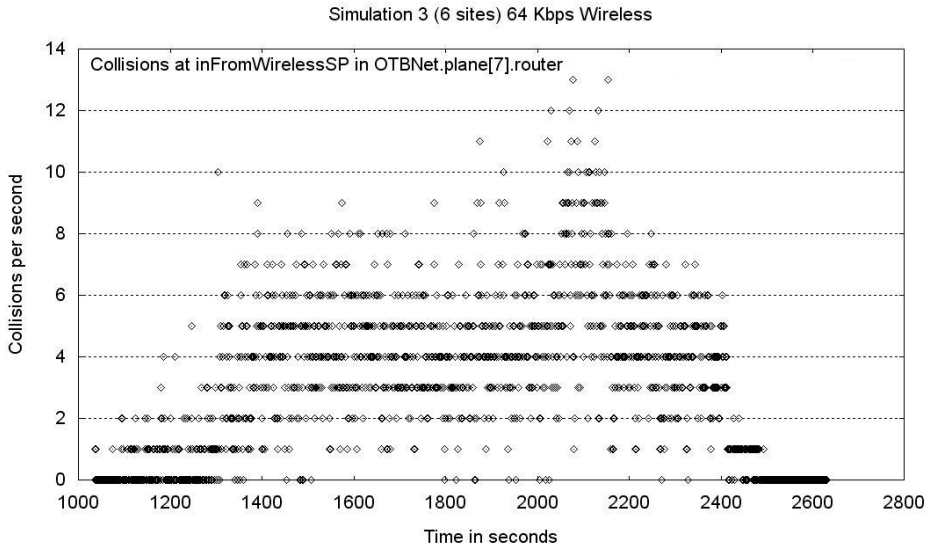


Figure 53: Collisions per second detected at the WSP wireless channel in plane 7 (64 Kbps)

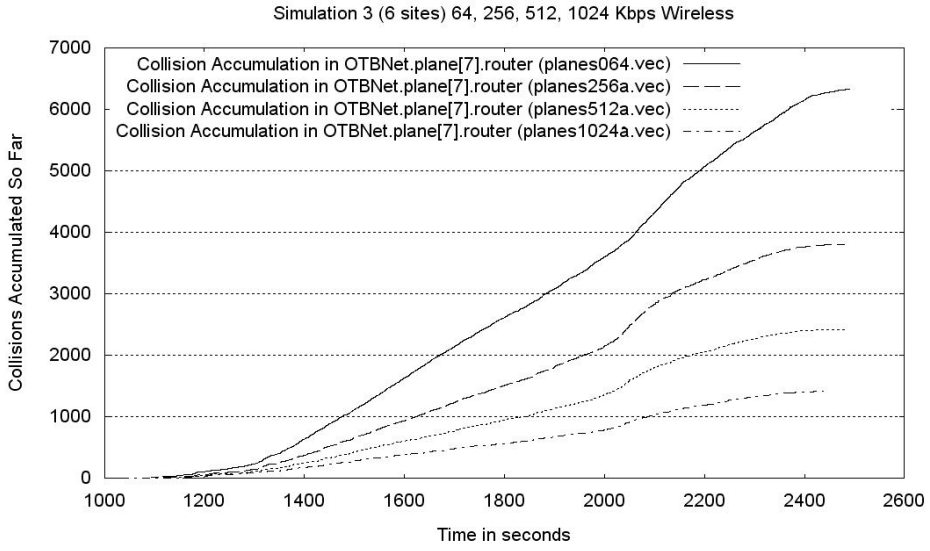


Figure 54: Collision accumulation at plane 7 during Simulation 3 (64, 256, 512, 1024 Kbps)

at regular time intervals. Positive points indicate that the bandwidth is enough to handle the PDUs in the neighborhood previous to the point. On the contrary, negative spikes indicate a lack of bandwidth in the wireless channels. Those spikes deserve more attention to understand and correct the problem. The OTB simulator produces the negative spikes when multiple PDUs are scheduled at the same or almost the same time. Identification of the PDUs responsible for the negative spikes is the first step towards the study and possible modification of the OTB scheduling policy.

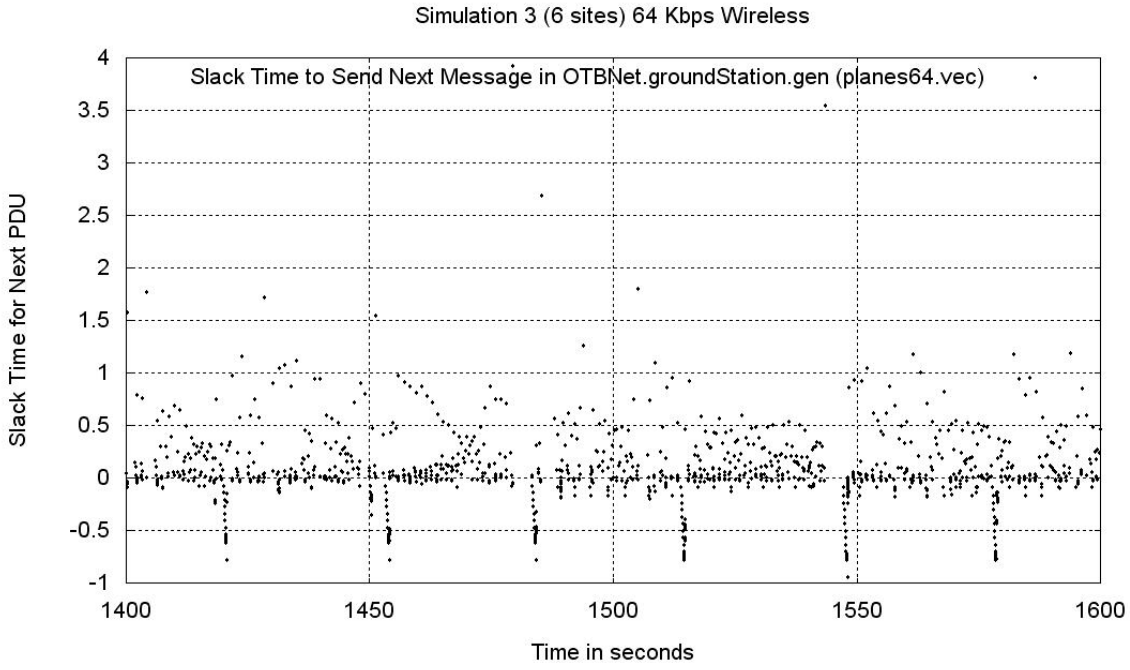


Figure 55: Slack time at ground station showing negative spikes (64 Kbps)

Because the phenomenon seems to be cyclic, one initial approach to explain it relays on the analysis of the different PDUs participating in the spike, correlating them with actions occurring in the vignette at those times.

The sample includes the spikes captured in the time interval [1400, 1600] seconds. This is a representative sample of spikes produced at the generators of PDUs. The

spikes were studied at 64 Kbps. Higher rates cause a decrease in the magnitude of the negative spikes, but the spikes are still present because they are caused mainly by OTB scheduling policies.

The six more relevant negative spikes shown in the graph are studied in the next paragraphs.

5.6.6.1 Spike at second 1420

Figure 56 shows the participating PDUs responsible for the negative spike, along with a close up of the spike graph. It is worth observing that eight `po_fire_parameters` PDUs were issued at the same time, as well as four `po_line` PDUs, among others.

5.6.6.2 Spike at second 1454

As with the previous spike, Figure 57 shows that at second 1454 eight `po_fire_parameters`, four `po_line`, five `po_task`, and five `po_task_state` are responsible for this spike.

The spikes at seconds 1484, 1514, 1548 and 1578 are very similar to the previous ones, and will not be commented out.

size	timestamp	PDU type
84	:23:39.536	po_point
84	:23:39.536	po_point
80	:23:39.883	po_task_state
528	:23:39.982	po_fire_parameters
528	:23:39.982	po_fire_parameters
528	:23:39.982	po_fire_parameters
528	:23:39.982	po_fire_parameters
528	:23:39.982	po_fire_parameters
528	:23:39.982	po_fire_parameters
528	:23:39.982	po_fire_parameters
528	:23:39.982	po_fire_parameters
152	:23:39.982	po_line
152	:23:39.982	po_line
152	:23:39.982	po_line
152	:23:39.982	po_line
56	:23:39.982	po_task_state
1272	:23:39.982	po_task
80	:23:39.982	po_task_state
80	:23:40.540	po_task_state
80	:23:40.633	po_task_state
56	:23:40.639	po_task_state

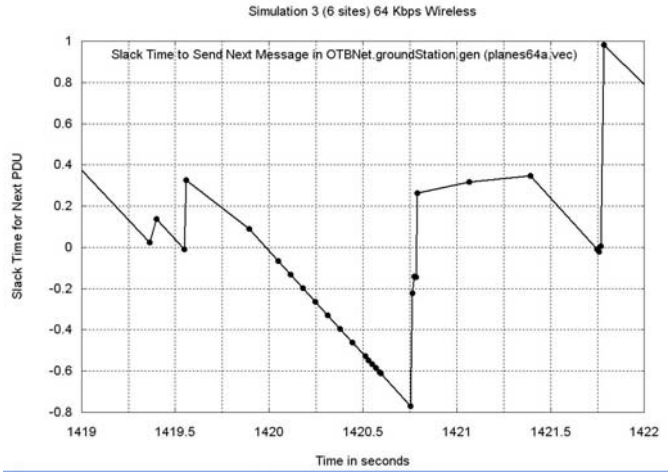


Figure 56: Negative spike at second 1420 showing participating PDUs

size	timestamp	PDU type
528	:24:13.263	po_fire_parameters
528	:24:13.263	po_fire_parameters
528	:24:13.263	po_fire_parameters
528	:24:13.263	po_fire_parameters
528	:24:13.263	po_fire_parameters
528	:24:13.263	po_fire_parameters
528	:24:13.263	po_fire_parameters
528	:24:13.263	po_fire_parameters
152	:24:13.263	po_line
152	:24:13.263	po_line
152	:24:13.263	po_line
152	:24:13.263	po_line
56	:24:13.263	po_task_state
1272	:24:13.263	po_task
80	:24:13.263	po_task_state
80	:24:13.458	po_task_state
80	:24:13.574	po_task
80	:24:13.574	po_task
80	:24:13.574	po_task
80	:24:13.574	po_task
48	:24:13.574	po_task_state
48	:24:13.574	po_task_state
56	:24:14.109	po_task_state

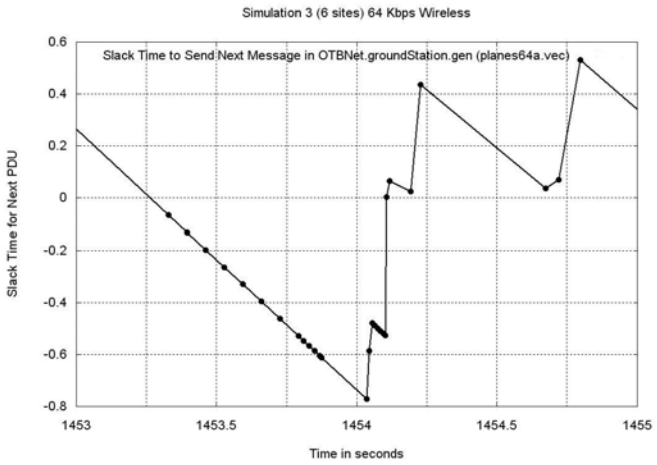


Figure 57: Negative spike at second 1454 showing participating PDUs

size	timestamp	PDU type
80	:24:43.226	po_task_state
80	:24:43.269	po_task_state
80	:24:43.305	po_task_state
528	:24:43.344	po_fire_parameters
528	:24:43.344	po_fire_parameters
528	:24:43.344	po_fire_parameters
528	:24:43.344	po_fire_parameters
528	:24:43.344	po_fire_parameters
528	:24:43.344	po_fire_parameters
528	:24:43.344	po_fire_parameters
528	:24:43.344	po_fire_parameters
152	:24:43.344	po_line
152	:24:43.344	po_line
152	:24:43.344	po_line
152	:24:43.344	po_line
56	:24:43.344	po_task_state
1272	:24:43.344	po_task
80	:24:43.344	po_task_state
80	:24:43.674	po_task
80	:24:43.674	po_task
80	:24:43.674	po_task
80	:24:43.674	po_task
48	:24:43.674	po_task_state
48	:24:43.674	po_task_state
48	:24:43.674	po_task_state
48	:24:43.674	po_task_state
100	:24:43.674	po_objects_present
56	:24:43.890	po_task_state
80	:24:44.529	po_task_state

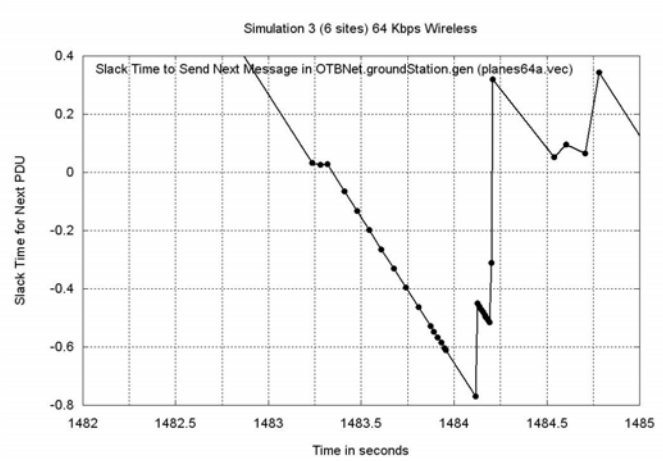


Figure 58: Negative spike at second 1484 showing participating PDUs

size	timestamp	PDU type
648	:25:13.777	po_unit
648	:25:13.777	po_unit
528	:25:13.777	po_fire_parameters
528	:25:13.777	po_fire_parameters
528	:25:13.777	po_fire_parameters
528	:25:13.777	po_fire_parameters
528	:25:13.777	po_fire_parameters
528	:25:13.777	po_fire_parameters
528	:25:13.777	po_fire_parameters
528	:25:13.777	po_fire_parameters
152	:25:13.777	po_line
152	:25:13.777	po_line
152	:25:13.777	po_line
152	:25:13.777	po_line
56	:25:13.777	po_task_state
1272	:25:13.777	po_task
80	:25:14.153	po_task
48	:25:14.153	po_task_state
48	:25:14.153	po_task_state
48	:25:14.153	po_task_state
48	:25:14.153	po_task_state
100	:25:14.153	po_objects_present
56	:25:14.284	po_task_state
80	:25:14.284	po_task_state
80	:25:14.323	po_task_state
80	:25:14.349	po_task_state
80	:25:14.409	po_task_state
112	:25:15.272	po_line

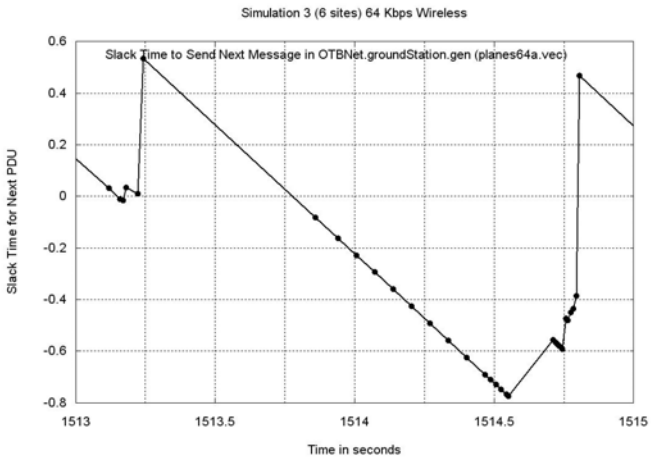


Figure 59: Negative spike at second 1514 showing participating PDUs

5.6.6.3 Spike at second 1484

5.6.6.4 Spike at second 1514

5.6.6.5 Spike at second 1548

size	timestamp	PDU type
648	:25:47.042	po_unit
648	:25:47.042	po_unit
528	:25:47.042	po_fire_parameters
528	:25:47.042	po_fire_parameters
528	:25:47.042	po_fire_parameters
528	:25:47.042	po_fire_parameters
528	:25:47.042	po_fire_parameters
528	:25:47.042	po_fire_parameters
528	:25:47.042	po_fire_parameters
528	:25:47.042	po_fire_parameters
152	:25:47.042	po_line
152	:25:47.042	po_line
152	:25:47.042	po_line
152	:25:47.042	po_line
56	:25:47.042	po_task_state
1272	:25:47.042	po_task
80	:25:47.042	po_task_state
80	:25:47.755	po_task_state
80	:25:47.820	po_task_state
80	:25:47.935	po_task_state
80	:25:48.031	po_task
48	:25:48.031	po_task_state
48	:25:48.031	po_task_state
48	:25:48.031	po_task_state
48	:25:48.031	po_task_state
100	:25:48.031	po_objects_present
112	:25:48.031	po_line
112	:25:48.031	po_line
112	:25:48.031	po_line
112	:25:48.031	po_line
184	:25:48.031	po_task
184	:25:48.031	po_task
184	:25:48.031	po_task
56	:25:48.080	po_task_state
80	:25:48.080	po_task_state

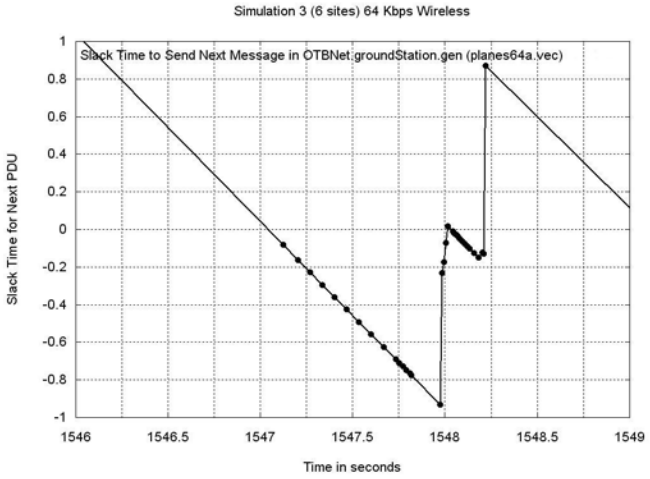


Figure 60: Negative spike at second 1548 showing participating PDUs

5.6.6.6 Spike at second 1578

size	timestamp	PDU type
112	:26:17.516	po_line
80	:26:17.558	po_task_state
648	:26:17.697	po_unit
648	:26:17.697	po_unit
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
528	:26:17.697	po_fire_parameters
152	:26:17.697	po_line
152	:26:17.697	po_line
152	:26:17.697	po_line
152	:26:17.697	po_line
56	:26:17.697	po_task_state
1272	:26:17.697	po_task
80	:26:17.864	po_task_state
80	:26:18.218	po_task_state
56	:26:18.254	po_task_state
80	:26:18.254	po_task_state
112	:26:18.533	po_line
112	:26:18.533	po_line
112	:26:18.533	po_line
184	:26:18.533	po_task
184	:26:18.533	po_task
184	:26:18.533	po_task
80	:26:18.649	po_task_state
80	:26:18.982	po_task_state

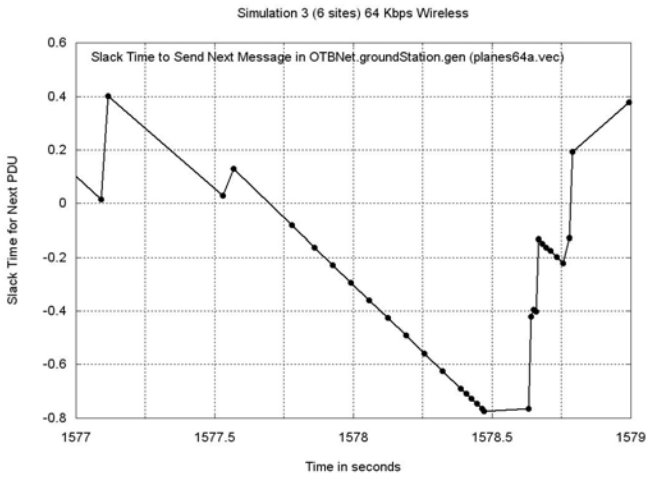


Figure 61: Negative spike at second 1578 showing participating PDUs

5.6.7 Conclusions of Simulation 3

As predicted by the independent analysis, 64 Kbps in the wireless links is completely insufficient to handle traffic in the interval [1600, 2550] seconds. Latencies of more than 70 and 110 seconds were detected at plane 0 for traffic coming from other planes and the ground station, respectively. As predicted, a big

improvement was achieved starting at 200 Kbps. Latencies less than 1 second were almost always the rule for messages received at the ground station. At the router in plane 0 and at the satellite, the queue lengths changed from 3400 and 2200 (max) to less than 50 and less than 25 (max), respectively, just by changing the bandwidth from 64 Kbps to 256 Kbps. Relatively few collisions were detected, which are not enough to significantly change the results or conclusions. A summary of the total number of collisions is given in Table 5.

Table 5: Total, relative percentage and average number of collisions per second in Simulation 3

Bandwidth	Collisions	Percentage	Frequency
64 Kbps	6320 coll.	10.5%	4.2 coll/sec
200 Kbps	4434 coll.	7.3%	2.9 coll/sec
256 Kbps	3804 coll.	6.3%	2.5 coll/sec
512 Kbps	2421 coll.	4.0%	1.6 coll/sec
1024 Kbps	1416 coll.	2.3%	0.9 coll/sec

The negative spikes in slack time studied in Simulation 3 are very similar, including three main types of PDUs: `po_fire_parameters`, `po_line` and `po_task_state` PDUs. In all cases, sequences of these PDUs were scheduled exactly at the same time, causing the spike. It seems that the main sequence of PDUs in a negative spike is of type `po_fire_parameters`, perhaps because the entity (ground station) is firing against some enemy at regular time intervals.

5.7 Simulation 4: Vignette MR1 Revisited

Given that site 1519 assigned to node 0 in plane 0 for Simulation 3 generates 83% of all the PDUs, it seemed interesting to assign it to the CONUS ground station connected to the satellite via a wireless channel. The idea was suggested

by PO_STRI personnel during an update presentation. The results obtained were certainly interesting, and leaded to the developing of the bundling algorithm described in Section 3.4.2.

5.7.1 Independent Analysis of Logged PDUs and Assignment

This simulation makes use of the same data set as in Simulation 3, and so the types of PDUs, data volumes and percentages remain the same. The only difference is that the assignment of sites 1519 and 1532 corresponding to computer 0 and ground station was swapped. Therefore, the assignment of sites to computers in this experiment is as follows.

```
Site 1532 ( 0): 7382 PDUs assigned to plane 0, node 0
Site 1526 ( 3): 1056 PDUs assigned to plane 1, node 0
Site 1529 ( 6): 483 PDUs assigned to plane 2, node 0
Site 1533 ( 9): 553 PDUs assigned to plane 3, node 0
Site 1538 (12): 637 PDUs assigned to plane 4, node 0
Site 1519 (24): 50230 PDUs assigned to ground station
```

The minimum bandwidth requirements are the same as in Simulation 3 and can be found in Figure 41.

5.7.2 Slack Time

As seen in Figure 62, the most noticeable fact is the enormous negative slack (-75 seconds) in the ground station at 64 Kbps. These results are as expected because the ground station has to transmit a large number of PDUs through a slow bus.

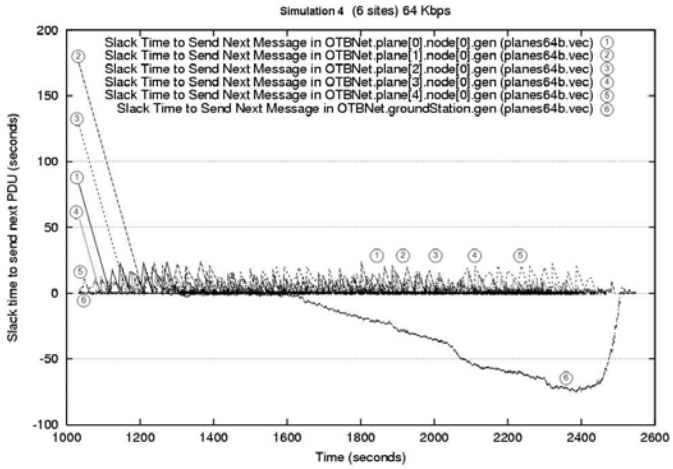


Figure 62: Slack time to send next message at planes 0, 1, 2, 3, 4 and ground station (64 Kbps)

Figure 63 shows the slack time at the ground station when the bandwidth is set to 128 Kbps. Just by increasing the speed from 64 to 128 Kbps, the negative slack time changes dramatically from values close to -75 seconds to values near -1.5 seconds. It is worth noting that a regular pattern of negative spikes is observed at intervals of approximately 28 seconds.

Figure 64 is a zoom in to the Y axis of the slack time at the ground station. The graph clearly show that most of the time the negative slack falls into the interval [-0.4, 0]. Lots of negative spikes of all sizes can be seen in an apparent uniform distribution during the majority of the simulation time.

The positive slack time has a different behavior. As seen, positive spikes are not produced. The reason is that when a positive slack is detected, the simulator

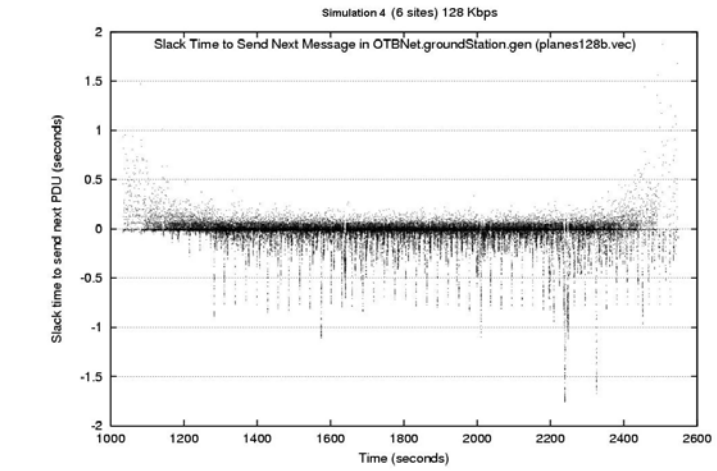


Figure 63: Slack time to send next message at ground station (128 Kbps)

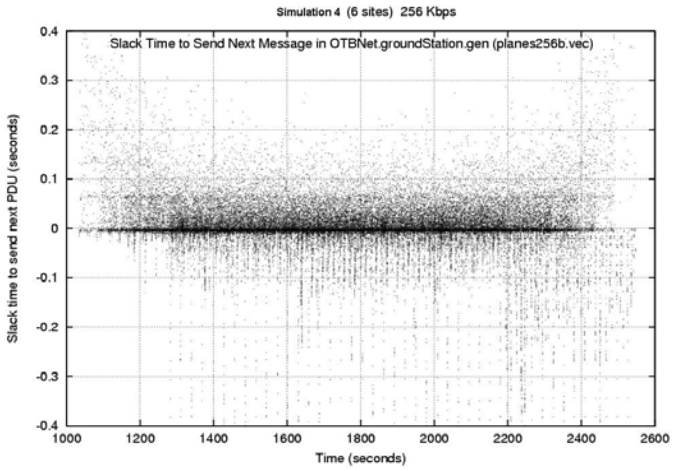


Figure 64: Zoom in of slack time to send next message at ground station (256 Kbps)

waits that time before processing the PDU, and the following PDUs are not read yet. When the simulator is ready to process the next PDU, some time has elapsed. Even if the second PDU has a positive slack, in the graph the points corresponding to the two consecutive PDUs are separated at least by the waiting time, and so a column or spike is not created.

5.7.3 Travel Time

Figure 65 shows the travel time of PDUs measured at node 0 in plane 7, using 64 Kbps in wireless links. The increasing curve comes from PDUs originated at the ground station that waited unbounded latencies at the satellite queue. On the other hand, the PDUs coming from nearby airplanes arrived with a negligible time delay for the scale used.

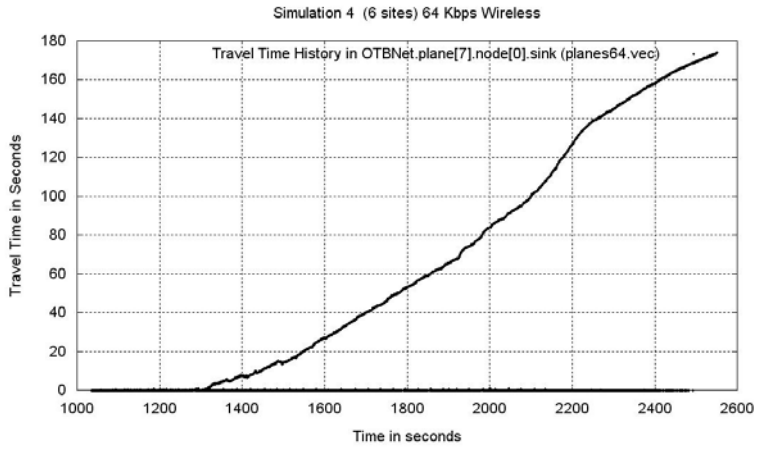


Figure 65: Travel time at plane 7 (64 Kbps)

Increasing the wireless bandwidth to 200 Kbps or more produces an enormous change in the travel time. Figure 66 displays travel times at 256 Kbps. All of the plotted PDUs fall below the level of 0.5 seconds. The graph indicates that the

PDUs belong to two different sets. The first set corresponds to PDUs sent by the ground station. These PDUs needed 0.255 seconds to travel the earth-satellite-earth distance plus some waiting time in satellite and router queues. The second set is made up of PDUs comming from other airplanes. These PDUs waited in the router queues only.

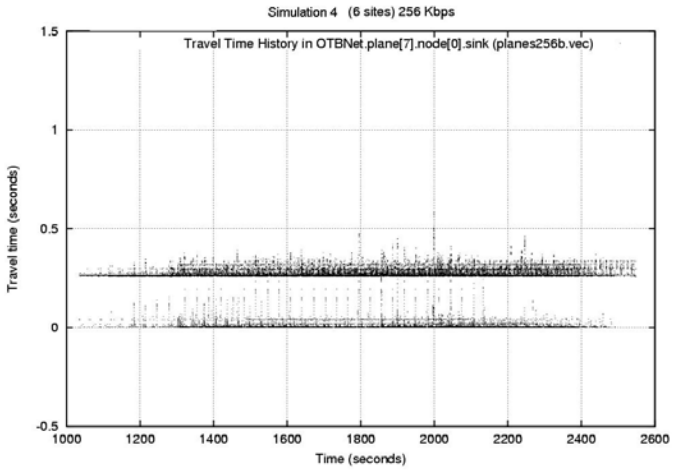


Figure 66: Zoom in of travel time at plane 7 (256 Kbps)

From the said figures, it can be concluded that the change in bandwidth from 64 Kbps to 256 Kbps is a key factor in the overall network performance, conclusion that was already predicted by the offline independent analysis.

5.7.4 Queue Length

Figure 67 plots the queue length at the router in plane 0 for a wireless bandwidth of 64 Kbps. The queue length is manageable, even at 64 Kbps, where the maximum number of messages in the system is less than 80. At higher speeds the queue become noticeable shorter.

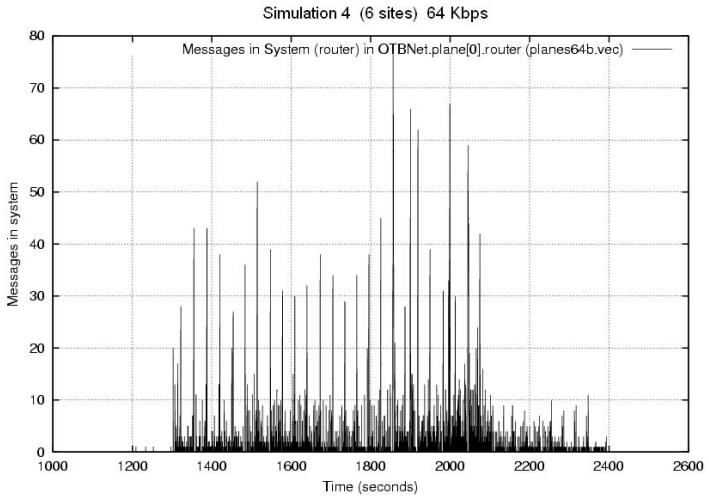


Figure 67: Messages in system at plane 0 (64 Kbps)

However, Figure 68 shows that at 64 Kbps the satellite queue becomes extremely long, reaching values over 6000 messages. Also, it is seen that the change from 64 Kbps to 256 Kbps is impressive, requiring storage for 35 messages only at the highest peak. This length is well handled and achievable, especially if the bundling and replication algorithms proposed in Section 3.4 are implemented.

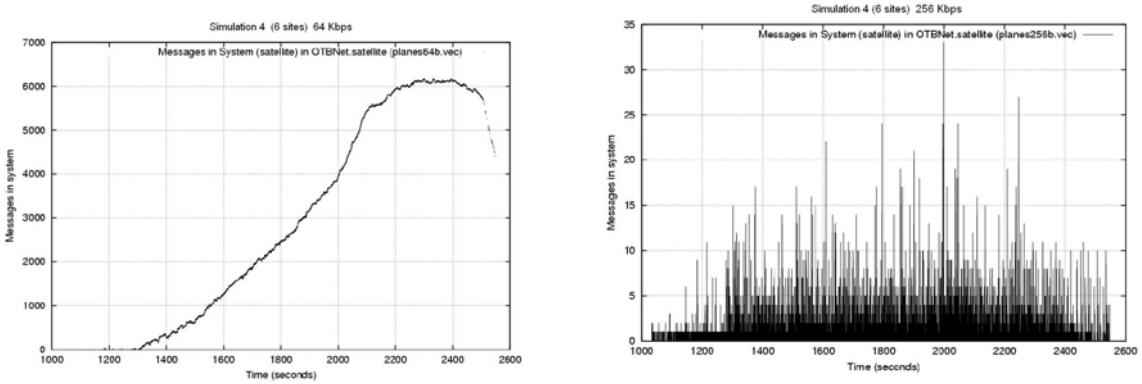


Figure 68: Messages in system at the satellite (64 and 256 Kbps)

By setting the wireless channels to a bandwidth of 1024 Kbps, Figure 69 exhibits what can be considered as an upper bound on the performance achievable on the

satellite queue. As observed, a satellite queue of fewer than 20 messages is very difficult to achieve for the MR1 vignette with the current technology and algorithms.

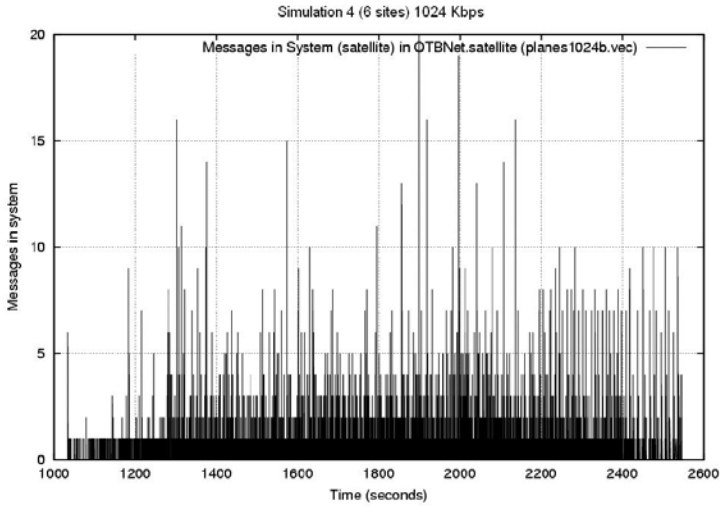


Figure 69: Messages in system at the satellite (1024 Kbps)

5.7.5 Collisions

Figure 70 is the summary of collision accumulation as seen by the sentinel airplane 7 at 64, 256, 512 and 1024 Kbps. At 64 Kbps the number of collisions represent approximately 8% of the total number of PDUs, while at 256 Kbps the percentage descends to 5%. As with simulation 3, collisions are small enough not to cause an important change in the rest of the statistics by not implementing a more standard treatment.

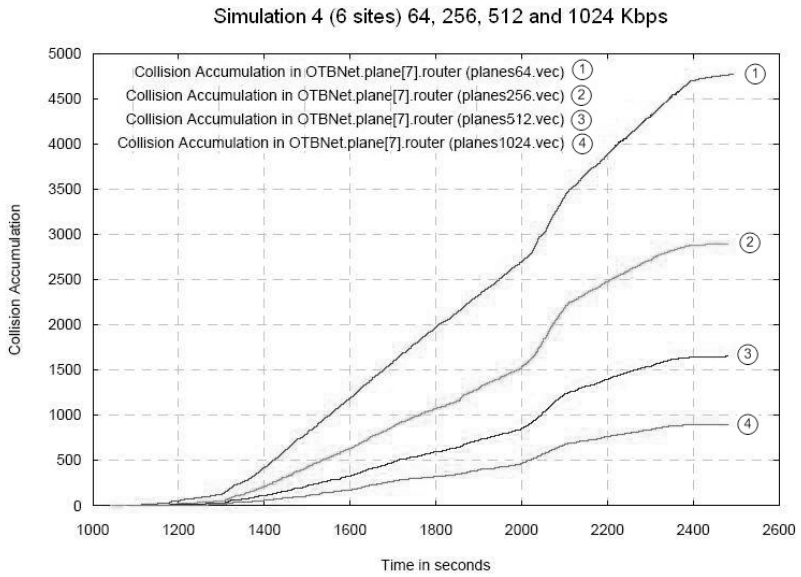


Figure 70: Collision accumulation at plane 7 (64, 256, 512, 1024 Kbps)

5.7.6 Conclusions of Simulation 4

The assignment of site 1532 to the ground station moves the most active computer to this CONUS station, making the bandwidth of the WGS link a key point for network performance assessment. At 64 Kbps very negative time slacks are produced. The reason is that the transmission time of the generator in the ground station is limited by the slow bandwidth and cannot schedule the PDUs as indicated by their timestamps. In other words, the slow bandwidth acts as a contention mechanism.

Increasing the wireless bandwidth to 256 Kbps produces an enormous change in the general performance of the system, result that was predicted by the independent analysis.

5.8 Simulation using Head of Line Strategy

HOL strategies are mentioned in the Ph.D. dissertation [Liu02], in the paper [DGR01], and in the research papers [PW03] and [LS93], among many others.

CHAPTER 6

TRAFFIC OPTIMIZATION USING PDUAlloy

The analysis of negative spikes in Section 5.6.6 induced the idea of a possible solution to eliminate or reduce them by means of bundling the participating PDUs into a single packet. In order to do so, the PDUs were examined in more detail, looking for similarities and redundancies in their fields.

Each type of PDU has its own internal structure made up of fields and values of different sizes. A study of all the logged PDUs in the MR1 vignette indicated that if two PDUs are of the same type and length then they have identical structure, as indicated in Section 3.4.2. This is a key point in the proposed bundling algorithm.

Another observation from the logged PDUs is the fact that OTB schedules some sequences of consecutive PDUs using exactly the same timestamp, as in the sample sequence shown in Figure 56. This causes a bottleneck in generators due to the impossibility of sending several packets at the same time. In most cases, consecutive PDUs of equal type and length differed in the contents of some few fields, giving the possibility of merging them into a single PDU.

6.1 Independent Analysis and Assignment of PDUs

The same input data from Simulations 3 and 4 is used in Simulation 5, and so the independent analysis is exactly the same as in those simulations, reason why it is omitted here.

The assignment of OTB sites to computer nodes in Simulation 5 is the same as in Simulation 4, and can be found in Section 5.7.1.

6.2 Input Data

The summary PDU files described in Figure 19 of Section 5.2 contain 4 characters at the end of each PDU. The characters are *S* standing for *send*, and *W* standing for *wait*. They provide information about the action to follow after processing each PDU. Six algorithms to predict that action are proposed and studied under this Simulation 5. They can be classified in two groups: on-line algorithms, which decide the next action based only on the already processed PDUs, and off-line algorithms, which know all the past and future sequence of PDUs in advance.

In this simulation the on-line algorithms are *neural-network* prediction (see details on Section 3.4.2.1), *Always-Wait* and *Always-Send*. The off-line ones are *type*, *type-and-length*, and *type-length-and-time*, which have the capability of a *perfect prediction* due to their knowledge of the future.

6.3 Slack Time

Figure 71 shows the slack time of the generator at the CONUS ground station for different predictive algorithms.

The graph was created assigning 64 Kbps to all the wireless links and 100 milliseconds to the timeout period. As seen in the diagram, up to the second 1600 all of the algorithms behaved alike, but then negative slack started to build up. The *Always-Send* algorithm, which is equivalent to the *non-bundling* algorithm used in Simulation 4 (see Figure 62), incurred in the largest negative slack, followed

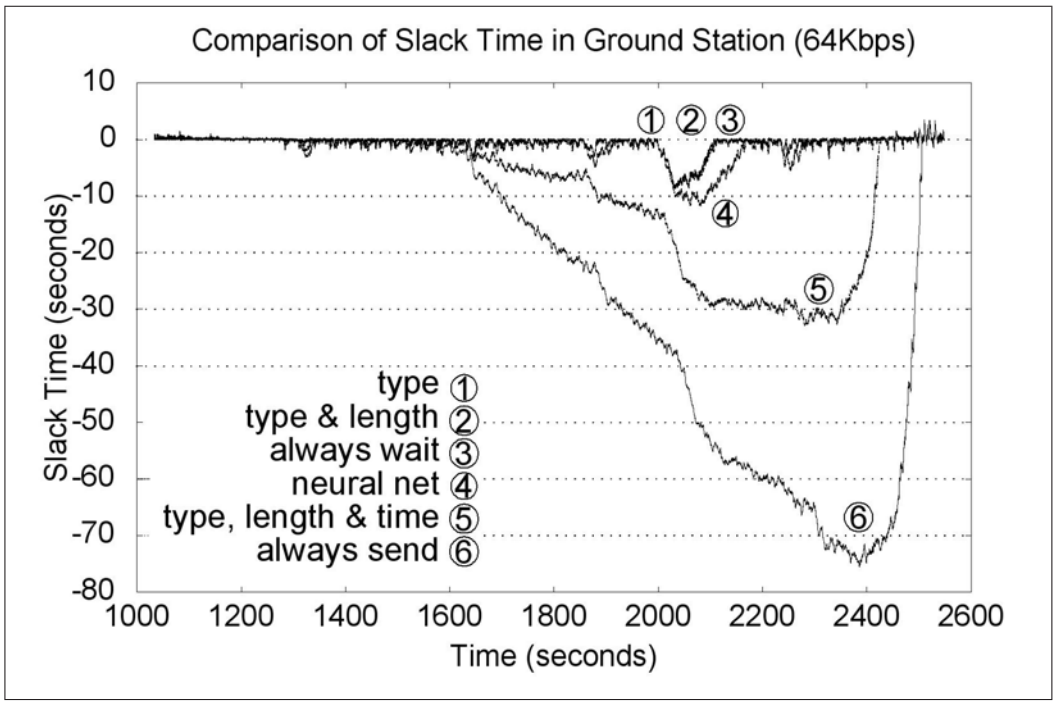


Figure 71: Slack time at ground station for the 6 predictive strategies (64 Kbps)

by *type-length-and-time*. The neural network approach performed relatively well, considering that its predictions are not perfectly accurate. The other algorithms are among the best in this simulation, and a close-up of their performance is shown in Figure 72.

From the graph, it can be concluded that the neural network approach could be improved by using a better learning mechanism and/or NN architecture. The NN algorithm predicts the PDU type based only on the time series of the past 48 PDU types. Therefore, its performance can be compared against the optimal *type* algorithm, obtaining its competitive ratio (as defined in [FL02]) for the cost function *negative slack time*.

Another observation from Figure 72 is that the decision of sending the current bundle based solely on the upcoming PDU type, is as good as the one that considers the type and the length of each PDU. Therefore, a NN approach could benefit from

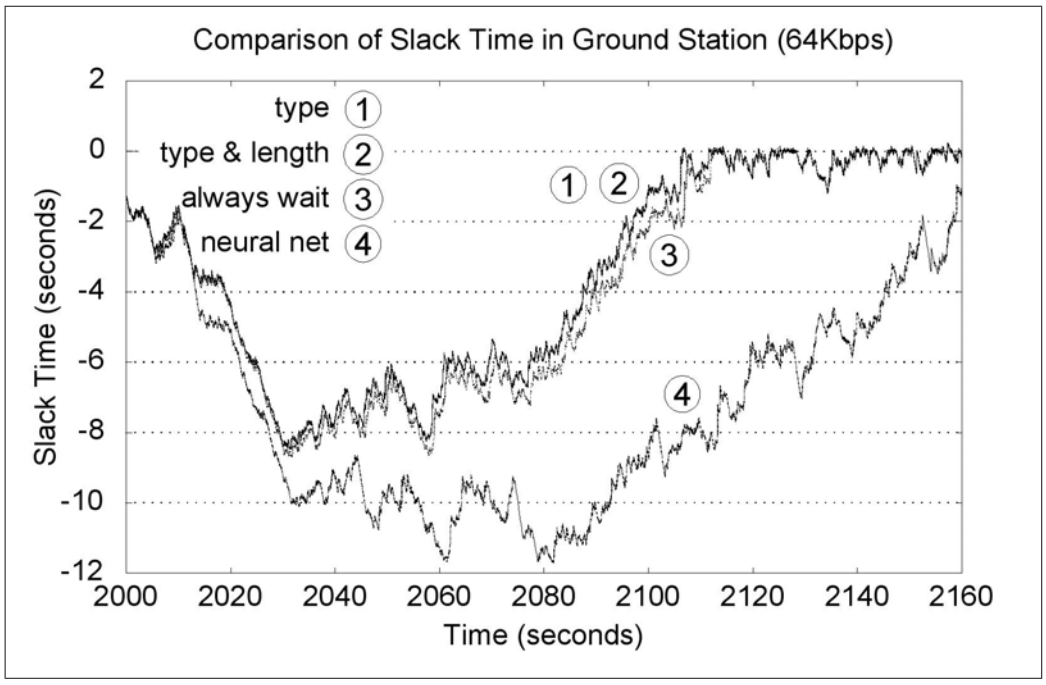


Figure 72: Comparison of negative slack for the four best algorithms

this observation by concentrating the effort in predicting the type only, instead of the type and the length.

However, the most interesting observation comes from the fact that the *Always-Wait* algorithm is almost as good as the one based on the *type-and-length*, and of course, *Always-Wait* is the simplest of all the strategies. The reason is that there is a high probability that the prediction based solely on the type agrees with the prediction based on the type and length. For example, an off-line examination of the PDUs indicated that from the 50230 PDUs sent by the CONUS ground station, 42911 (85.4 %) implied the same action (wait or send) for both algorithms.

Table 6 shows the slack time average and standard deviation for all combinations of algorithms and bandwidths measured at the ground station. The average is a signed number; therefore, the larger the average is, the better the algorithm performs. The average was calculated considering all the PDUs generated during the simulation.

Table 6: Slack time average and standard deviation for all the studied algorithms and bandwidth combinations measured at the ground station

Avg: Std:	64 Kbps	128 Kbps	256 Kbps	512 Kbps
type	-0.758 1.600	-0.017 0.109	0.015 0.073	0.024 0.066
type+length	-0.760 1.601	-0.018 0.110	0.015 0.073	0.024 0.066
type+length+timestamp	-10.659 11.711	-0.027 0.115	0.013 0.073	0.023 0.066
always wait	-0.802 1.689	-0.017 0.109	0.016 0.073	0.024 0.066
NN	-1.579 2.638	-0.044 0.162	0.008 0.085	0.022 0.069
always send	-26.181 26.033	-0.054 0.176	0.006 0.085	0.021 0.069

From this table it is concluded that the *Always-Send* is the worst of the six algorithms, and *Always-Wait* is among the best ones. Because, *Always-Send* corresponds to the non-bundling option, it is inferred that the type of bundling proposed is of advantage to the DIS protocol.

Another observation comes from the fact that at 64 and 128 Kbps, the average slack time was negative for all the algorithms, but for 256 and above it is positive. A negative average indicates that the corresponding bandwidth is insufficient to handle the PDU traffic. Therefore, for the MR1 vignette, the wireless bandwidth should be at least 256 Kbps.

6.4 Travel Time

Every time a bundle is sent, the current time (T_{send}) is attached to it, allowing the destinations to calculate the travel time T_{trav}, as indicated in Equation 5.6. Figure 73 shows the travel time measured at sink 0 onboard plane 0, for the *Always-Wait* strategy, using 64 and 128 Kbps in wireless links. It is clear from the graph that 64 Kbps is not enough bandwidth to handle all the traffic required by the simulation, even with bundling. As seen, during the interval from second 2000 to second 2400 many of the PDUs took almost 40 seconds to arrive at their destinations, making the OTB simulation useless. However, a big improvement is obtained just by duplicating the bandwidth. At 128 Kbps, the latency was close to 0.8 seconds, as observed in Figure 74.

Figure 74 shows that most of the PDUs take less than 0.4 seconds to reach their destinations. It is interesting to note the large concentration of PDUs near 0.25 seconds, which is the propagation delay for satellite signals. The graph also shows

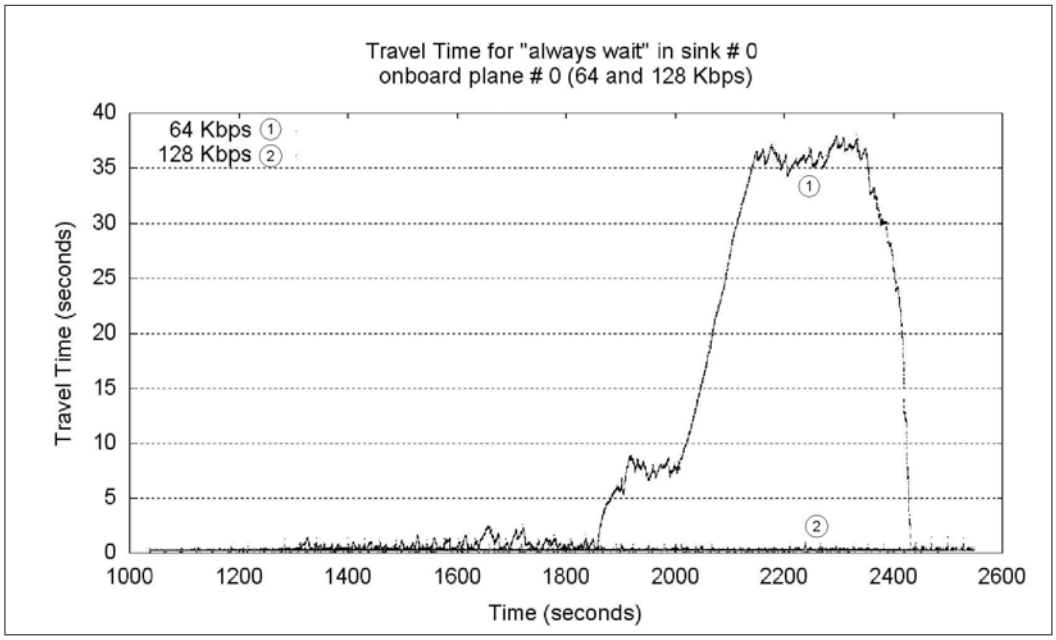


Figure 73: Travel time for the *Always-Wait* strategy, at destination 0 onboard plane 0, using 64 and 128 Kbps in wireless links

that some PDUs take less than 0.1 seconds of travel time. Those PDUs correspond to messages sent from other airplanes without passing through the satellite.

Table 7 shows the average and standard deviation of the travel time for each combination of algorithm and bandwidth, measured at sink 0 onboard plane 0. Considering that approximately 83 % of the PDU traffic arriving at sink 0 comes from the ground station via satellite, and that for those PDUs, 0.255 seconds is an unavoidable delay, the table shows a very good behavior of the algorithms at 256 Kbps or more, giving a slight advantage to *Always-Wait* bundling.

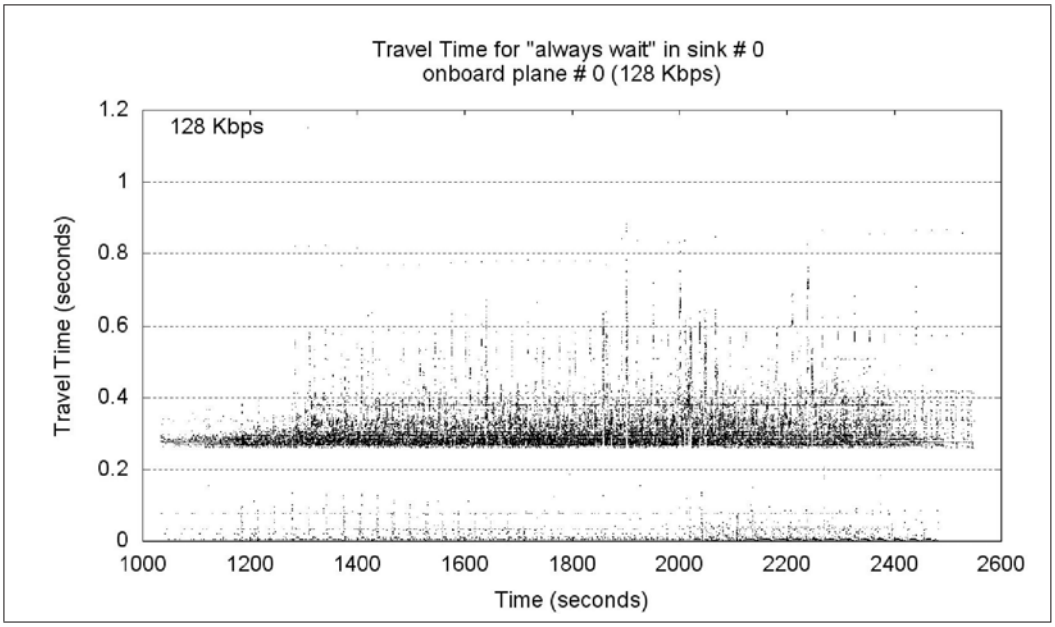


Figure 74: Close-up of *travel-time* at sink 0, plane 0 (128 Kbps)

Table 7: Average and standard deviation of travel time measured at sink 0

Avg: Std:	64 Kbps	128 Kbps	256 Kbps	512 Kbps
type	9.20 13.2	0.304 0.099	0.262 0.069	0.249 0.064
type+length	9.24 13.2	0.306 0.101	0.262 0.069	0.249 0.064
always wait	9.43 13.5	0.303 0.099	0.261 0.069	0.249 0.064
NN	28.7 33.2	0.314 0.119	0.261 0.069	0.248 0.064
always send	64.0 58.0	0.333 0.153	0.263 0.062	0.251 0.057

6.5 Queue Length

Due to the nature of the PDU traffic in the simulation, two queues to focus attention on are the router queue onboard any aircraft, for instance airplane 0, and the satellite queue. Figure 75 shows the satellite queue at 64 and 128 Kbps.

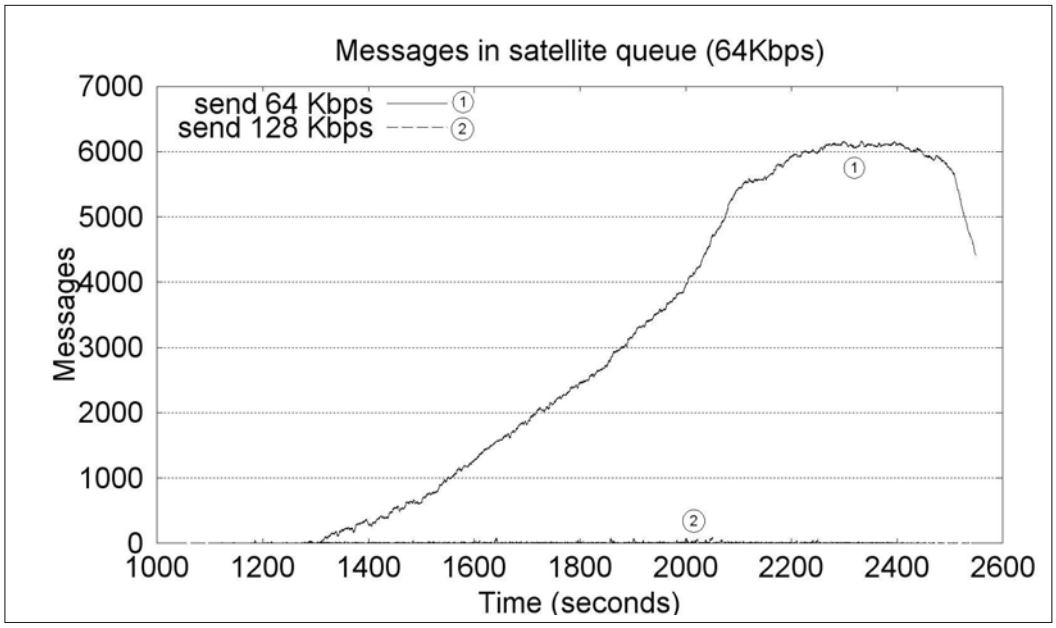


Figure 75: Messages in satellite at 64 and 128 Kbps showing the impact of a higher bandwidth on its queue

It is clear from the graph that 64 Kbps is an insufficient bandwidth, causing the satellite queue to grow unbounded. The reason for having a descent after reaching a maximum of about 6000 messages, is that the simulation is approaching its end and no more messages are sent from the generators. However, at 128 Kbps a significant change in the queue length is produced, keeping it at reasonably low values.

Another observation is that at 64 Kbps the graph does not reach zero at the end. This occurs because the queue status is reported only if another message enters the queue. After the arrival of the last message to the queue, the messages are consumed without being reported.

Table 8 displays the average and standard deviation of the satellite queue length for combinations of different algorithms and bandwidths. Again, *Always-Wait* seems to be the best algorithm, closely followed by *type* and *type-and-length*.

Table 8: Average and standard deviation in the satellite queue length for combinations of algorithm and bandwidth

Avg: Std:	64 Kbps	128 Kbps	256 Kbps	512 Kbps
type	316.97 411.43	2.38 3.97	0.91 1.72	0.56 1.23
type+length	318.154 412.273	2.44 4.13	0.92 1.75	0.56 1.26
always wait	327.278 421.161	2.30 3.88	0.85 1.69	0.49 1.16
NN	1028.47 1045.26	3.58 6.37	1.24 2.18	0.79 1.52
always send	2962.94 2236.83	5.40 10.78	1.22 2.55	0.63 1.57

6.6 Collisions

Collision accumulation in plane 7 at different bandwidth rates is given in Figure 76. The results from the simulation indicate that at 64 Kbps the highest collision rate measured at the router aboard airplane 7 was close to 12 collisions per second, and this occurred during the time interval [2050, 2100] in the WSP link that connects the satellite to the planes. At 64 Kbps, fewer than 4800 collisions were detected in all for the *Always-Send* algorithm, which represents less than 8 % of the total number of PDUs. On the other hand, at 256 Kbps the total number of collisions for the *Always-Wait* algorithm was close to 2100, or 5.3 % of all the bundles.

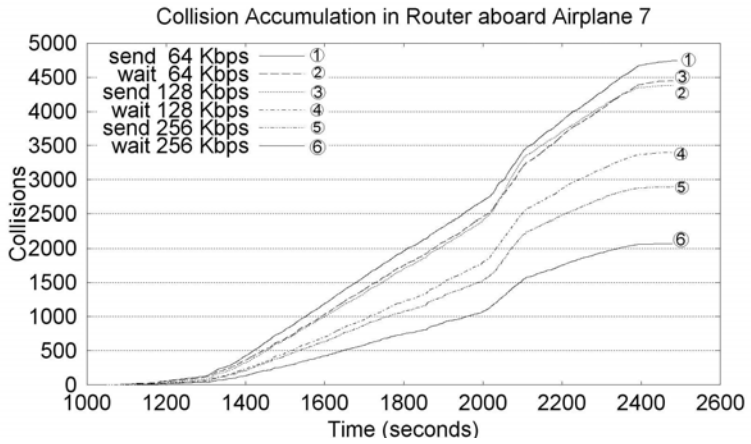


Figure 76: Collision accumulation at plane 7 (64, 256, 512, 1024 Kbps)

As Figure 76 shows, at 128 and 256 Kbps there is roughly a total difference of 1000 fewer collisions for the *Always-Wait* than for the *Always-Send* algorithm, which indicates that bundling significantly reduces the number of collisions, given the same bandwidth for both algorithms. In addition, it can be noted that as the bandwidth increases, the number of collisions decreases, which is intuitively explained because at higher bandwidths the packets take less transmission time, and so the probability of a collision gets lower.

6.7 Conclusions of Simulation 5

The main conclusion of this simulation is that the type of bundling proposed in this dissertation proved to be successful during the simulation of the MR1 vignette. All the algorithms based on bundling performed a lot better than the non-bundling *Always-Send* algorithm.

prediction based solely on the PDU type is almost as good as the prediction based on the type and the length, and these predictions are better than the *Always-Wait* algorithm by half a second in some cases. Therefore, a NN approach could be useful if the percentage of successful guesses is so high that outperforms the *Always-Wait* algorithm.

Another conclusion is that the *Always-Wait* algorithm, although not optimal, gives very good results that can be acceptable in many cases, especially if the bandwidth is incremented. Let's take into account that the shown results are simulations at 64 KBps. At higher bandwidths, the difference between *Always-Wait* and the perfect guessing algorithms (*type*, *type-and-length*)becomes smaller, giving the easy-to-program *Always-Wait* strategy a relevant importance.

The final conclusion about the bandwidth is that 256 Kbps in wireless channels is the minimum bandwidth for the MR1 vignette that passes all the tests (slack time, travel time, queue length, and collisions) in an acceptable way.

CHAPTER 7

CONCLUSIONS

There are three main sets of conclusions that can be drawn. The first set corresponds to conclusions about the required bandwidth in the wireless channels to carry out the OTB simulation. The second set corresponds to conclusions about the effectiveness of the bundling techniques.

The simulation issues in this dissertation can be divided into three main areas: re-scheduling and transmission of PDUs, replication and prediction of PDUs, and PDU compression. In the following, each area is briefly addressed.

7.1 Scheduling

The re-scheduling and transmission of PDUs is an attempt to reduce the negative slack spikes by transferring some of their PDUs to periods of positive slack. Not only the `po_fire_parameters` PDUs are subject to be rescheduled, but any PDU that involves some sort of negative slack could be reschedule. The goal is to obtain a traffic as close as possible to a burst-free model to keep the channels busy but not flooded.

The DIS protocol is responsible for the timestamps of the PDU packets. If many PDUs are scheduled not only at the same microsecond, but also within a very short time interval, the effect is similar to a negative spike. The experiments with the OMNeT simulation showed that mixed with negative spikes there are many positive

ones. The positive spikes indicate that the channel is not used during those intervals and so rescheduling of the PDUs could bring a better utilization of the channel. If a sequence of PDUs timestamped at almost the same time followed by periods of rest can be recognized and predicted, then the scheduler could implement a type of contention to refrain from sending those PDUs so close to each other and spread the sending times evenly throughout the intervals of low traffic. In doing so, the length of each PDU must be taken into account because it is proportional to the transmission time.

The proposed research will require access to the specific formats and characteristics of PO_PDUs. Also, the implicit assumption that in OTB some PDUs can be rescheduled and be sent in a different order without adversely affecting the overal simulation must be corroborated. If that is the case, we propose to identify priority levels for PDUs.

It is possible to introduce modifications in the PDU scheduling aimed at reducing the traffic by sending just one PDU in cases where several of them are sent at the same timestamp.

The observations pointed out in the conclusions suggest that it is possible to introduce modifications in the PDU scheduling aimed at reducing the traffic by sending just one PDU in cases where several of them are sent at the same timestamp. The idea is to investigate the possibility of introducing a kind of protocol compression to eliminate redundancy in consecutive PDUs. For instance, if several `po_fire_parameters` PDUs are sent, only one real PDU could actually be sent, along with some new fields indicating the number of PDUs scheduled at this time as well as an indication of the changes to be applied in order to extract the other PDUs from the given one.

A side effect of reducing the PDU traffic is a decrease of collisions, especially if the PDUs are relatively long, as is the case of `po_fire_parameters` PDUs. Ten

consecutive PDUs of this type account for 5280 bytes plus the time gaps between frames. During the transmission time of these PDUs, the channels are heavily occupied and any other attempt to transmit from another station over the same channel will end up in a collision. By sending just one PDU of approximately 550 bytes will decrease the probability of having a collision.

`po_fire_parameters` PDUs can be successfully compressed under certain conditions.

A side effect of reducing the PDU traffic is a decrease of collisions, especially if the PDUs are relatively long, as is the case of `po_fire_parameters` PDUs. Ten consecutive PDUs of this type account for 5280 bytes plus the time gaps between frames. During the transmission time of these PDUs, the channels are heavily occupied and any other attempt to transmit from another station over the same channel will end up in a collision. By sending just one PDU of approximately 550 bytes will decrease the probability of having a collision.

The re-scheduling and transmission of PDUs is an attempt to reduce the negative slack spikes by transferring some of their PDUs to periods of positive slack. Not only the `po_fire_parameters` PDUs are subject to be rescheduled, but any PDU that involves some sort of negative slack could be reschedule. to obtain a traffic as close as possible to a burst-free model to keep the channels busy but not flooded.

The experiments with the OMNeT simulation showed that mixed with negative spikes there are many positive ones. The positive spikes indicate that the channel is not used during those intervals and so rescheduling of the PDUs could bring a better utilization of the channel. If a sequence of PDUs timestamped at almost the same time followed by periods of rest can be recognized and predicted, then the scheduler could implement a type of contention to refrain from sending those PDUs so close to each other and spread the sending times evenly throughout the intervals of low traffic.

some PDUs can be rescheduled and be sent in a different order without adversely affecting the overal simulation

Besides the common compression algorithms, another strategy to consider is the concatenation of several consecutive PDUs scheduled during very short periods of time. The time gap between packets is also a variable to consider. It is possible to save TCP/IP headers and inter-packet time gaps by assembling together individual PDUs into a large compact block. If the size of the largest acceptable block is known, the problem of assembling shorter PDUs is twofold. First, a new set of PDUs is collected and concatenated as long as the total size does not surpass the block length. Second, while waiting for the next PDU a decision must be made regarding the convenience of sending this block right now, or keep waiting for a while. Here, the possibility of predicting the timestamp of the next PDU is a big help to this decision. Some pattern recognition techniques could be applied to predict a sequence of very close PDUs followed by a positive spike.

7.1.1 Required Bandwidth

The goal behind the development of this research was to estimate the required bandwidth in the wireless channels for the effective communication of the OTB modules in the flying network depicted in Figure 1. The LAN segments were assumed Ethernet at 100 Mbps.

A vignette was prepared and run by OTB, simulating the 24 flying sites plus the ground station. The PDU traffic generated was captured and used as input to the OMNeT simulator, preserving the original timestamps, types and lengths. The OMNeT simulator was run under several combinations of wireless bandwidths (64,

128, 256, 512, 1024 Kbps) and bundling techniques (Always-Send, neural network, type, type+length, Always-Wait).

From the results of the OMNeT simulation, it is concluded that 64 Kbps in the wireless links are not enough to handle the PDU traffic, due to the enormous negative slack reported in the generators (Figure 71), the big travel time latency reported in Figure 73, and the long satellite queue shown in Figure 75. However, at 128 Kbps the scenario changes dramatically, and at 256 Kbps it gets even better. It seems that an average of 0.26 seconds in the travel time and 2.3 messages in the satellite queue are good indicators of performance. However, the negative average of -0.017 seconds indicates that 128 is not really enough bandwidth. Therefore, the conclusion is that the required bandwidth should be at least 256 Kbps in the wireless links.

The independent analysis performed on the logged data is an important procedure in the assessment of bandwidth because it gives a good initial insight about the minimum instant bandwidth required at a fraction of the cost of a complete simulation. It can be used also to identify periods of low and high network traffic, and correlate them with actions being developed by the simulated parties for a better understanding of the simulation behavior.

7.1.2 Effectiveness of bundling

All of the statistics presented indicate that bundling is an effective technique for reducing the PDU traffic and better utilize the bandwidth. The reductions in negative slack (Figures 71 and 72), travel time (Table 7), satellite queue length (Table 8), and number of collisions (Figure 39) are all indicators in that sense.

The replication of PDUs through bundling presented in this research differs from other proposals [US95a, Tay95, Tay96b, Tay96a, Ful96, BCL97, PW98, WMS01] in several ways. First, bundling takes into account the internal structure of each PDU; only PDUs of the same type and length are put together in a bundle. Second, the resulting bundle has a structure similar to any other PDU and can be considered a PDU of a different type, subject to further bundling or compression technique if desired. Third, the bundling algorithm is simple and easy to implement, as well as the extraction of individual PDUs at the destination. Each bundle is independent of the others and all the information needed to extract the PDUs is contained in the same bundle. A previous *basic* PDU sent to the destinations containing static values is not used in this approach.

The bandwidth analysis showed that, on the average 256 Kbps in the wireless channels are sufficient to handle the traffic of experiments 1 and 2 corresponding to the contracted vignette, except for the negative spikes of the slack time detected at the sending stations.

The main cause of those negatives spikes is the scheduling of PDUs having exactly the same timestamp. The analysis of the largest spikes showed that PDUs of type `po_fire_parameters` are the main components of those spikes and sequences of 8 or more PDUs are common. Each po_fire_parameters PDU has a length of 528 bytes.

Comparisons of samples of po_fire_parameters PDUs for the same spike indicated that they are very similar, having differences related to PDU identification and memory address of the PDU fields only. Other types of PDUs scheduled at exactly the same timestamp have not been investigated yet, but it is quite possible that PDUs of the same type bearing the same timestamp are very similar.

In Simulation 1 ... as predicted, 64 Kbps in the wireless links is insufficient to handle Embedded Training traffic under a DIS-like protocol. Latencies of more than 70 and 100 seconds, respectively, were detected for traffic from simulation stations

on other planes and at the ground station where the Opposing Force simulated entities would be controlled. As predicted, a significant improvement was achieved at 200 Kbps, where latencies less than 1 second were almost always the case for messages received at the ground station.

At the router in plane 0 and at the satellite, the queue lengths changed from 3400 and 2200 (max) to less than 60 and less than 40 (max), just by changing the bandwidth from 64 Kbps to 200 Kbps. As seen by the listener router at plane 7, collisions are manageable, and decrease correspondingly as the bandwidth increases, as shown in Table 9.

Table 9: Collision Accumulation, percentage and average collisions per second at plane 7 for different bandwidths

Bandwidth Kbps	collisions	percentage	collisions/sec
64	6300	10 %	2.5
200	4400	7.3 %	1.7
512	2300	3.8 %	0.9
1024	1300	2.1 %	0.5

In simulation 2 ... the assignment of site 1532 to the ground station moves the leadership computer to this station, making the bandwidth of the wirelessGS link a key point. At 64 Kbps very negative slacks are produced. This is easy to explain. The generator inside the ground station is limited by the slow bandwidth and cannot schedule the PDUs as indicated by their timestamps. In other words, the slow bandwidth serves as a contention mechanism.

Increasing the wireless bandwidth to 256 Kbps produces an enormous change in the general performance of the system. The experiments showed that the negative spikes have a very similar PDU structure, with 3 main types of PDUs: po_fire_parameters, po_line and po_task_state PDUs.

It seems that the sequence mainly responsible of negative spikes is of type po_fire_parameters, perhaps because the entity studied (ground station) is firing against some enemy. This hypothesis needs to be corroborated against an actual run of the OTB vignette. If the hypothesis is corroborated, then it can be concluded that firing activities cause those spikes.

Also, although not a universal contribution, through this research the Electrical and Computer Engineering Department of the University of Central Florida got familiar with the OMNeT software, which is in the public domain and provides a quality simulation environment for C++ programmers. The development of the simulator for handling PDUs of an OTB application is an example of OMNeT usage that can serve as a starting basis for other projects.

CHAPTER 8

FUTURE WORK

8.1 Future Work

Better NN predictive algorithm. Another branch of research could be based on the prediction of the type for the upcoming PDUs. The neural network developed in this study was very simple, having an accuracy of prediction close to 70 %. If an improved neural network is developed, it could beat the *Always-Wait* strategy. However, a careful comparison in terms of simplicity and usage of CPU time and memory between both algorithms would be required.

Specific format of PO_PDUs, not only regular PDUs, must be studied and incorporated in the bundling strategies.

we propose to identify priority levels for PDUs. By using Head-of-Line (HOL) queueing service strategies such that high priority PDUs are put at the front of the queue, the critical PDUs will be scheduled on time for the consistency of the simulation.

technique that can be used to diminish negative spikes and in general make a better usage of the available bandwidth is related to data compression. Compression can be applied at two levels: data compression of the PDU data, and compression of the TCP/IP headers.

Several possibilities of future work are open. The bundling algorithm could be extended to consider PDUs of the same type but different length as candidates to

be included in the bundle. Also, the bundling of PDUs of different types could also be researched as long as the resulting bundle still keeps the structure of a PDU.

The bundling strategy aimed at preserving the message structure could be applied to other communication protocols or data streams besides DIS. For instance, if a large database needs to be transmitted through a slow network and the records have some sequence relationship such that repeated fields are often found in consecutive records, the records could be bundle using the algorithms presented in this article.

The implementation of the said PDU compression and rescheduling techniques could be made inside OTB directly, or by appending a filter to the OTB output, together with a de-filter module at the receiving site. The filter has the advantage of not modifying the current OTB implementation, at a cost of less efficiency. But for the goals of this research, it is enough to demonstrate that the proposed techniques are reasonable and achievable.

It must be investigated whether the compression of PDUs can be done by extending the current PDUs with new fields, or by creating a new PDU type with the new fields, and then send it as a prefix to the PDU that will be expanded.

An additional product obtainable from the project is the development and maintainability of UCF OMNeT++ models and logger files based on generic libraries suitable for FCS capacity planning and requirements generation. A self-contained executable demo is a valuable help for future presentations of the project.

APPENDIX A
MR1 VIGNETTE

APPENDIX A

MR1 VIGNETTE

This vignette is due to Dr. Avelino González and Dr. Michael Georgiopoulos.

A.1 Background

In 2014, twenty years of independence for the Trans-Caucasus States found serious socio-political, ethno-religious, and economic conflict spreading throughout the region. Azerbaijan emerged as the leading economic power through the exploitation of Caspian and Central Asian oil reserves. Azerbaijan's politics were deeply divided; its citizens and Karabakh refugees demanded the government take military action against the Armenian Karabakh that forced them to flee. The Azerbaijani government refused to act, and refugees from the Nagorno-Karabakh Internal Liberation Organization [NKILO], using terror and armed force to achieve their goals, began a cross-border unconventional campaign designed to force a confrontation between the two countries. Observing these developments, Armenia and Iran viewed the Azerbaijani government's instability as an opportunity to expand their influence in the region for political gain. Armenia began massing maneuver forces along the Azerbaijani border and repositioned mobile Theater Ballistic Missile launchers. Both countries perceived a low risk of failure in executing their campaign strategy and were willing to impose a military solution upon *the Azerbaijani problem.*

In November 2014, initial reports of the Caspian Sea Peninsula crisis caused the U.S. to take steps to improve its awareness of the developing situation. The Secretary of Defense redirected intelligence assets to focus on the region and directed political and military planners to formulate contingency plans for U.S. engagement in the region. They determined an Army Objective Force Unit of Employment 2, operating as the Army component of a joint force, would be required to accomplish U.S. goals in the region and assigned operational control of the 15^{th} Division air-ground task force to USEUCOM for planning purposes. Warning orders were issued through USEUCOM to the U.S. 15^{th} Division air-ground task force, and supporting attack and lift aviation assets to begin their own planning. US Army Europe (USAREUR) and its theater support command (TSC) reviewed and updated contingency plans and refined the sustainment preparation of the theater. The TSC issued warning orders and created a provisional logistics/sustainment task organization called the Area Support Group (ASG) that would support land forces employed in theater.

In late November, the Azeri Islamic Brotherhood (AIB), a coalition of anti-government factions supported by NKILO and the Azerbaijani National Front for Revolutionary Action (ANFRA) military forces, subverted the bulk of an Azeri Motorized Rifle Brigade, which mutinied to realign with this faction. The brigade seized control of most of the historically significant Icheri Sheher (Inner Town) district in Baku. However, a desperate defense by loyal government forces managed to secure the centers of government within the capital city. Meanwhile, two armed clan-based factions of the Azeri Islamic Brotherhood, the Aziz and Daha, extended their control of the eastern and western outskirts of Baku, respectively, and intensified their efforts to overthrow the legitimate government. As a last resort, the Azerbaijani government requested assistance from the Russian Federation to defeat the insurgents and preclude an anticipated invasion by Armenian forces. On 15 December, Russia proposed a coalition of U.S. and Russian forces to restore

order within Azerbaijan and stabilize the government. Two days later, the U.S. agreed to the proposal and the two nations created a coalition force and outlined its employment plan. The joint force commander, United States European Command (USEUCOM), and his Russian counterpart formed a coalition staff that included a coalition/joint theater logistics management element (C/JTLME). The C/JTLME continued to develop plans to logistically support coalition forces employed in theater and to determine the most efficient use of all coalition movement, sustainment, and facilities assets.

United States European Command focused its main effort at developing the situation and expanding the knowledge base already resident from the Operational Net Assessment of this region. They pre-positioned incremental force packages to establish a military presence in the region and deter any further hostilities, establishing a C4ISR architecture, and posturing to project forces directly into Azerbaijan and to dismantle Armenian C4ISR and fires systems. The combatant commander deployed Special Operations Forces (SOF) into the region, adding an additional layer of intelligence collection assets to the national-level space and air-based assets already operating over the region. Initially, their efforts were focused on developing the situation in the region of the beleaguered government in Baku. But as the 15^{th} Division matured its plans, SOF teams shifted to provide coverage of the airfields the 15^{th} Division planned to use as tactical points of entry for one brigade-sized Unit of Action (UA), the 1^{st} Brigade UAs. The 1^{st} Brigade UA is composed of three Battalions, the 1^{st}, 2^{nd} and 3^{rd}.

A.2 General Vignette Description

This section describes the vignette in detail. It focuses on the 3^{rd} battalion of the 1^{st} Brigade Unit of Action. More specifically, it focuses on the lead element of

the 3^{rd} battalion - the Alpha Company. This company comes upon fortified defenses of the ANFRA forces and must destroy them to make way for the main element of the 3^{rd} battalion coming up behind them. This is described in this section.

A.2.1 Situation and Mission Prior to Start of Vignette

The 1^{st} and 2^{nd} Battalions of the 1^{st} Brigade UA are already on the ground before the beginning of this vignette. They have attacked the enemy forces in the city of Baku, defeated the subverted Azer brigade that controlled the City Center (referred to as the *Icheri Sheher Brigade*). Moreover, they confronted and routed the AIB forces in the vicinity of Baku. The 1^{st} Battalion was subsequently tasked with pursuing the withdrawing AIB enemy forces retreating towards Agdam, and to continue on to Agdam and occupy it. The 2^{nd} Battalion was ordered to maintain pressure on the Icheri Sheher Brigade in Baku to defeat it in detail.

In the meantime, 300 Km to the west, ANFRA forces, attacked across the Armenian border, seized the city of Agdam, and continued eastward to join with the retreating AIB forces and attempt to relieve the beleaguered Icheri Sheher Brigade in Baku. However, surprised by the rapid defeat of their allies in Baku, the ANFRA forces suddenly found themselves in an exposed position in the wide river valley between Agdam and Baku. Aware that the US forces (the 1^{st} Brigade UA) were mounting an operation to move westward to secure Agdam and restore the border, ANFRA forces began a delaying operation, designed to buy time for establishing a defense of Agdam while slowing and inflicting casualties on the attacking US force. Keys to their hopes of success were preservation of the delaying force and effective use of target acquisition systems linked to long-range artillery systems.

The 3^{rd} Battalion of the 1^{st} UA Brigade now comes into the picture in this vignette with orders to attack and destroy the delaying forces of the ANFRA in order to permit the 2^{nd} battalion to complete its mission of recapturing Agdam. The 3^{rd} Battalion is in the midst of an airlift operation from a transfer point in Turkey when its specific mission is given to the commander. It must land, stage the assets, organize itself and very rapidly move to accomplish its objective. Speed in this mission is of the essence.

A.2.2 The 1^{st} UA Prepares for Entry Operations

The commander of the 3^{rd} Battalion, on the way to the AOR via an airlift operation, was given a warning order to prepare to deploy immediately upon landing, and attack and destroy the delaying forces of the ANFRA. If successful, this would permit the 2^{nd} Battalion of the 1^{st} UA Brigade to complete its mission. The commander of the 1^{st} UA used information from coalition/joint theater logistics management element (C/JTLME) fused with intelligence reporting from airborne assets and SOF teams operating in the area to select one airfield in vicinity of Baku (60 Km NW of the city) as his planned point of entry, as shown in Figure 1.

3.3 Mounted Formation Conducts Pursuit and Exploitation

Shortly after landing in their designated entry points, the 3^{rd} Battalion of the 1^{st} UA reorganizes and moves towards the ANFRA forces in open rolling terrain with some variance of complexity, such as defiles and small villages. The enemy is a combination of conventional forces, paramilitary, and special police challenging the UA forces with both direct military combat engagements and asymmetric means. The 3^{rd} Battalion moves to contact with the ANFRA forces with the intent to maintain pressure on delaying forces, dislocate them, and force them into a

battle while moving through open and rolling terrain so they could be destroyed by assault. To minimize his vulnerability to the enemy's long-range artillery systems, the commander planned to move his battalion dispersed on multiple axes while fighting an aggressive counter-reconnaissance effort. The result was near autonomous operations by each company, a common operating picture enhanced by situational awareness and networked fires ensured the force remained interdependent and mutually supporting.

A.3 Specific Vignette for Project

As the 3^{rd} Battalion of the 1^{st} brigade UA advanced rapidly to meet the flank of the delaying force, the aviation detachment identified an enemy defensive position 60 Km in advance of the 3^{rd} Battalion's lead elements (the Alpha company). The position was carefully selected by ANFRA forces to protect the AIB force withdrawing from Baku. The positions overlooked the best approaches to a river crossing along their line of withdrawal. Knowing that the lead Company (Alpha) would close on the reported location in just over an hour, the aviation unit used its sensors to identify specific target locations within the enemy position. Other sensors, mounted on unmanned aerial vehicles (UAV), were diverted from other areas to further develop the common operational picture. Their observations revealed that the position was well defended by a combination of dismounted infantry elements, Draega tanks, and Garm missile launchers in hastily prepared survivability positions. Minefields protecting the position from direct assault were still incomplete and operators of the advanced sensors on UAVs observing the area located several exploitable gaps and ensured they were portrayed on the common operational picture (COP). The scenario is depicted in Figure 77.

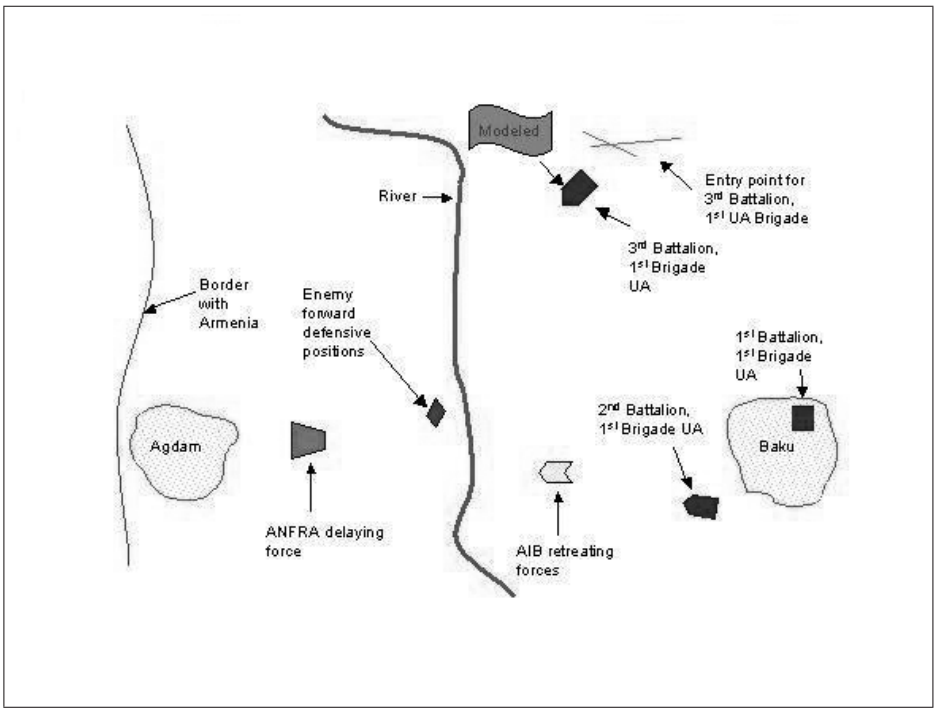


Figure 77: Overall View of Theater of Operations

Quickly adapting his scheme of maneuver to the developing situation, the alpha company commander directed his reconnaissance assets to locate river crossing sites that were beyond the line of sight of the defensive position. When one was located north of the defensive position, the alpha company commander used his embedded collaborative planning tools to locate an ideal engagement area on routes the defenders would probably use as they were dislodged from their positions.

The Alpha Company commander directed the first platoon to cross north of the river and occupy positions that allowed them to place direct fires on defending forces as they entered the engagement area. Teamed with RAH-66 Comanches from the UA's aviation detachment, the 1^{st} platoon brought the integrated fires of the UA's network to bear on the withdrawing forces.

The Second platoon was directed to cross the river some distance south of the defensive position and occupy positions that forced the withdrawing enemy towards

the engagement area. The remaining two platoons were ordered to attack the enemy position and compel the defending forces to withdraw, enabling their defeat in detail. Still 30 km from the enemy position, the alpha company commander reviewed the continuously updated common operational picture (COP) for obstacles along his intended axis of advance. While he watched, a newly identified minefield was posted on the display. Using the same planning tools, he quickly determined new routes for each of his platoons, directing them towards bypasses around the minefield, using line-of-sight evaluation tools to ensure the force stayed out of the enemy's line-of-sight as they maneuvered around the flank of the defending forces. Figure 78 provides detail about the target defensive positions as well as the crossing points for the 1^{st} and 2^{nd} platoons.

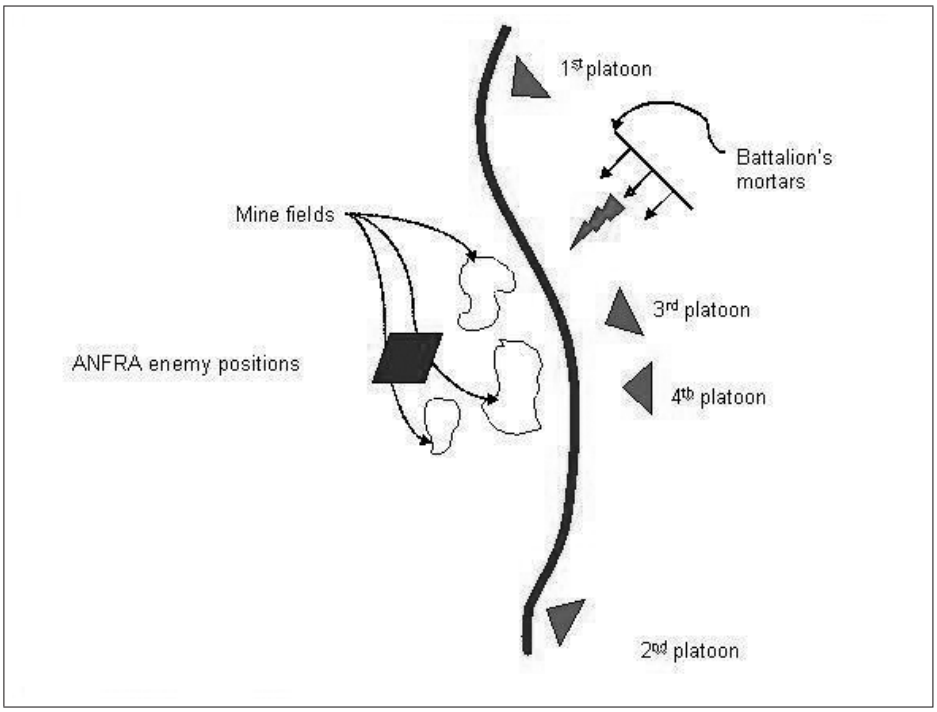


Figure 78: Details of attack on defensive positions of ANFRA

When they closed to a range of 12 km, the alpha company's mortars began the attack on the defensive position. Pulling pin-point targeting data from the common

operational picture, they delivered precision munitions aimed directly at the vehicles defiladed in the survivability positions within the enemy's defense. Their lethal, top-attack munitions quickly destroyed all but five vehicles.

Still too far away to directly observe the enemy positions, the Alpha Company commander used the split screen option on his display to watch both the map display of the common operational picture and live-video feed from the unmanned aerial vehicles observing the enemy's position. He watched as the five surviving vehicles, three Draega tanks and two Garm missile launchers, left their positions to flee towards Agdam, leaving the remaining dismounted defenders easy prey for the mounted supported by dismounted combined arms assault that was to follow. The icons on his common operational picture display indicated the fleeing vehicles had taken an unanticipated route and were going to bypass the planned engagement area. The commander quickly redirected the UAV to reconnoiter a route that his display indicated would allow his 1^{st} platoon to outflank the retreating vehicles while he pursued them with his remaining two platoons.

With the reconnaissance of the UAV assuring the route was clear of obstacles, the 1^{st} platoon advanced rapidly and quickly overtook the fleeing enemy vehicles. Two of the enemy tanks were destroyed with direct fire while the platoon moved parallel to the fleeing enemy force, but the remaining three vehicles found cover behind a low ridge that separated the two forces. Using his embedded planning tools, the 1^{st} platoon leader quickly identified a position in advance of the moving forces that would give him clear shots. Accelerating to speeds of 60 Km/h, the platoon darted in front of the enemy and was there waiting as they crested the ridge and employed direct fire to destroy these enemy forces. With the last of the enemy vehicles confirmed destroyed, the platoon leader ordered the platoon into a traveling over watch formation and continued movement to the west. Figure 79 depicts the mentioned scenario.

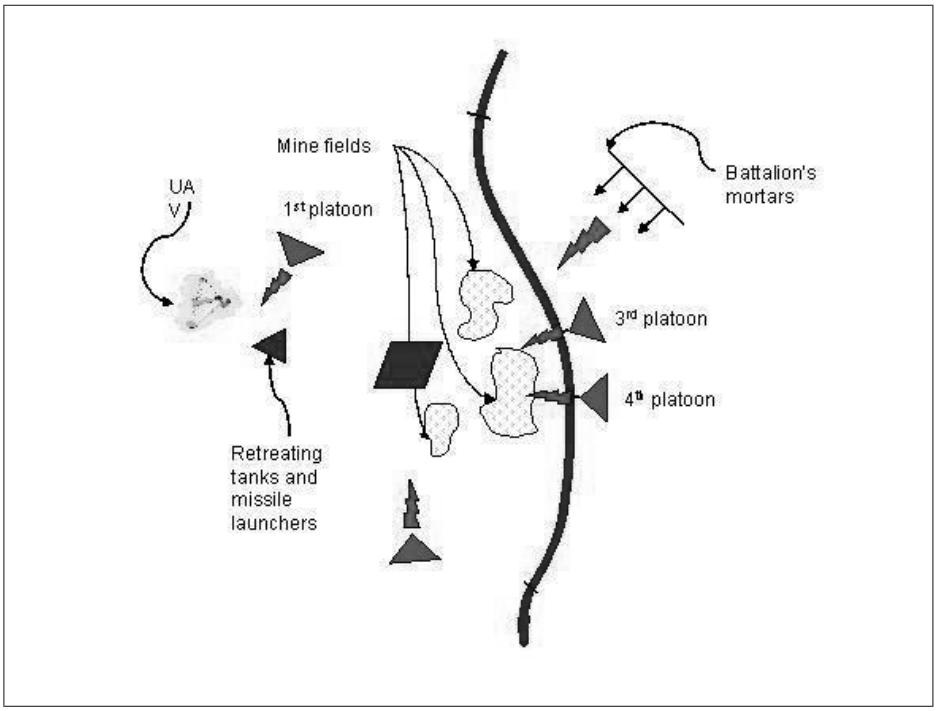


Figure 79: Details of advances on the defensive positions after mortal fire

Though the remainder of the company was still beyond his direct observation, his Common Operational Picture (COP) display assured him they were moving on parallel routes and that he was well within the supporting range of their fires as well as those of the battalion's mortars. As they moved towards Agdam, embedded logistics planning tools that had monitored the unit's ammunition usage in the recent engagement automatically transmitted an update to the battalion's logistics center. This constantly updated flow of information enabled the battalion staff to effectively plan en-route re-supply operations that allowed the battalion to maintain its momentum as they continued their pressure on the delaying enemy forces.

In summary, the 1^{st} platoon overtakes and destroys the retreating tanks and missile launchers. The 3^{rd} and 4^{th} platoon force the remaining dismounted enemy forces in the defensive position to flee into the path of the 2^{nd} platoon, ensuring their surrender/destruction. The success in overcoming the defensive position enabled

the main elements of the 3^{rd} battalion (Bravo and Echo companies) to overtake the main elements of the ANFRA delaying forces and engage them into a pitched battle, defeating them.

APPENDIX B
NED SOURCE CODE

APPENDIX B

NED SOURCE CODE

This appendix contains the source code of the ".ned" files used in this simulation.

B.1 File Generator.ned

```
//--------------------------------------------------------------
// file: generator.ned
//--------------------------------------------------------------
simple Generator
parameters:
  startTime: numeric,
  fromAddr: numeric,   // origin, unique ID within WAN
  totalNodes: numeric; // number of nodes within WAN
// (routers not counted)
gates:
  out: out;
endsimple
```

B.2 File Router.ned

```
//--------------------------------------------------------------
// file: router.ned
//--------------------------------------------------------------
simple Router
parameters:
  startTime: numeric,
  routerID : numeric,
  nodesPerPlane: numeric,
  totalNodes: numeric,
```

```
  LANposition : numeric, // Local LAN position
  routerServiceTime: numeric;
 gates:
  in: inFromLocal;      // gate #0
  out: outToLocal;      // gate #1
  in: inFromWirelessPP; // gate #2
  out: outToWirelessPP; // gate #3
  in: inFromWirelessSP; // gate #4
 out: outToWirelessSP;   // gate #5
endsimple
```

B.3 File Satellite.ned

```
//---------------------------------------------------------------
// file: satellite.ned
//---------------------------------------------------------------
simple Satellite
parameters:
startTime: numeric,
satelliteID : numeric,
satServiceTime : numeric,
totalNodes : numeric,
WGSposition : numeric, // Position at wirelessGS
WSPposition : numeric; // Position at wirelessSP
gates:
in: inBus1; // gate #0 (wirelessGS)
out: outBus1; // gate #1 (wirelessGS)
in: inBus2; // gate #2 (wirelessSP)
out: outBus2; // gate #3 (wirelessSP)
endsimple
```

B.4 File Simplebus.ned

```
//---------------------------------------------------------------
// File: simplebus.ned
// Based on an example by Andras Varga
//---------------------------------------------------------------
// Generic bus module. Features:
```

```
 // - propagation delay modelling (proportional to distance)
 // - data rate modelling
 // - optional collision modeling
 // - optional collision signalling (if turned off, collided
 // frames are simply discarded
 // - full duplex or half duplex (simplex) bus. On a full duplex
 // bus, frames are assumed to propagate in one direction only
 // (upstream or downstream), and transmissions of opposite
 // directions don't collide.
 // - models several independent channels
 //
 // Usage:
 // Set the parameters of the bus module and connect the stations
 // to it. Each station is expected to have a "position" attribute
 // which holds the station's distance from one end of the bus.
 // There should be NO data rate set for the connecting links!
 //
 // Frames may have "channel" and "upstream" attributes; if they
 // are not present, the default values are 0 and TRUE. "upstream"
 // is only significant on a full duplex bus.
 //
 // The cMessages sent to the bus are interpreted as the start
 // of a transmission. Length of transmission is calculated from
 // the frame length and the bus data rate.
 //
 // The cMessages send out by the bus should be interpreted as the
 // _end_ of the transmission. Collision signal is an empty cMessage
 // with the name "collision". simple SimpleBus
 parameters:
 busType: string, // Types are: LAN, WPP, WSP, WGS.
   numChannels, // number of independent channels
   wantCollisionModeling, // collision modeling flag
   wantCollisionSignal, // "send collision signals" flag
   isFullDuplex, // channel mode
   delaySecPerMeter, // delay of the bus
   dataRateBps, // data rate of the bus
   gapTime; // minimum gap between consecutive packets.
 gates:
   in: in[ ];
   out: out[ ];
endsimple
```

B.5 File Sink.ned

```
//-------------------------------------------------------------
// file: Sink.ned
//-------------------------------------------------------------
simple Sink
gates:
  in: in;
endsimple
```

B.6 File TheNet.ned

```
//-------------------------------------------------------------
// file: theNet.ned
//-------------------------------------------------------------
import "generator.ned";
import "simplebus.ned";
import "sink.ned";
import "router.ned";
import "satellite.ned";
// ------------ Module GroundStation -------------------------
// module GroundStation
parameters:
  nodeID : numeric,
  WGSposition : numeric;
gates:
  out: out;
  in: in;
submodules:
  gen: Generator;
  parameters:
    startTime = ancestor startTime,
    fromAddr = nodeID,
    totalNodes = ancestor nodesPerPlane * ancestor numPlanes;
    display: "i=gen;p=120,49;b=32,30";
    sink: Sink;
    display: "i=sink;p=81,49;b=32,30";
 connections:
   gen.out --> out;
   sink.in <-- in;
   display: "p=18,2;b=176,102";
```

```
endmodule

// ---------- Module computer Node -------------------------
module Node
 parameters:
 nodeID : numeric,
 LANposition : numeric;
 gates:
 out: out;
 in: in;
 submodules:
 gen: Generator;
 parameters:
 startTime = ancestor startTime,
 fromAddr = nodeID,
 totalNodes = ancestor totalNodes;
 display: "i=gen;p=120,49;b=32,30";
 sink: Sink;
 display: "i=sink;p=81,49;b=32,30";
 connections:
 gen.out --> out;
 sink.in <-- in;
 display: "p=18,2;b=176,102";
endmodule

// ------------------ Module Plane -------------------------
 // module Plane
 parameters:
   planeID : numeric,
   nodesPerPlane : numeric,
   totalNodes : numeric,
   WPPposition : numeric,
   WSPposition : numeric,
   routerServiceTime : numeric;
 gates:
   in: inFromWirelessPP;
   out: outToWirelessPP;
   in: inFromWirelessSP;
   out: outToWirelessSP;
 submodules:
   router: Router;
     parameters:
     startTime = ancestor startTime,
     routerID = planeID,
     nodesPerPlane = nodesPerPlane,
```

```
    totalNodes = totalNodes,
    LANposition = 10 * nodesPerPlane,
    routerServiceTime = routerServiceTime;
    display: "i=router;p=123,49;b=32,32";
 //- - - - - - - - - - - - - - - - - - - - - - - - - -
 node: Node[nodesPerPlane];
 parameters:
   nodeID = planeID*nodesPerPlane + index,
   LANposition = 10 * index;
   display: "b=38,32;p=43,151,row,45;i=pc";
 //- - - - - - - - - - - - - - - - - - - - - - - - - -
 ethernetBus: SimpleBus;
 parameters:
   busType = "LAN",
   numChannels = 1,
   wantCollisionModeling = 1,
   wantCollisionSignal = 1,
   isFullDuplex = 0,
   delaySecPerMeter = ancestor LANdelay,
   dataRateBps = ancestor LANbandwidth,
   gapTime = ancestor LANgapTime;
 gatesizes:
   in[nodesPerPlane + 1],
   out[nodesPerPlane + 1];
   display: "p=88,97;b=156,10,rect";
 //- - - - - - - - - - - - - - - - - - - - - - - - - -
 connections:
 router.outToLocal --> ethernetBus.in[nodesPerPlane];
 router.inFromLocal <-- ethernetBus.out[nodesPerPlane];
 router.outToWirelessPP --> outToWirelessPP;
 router.inFromWirelessPP <-- inFromWirelessPP;
 router.outToWirelessSP --> outToWirelessSP;
 router.inFromWirelessSP <-- inFromWirelessSP;
 for i=0..nodesPerPlane-1 do
 node[i].out --> ethernetBus.in[i];
 node[i].in <-- ethernetBus.out[i];
 endfor;
 display: "p=2,2;b=168,184";
endmodule

// ----------------- Module TheNet -------------------------
module TheNet
 parameters:
 startTime : numeric,
 nodesPerPlane : numeric,
```

```
numPlanes : numeric,

LANgapTime : numeric,
LANbandwidth : numeric,
LANdelay : numeric,

WPPgapTime : numeric,
WPPbandwidth : numeric,
WPPdelay : numeric,

WSPgapTime : numeric,
WSPbandwidth : numeric,
WSPdelay : numeric,

WGSgapTime : numeric,
WGSbandwidth : numeric,
WGSdelay : numeric,

satServiceTime : numeric,
routerServiceTime : numeric;
submodules:
//- - - - - - - - - - - - - - - - - - - - - - - - - -
plane: Plane[numPlanes];
parameters:
  planeID = index,
  nodesPerPlane = nodesPerPlane,
  WPPposition = 100 * index,
  WSPposition = 100 * index,
  totalNodes = nodesPerPlane * numPlanes,
  routerServiceTime = routerServiceTime;
  display: "i=airplane;p=62,90,row,60;b=35,35";
//- - - - - - - - - - - - - - - - - - - - - - - - - -
  wirelessPP: SimpleBus;
  parameters:
  busType = "WPP",
  numChannels = 1,
  wantCollisionModeling = 1,
  wantCollisionSignal = 1,
  isFullDuplex = 0,
  delaySecPerMeter = WPPdelay,
  dataRateBps = WPPbandwidth,
  gapTime = WPPgapTime;
gatesizes:
  in[numPlanes],
  out[numPlanes];
```

```
  display: "p=264,33;b=476,10,rect";
//- - - - - - - - - - - - - - - - - - - - - - - - - -
wirelessSP: SimpleBus;
parameters:
  busType = "WSP",
  numChannels = 1,
  wantCollisionModeling = 1,
  wantCollisionSignal = 1,
  isFullDuplex = 0,
  delaySecPerMeter = WSPdelay,
  dataRateBps = WSPbandwidth,
  gapTime = WSPgapTime;
gatesizes:
  in[numPlanes+1],
  out[numPlanes+1];
  display: "p=268,153;b=468,10,rect";
//- - - - - - - - - - - - - - - - - - - - - - - - - -
wirelessGS: SimpleBus;
parameters:
  busType = "WGS",
  numChannels = 1,
  wantCollisionModeling = 1,
  wantCollisionSignal = 1,
  isFullDuplex = 0,
  delaySecPerMeter = WGSdelay,
  dataRateBps = WGSbandwidth,
  gapTime = WGSgapTime;
gatesizes:
  in[2],
  out[2];
  display: "p=272,281;b=476,10,rect";
//- - - - - - - - - - - - - - - - - - - - - - - - - -
groundStation: GroundStation;
parameters:
  nodeID = nodesPerPlane * numPlanes,
  WGSposition = 0;
  display: "b=32,32;p=67,215,row,45;i=ground";
//- - - - - - - - - - - - - - - - - - - - - - - - - -
satellite: Satellite;
parameters:
  startTime = startTime,
  satelliteID = 1,
  satServiceTime = satServiceTime,
  totalNodes = nodesPerPlane * numPlanes,
  WSPposition = 38300E3, //35800 Km + 2500 Km
```

```
    WGSposition = 38300E3; //35800 Km + 2500 Km
    display: "i=satellite;p=315,217;b=32,32";
  //- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  connections:
  for i=0..numPlanes-1 do
    plane[i].outToWirelessPP --> wirelessPP.in[i];
    plane[i].inFromWirelessPP <-- wirelessPP.out[i];
    plane[i].outToWirelessSP --> wirelessSP.in[i];
    plane[i].inFromWirelessSP <-- wirelessSP.out[i];
  endfor;
    groundStation.out --> wirelessGS.in[0];
    groundStation.in <-- wirelessGS.out[0];
    satellite.inBus1 <-- wirelessGS.out[1];
    satellite.outBus1 --> wirelessGS.in[1];
    satellite.inBus2 <-- wirelessSP.out[numPlanes];
    satellite.outBus2 --> wirelessSP.in[numPlanes];
    display: "p=10,2;b=508,308";
endmodule

// ------------------------ OTBNet -------------------------
// Instantiates the network
 network OTBNet : TheNet
 parameters:
    startTime = input, // First PDU timestamp in seconds
    nodesPerPlane = input, // Set to 3 in this simulation
    numPlanes = input, // Set to 8 in this simulation

    LANgapTime = input, // Minimum gap time between frames in the LAN
    LANbandwidth = input, // LAN inside planes (set to 100 Mbps)
    LANdelay = input, // nanosec/meter (set to 70% light speed)

    WPPgapTime = input, // Minimum gap time in the wireless PP
    WPPbandwidth = input, // Wireless bandwidth Plane-to-Plane (PP)
    WPPdelay = input, // nanosec/meter (light speed)

    WSPgapTime = input, // Minimum gap time in the wireless SP
    WSPbandwidth = input, // Wireless bandwidth Satellite-to-Plane (SP)
    WSPdelay = input, // nanosec/meter (light speed)

    WGSgapTime = input, // Minimum gap time in the wireless GS
    WGSbandwidth = input, // Wireless bandwidth Ground-to-Satellite (GS)
    WGSdelay = input, // nanosec/meter (light speed)

    satServiceTime = input,
// Service time per PDU in satellite under best conditions
```

```
   routerServiceTime = input;
// Service time per PDU in routers under best conditions
endnetwork
```

B.7 File Omnetpp.ini

```
 [General] network = OTBNet
 ini-warnings = no
 random-seed = 1
 warnings = yes
 snapshot-file = planes.sna
 output-vector-file = planes.vec
 sim-time-limit = 2550s # simulated seconds
 cpu-time-limit = 20h # 20 hours of real cpu time max.
 total-stack-kb = 4096 # 4 MByte, increase if necessary

[Cmdenv]
module-messages = yes
verbose-simulation = yes
display-update = 0.5s

[Tkenv]
default-run=1
use-mainwindow = yes
print-banners = yes
slowexec-delay = 300ms
update-freq-fast = 10
update-freq-express = 100
breakpoints-enabled = yes

[DisplayStrings]

[Parameters]

[Run 1]
OTBNet.startTime = 1034s
OTBNet.nodesPerPlane = 3
OTBNet.numPlanes = 8

OTBNet.LANgapTime = 50us
OTBNet.LANbandwidth = 100E6 # 100 MBps
```

```
OTBNet.LANdelay = 4.761904762ns # nanosec/meter (70% light speed)

OTBNet.WPPgapTime = 50us
OTBNet.WPPbandwidth = 512000
OTBNet.WPPdelay = 3.333333333ns # nanosec/meter (light speed)

OTBNet.WSPgapTime = 50us
OTBNet.WSPbandwidth = 512000
OTBNet.WSPdelay = 3.333333333ns # nanosec/meter (light speed)

OTBNet.WGSgapTime = 50us
OTBNet.WGSbandwidth = 512000
OTBNet.WGSdelay = 3.333333333ns # nanosec/meter (light speed)

OTBNet.satServiceTime = 5us
OTBNet.routerServiceTime = 5us
```

APPENDIX C
AWK SOURCE CODE

APPENDIX C

AWK SOURCE CODE

This appendix contains the source code of the ".awk" files used to parse and extract data from the OTB logger files.

C.1 AWK Script for PDU Parsing

Awk program that parses the PDU file generated by OTB and creates files "data*nnnn*.txt" for each generator site identified as *nnnn*.

```
# Process original PDU data files
# with ID numbers added to each "<dis204" (juan.data)

BEGIN {
RS = "\n\\<|\n<";
 # \n is new line, \\< is
 #finally \< and matches the empty string
 #at the beginning of a word.
 origsite = "";
 orighost = "";
 origapplic = "";
 sizeof = "";
 time = "";
 len = "";
 pduName = "";
 pduCount = "?";
 pduId = 0;
 PDUtype = "";
}

/dis204/ {$1 = "<" $1;
 if (orighost == "") orighost = origapplic;
# origin = origsite orighost;
```

```
 origin = origsite;
 PDUlength = (len != "" \&\& len != 0 ? len : sizeof);
 if (PDUtype != "") bytes[PDUtype] = bytes[PDUtype] + PDUlength;
 PDUtype = $0;
 class[PDUtype]++;
 if (origin != "" \&\& time != "" \&\& PDUlength != "" \&\&
    PDUlength != 0)
    {if (!(origin in node)) node[origin] = nodecount++;
     printf "%-12s %5d | %s %5d %s %d\n",
     hextime, PDUlength, time, ++counter[node[origin]],
     pduName, pduId > "data" origin ".txt";
     printf "%-12s %5d | %s %5d %s %d\n",
     hextime, PDUlength, time, counter[node[origin]],
     pduName, pduId > "allpdu.txt";
    }
 else print "dis204 previous to record " NR \
 " has missing parts. pduCount = " pduCount \
 " origin = " origin " time = " time " len = " len;
 origsite = "";
 orighost = "";
 origapplic = "";
 sizeof = "";
 time = "";
 len = "";
 pduName = $0;
 pduCount = "?";
 pduId++;
}

/\.site\>/ {if (origsite == "") origsite = $5}
/\.host\>/ {if (orighost == "") orighost = $5;}
/\.application \>/ {if (origapplic == "") origapplic = $5;}
/\.length\>/ {if (len == "" || len < $5) len = $5}
/\.sizeof\>/ {if (sizeof == "" || sizeof < $5) sizeof = $5}
/\.timestamp\>/ {if (time == "") {hextime = $3; time = $5;}}
/\.pdu_count\>/ {if (pduCount == "?") pduCount = $5;}

END {
 if (orighost == "") orighost = origapplic;
# origin = origsite orighost;
 origin = origsite;
 PDUlength = (len != "" \&\& len != 0 ? len : sizeof);
 bytes[PDUtype] = bytes[PDUtype] + PDUlength;
 for (i in class)
 {printf "%-35s %5d : %8d\n", i, class[i], bytes[i]
```

```
        > "pduTypesCount.txt";
 tot += class[i];
 btot += bytes[i];
}
 printf "\nTotal PDUs = %d, bytes = %d\n", tot, btot
        > "pduTypesCount.txt";

 if (origin != "" \&\& time != "" \&\& PDUlength != "" \&\&
     PDUlength != 0)
     {if (!(origin in node)) node[origin] = nodecount++;
      printf "%-12s %5d | %s %5d %s %d\n",
      hextime, PDUlength, time, ++counter[node[origin]],
      pduName, pduId > "data" origin ".txt";
      printf "%-12s %5d | %s %5d %s %d\n",
      hextime, PDUlength, time, counter[node[origin]],
      pduName, pduId > "allpdu.txt";
     }
 else print "dis204 previous to record " NR \
 " has missing parts. pduCount = " pduCount \
 " origin = " origin " time = " time " len = " len;
 for(origin in node) {
   printf "%5d %s\n", counter[node[origin]], "data" origin ".txt"
          > "nodes.txt";
   close("data" origin ".txt");
 }
 close("nodes.txt");
 close("allpdu.txt");
 system("sort /R nodes.txt /O nodes.txt" );
 system("sort /+21 allpdu.txt /O allpdusort.txt" );
 RS = "\n";
 getline < "nodes.txt";
 system("ren " $2 " data24.txt");
 system("sort /+21 data24.txt /O data24.txt");
 i = 0;
 while ((getline < "nodes.txt") > 0) {
 system("ren " $2 " data" i ".txt");
 system("sort /+21 data" i ".txt" " /O data" i ".txt");
 i+=3;
}
}
```

C.2 AWK Script for Independent Analysis

This awk calculates the bandwith required to schedule sets of PDUs at time intervals of at least 2 seconds.

```
 BEGIN {
 tsegment = 2.;  # time interval of 2 seconds
 gap = 0.000050; # 50 microseconds
 tgaps = 0;      # sum of all the gaps in this time interval
 tbytes = 0;     # total of bytes in this time interval
 tcurr = 0;      # current time within the time interval
 PDUcount = 0;   # number of PDUs in this time interval
 firstime = "T"; # flag initially true.
 printf "vector 0 \"band.awk\"
 \"Minimum bandwidth requirements over time\" 1\n"
}
 {
 split($4, t, ":"); tsec = t[2]*60+t[3]; # timestamp in seconds
 PDUcount++;
 if (firstime == "T")
 {
 tbytes = $2;
 tcurr = tsec;
 tgaps = gap;
 firstime = "F";
}
 else {
 interval = tsec - tcurr - tgaps; # current size of time interval
 if (interval <= 0 || tsec - tcurr < tsegment)
 {
 tgaps = tgaps + gap;
 tbytes = tbytes + $2;
}
 else
 {
 bw = tbytes*8./interval;
 printf "0 %f %f\n", tcurr, bw
 printf "0 %f %f\n", tsec, bw
 tbytes = $2;
 tcurr = tsec;
 tgaps = gap;
 PDUcount = 1;
}
}
```

```
}
 END {
 if (interval <= 0)
 {tsec += tsegment;
 interval = tsec - tcurr - tgaps;
}
 bw = tbytes*8./interval;
 printf "0 %f %f\n", tcurr, bw;
 printf "0 %f %f\n", tsec, bw;
}
```

APPENDIX D
SIMULATOR SOURCE CODE

APPENDIX D

SIMULATOR SOURCE CODE

This appendix contains the source code of the vignette simulator using the OMNeT++ discrete event simulator as the engine, as well as some other auxiliary programs used to prepare the input data and extract specific statistics from the simulator output.

```
//--------------------------------------------------------------------
// file: vecstats.cpp
//--------------------------------------------------------------------

#include <stdio.h>
#include <stdlib.h>
#include <float.h>
#include <math.h>
#define linesize 100

int main(int argc, char *argv[])
{
 FILE *fd;
 char line[linesize];
 double min, max, sum, avg1, avg2, std, variance, area,
        tInterval, minInterval, maxInterval,
        t1, t2, mt1, mt2, Mt1, Mt2, val1, val2, time1, time2;
 int counter;

 min = DBL_MAX;
 max = 0.;
 sum = area = 0.;
 counter = 0;
 t1 = DBL_MAX;
 t2 = 0.;
 maxInterval = 0.;
 minInterval = DBL_MAX;

 if (argc < 2)
```

```
 {
  printf("Usage: %s <band.vec>\n", argv[0]);
  return 1;
 }

if ((fd = fopen(argv[1], "r")) == NULL)
 {
  printf("Cannot open %s\n", argv[1]);
  return 2;
 }
fgets(line, linesize, fd);
printf("%s", line);

while (fscanf(fd, " %*d %lf %lf", &time1, &val1) != EOF &&
       fscanf(fd, " %*d %lf %lf", &time2, &val2) != EOF )
{
  counter++;
  if (time1 < t1) t1 = time1;
  if (time2 > t2) t2 = time2;\

  if ((time2 - time1) < minInterval)
  {
    minInterval = time2 - time1;
    mt1 = time1;
    mt2 = time2;
  }
  if ((time2 - time1) > maxInterval)
  {
    maxInterval = time2 - time1;
    Mt1 = time1;
    Mt2 = time2;
  }
  if (val1 < min) min = val1;
  if (val1 > max) max = val1;
  sum += val1;
  area += (time2-time1)* (val1+val2)/2.;
}

tInterval = t2 - t1;
avg1 = area / tInterval;
avg2 = sum / counter;
printf("Samples    = %d\n", counter);
printf("Init time  = %11lf\n", t1);
printf("Final time = %11lf\n", t2);
printf("Min time interval = [ %11lf, %11lf ], length = %lf\n",
```

```
        mt1, mt2, minInterval);
 printf("Max time interval = [ %11lf, %11lf ], length = %lf\n",
        Mt1, Mt2, maxInterval);
 printf("Minimum bandwidth =%14.1lf\n", min);
 printf("Maximum bandwidth =%14.1lf\n", max);
 printf("Point average     =%14.1lf\n", avg1);
 printf("Area average      =%14.1lf\n", avg2);

 rewind(fd);
 sum = 0.;
 fgets(line, linesize, fd);
 while (fscanf(fd, " %*d %lf %lf", &time1, &val1) != EOF &&
        fscanf(fd, " %*d %lf %lf", &time2, &val2) != EOF )
 {
   sum += (val1 - avg2)* (val1 - avg2);
 }
 variance = sum / (counter - 1.);
 std = sqrt(variance);
 printf("Sample variance   =%14.1lf\n", variance);
 printf("Std deviation     =%14.1lf\n", std);
}


//---------------------------------------------------------------------
// file: pduAnal.c
//---------------------------------------------------------------------

/*This program reads in the original PDU log file as well as the PDU
 summary file corresponding to a given generator, and produces the
 file "extrabyt.txt" that contains pairs of
 (PDU ID, contribution in bytes of that PDU to the group)
*/
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include <assert.h>

#define true 1
#define false 0
#define MAXstring 5000
#define MAXpdus 65000
#define PDUsimilarity 0.49

int PDUcompareOK (FILE *fd1, FILE *fd2, long int p1, long int p2,
```

```
                  int len1, float threshold, int *extraBytes,
                  int *diffLbl);
int readStr(FILE *fd, char a[], char b[], char c[], char d[]);
char buffer[MAXstring*4], buffer2[MAXstring*4];
char pdu1[MAXstring*4], pdu2[MAXstring*4];
char a1[MAXstring], b1[MAXstring], c1[MAXstring], d1[MAXstring];
char a2[MAXstring], b2[MAXstring], c2[MAXstring], d2[MAXstring];

// ------------------------------------------------------------------
int main(int argc, char *argv[]) {
  FILE *fdO1, *fdO2, *fdS, *fdExtraBytes;
  int moreData = 1, pduCount = 0, blockCount, sameBlock, newBlock,
      i, j;
  int ch, endf, len1, len2, id1, id2, extraBytes, diffLbl,
      sumExtraBytes, sumDiffLbl;
  unsigned int timeStamp1, timeStamp2;
  long int fpos[MAXpdus], currpos;
  char  a[MAXstring], b[MAXstring], c[MAXstring], d[MAXstring];
  char type1[50], type2[50];
  double schedTimeSec1, schedTimeSec2, timeSpan,
         hour_equiv = (pow(2.0, 31.0) - 1.0);
  float threshold = PDUsimilarity;
  if (argc != 3) {
     printf("Usage: %s  <file_itsec.data>  <file_dataNN.txt>\n",
             argv[0]);
     return 1;
  }
  fdO1 = fopen(argv[1], "r");  // Original PDU file (the large one)
  fdO2 = fopen(argv[1], "r");  // Original PDU file (the large one)
                               // Same file opened twice
  fpos[0] = -1;
  currpos = ftell(fdO1);
  while ( fgets(buffer, MAXstring*4, fdO1) != NULL ) {
     if (buffer[0] == '<') fpos[++pduCount] = currpos;
     currpos = ftell(fdO1);
  }
//  printf ("Number of PDUs in file %s: pduCount=%d\n",
//           argv[1], pduCount);

// - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  fdS = fopen(argv[2], "r");   // Summary file of PDUs.
  fscanf(fdS, "%x %d %*[^<]%*s %s %*[^:]: %d",
         &timeStamp2, &len2, type2, &id2);
  schedTimeSec2 = (double)(timeStamp2/2)  * 3600.0 / hour_equiv;
  newBlock = true;
```

```
//To store information about extra bytes.
  fdExtraBytes = fopen("extrabyt.txt", "w");

  while (newBlock) {
//newblock = true means not EOF yet and a new empty block is ready.
     len1 = len2;
     id1 = id2;
     strcpy (type1, type2);
     blockCount = 1;
     timeSpan = 0.;
     sumExtraBytes = 0;
     schedTimeSec1 = schedTimeSec2;
     sameBlock = true;
     do {
       endf = fscanf(fdS, "%x %d %*[^<]%*s %s %*[^:]: %d",
                    &timeStamp2, &len2, type2, &id2);
       if (endf == EOF) {newBlock = false; break;}
       schedTimeSec2 = (double)(timeStamp2/2)  * 3600.0 / hour_equiv;
       if ( len1 == len2 && strcmp(type1, type2) == 0 &&
            PDUcompareOK(fdO1, fdO2, fpos[id1], fpos[id2], len1,
                         threshold, &extraBytes, &diffLbl) ) {
          blockCount++;
          sumDiffLbl += diffLbl;
          sumExtraBytes += extraBytes;
          timeSpan = schedTimeSec2 - schedTimeSec1;
          fprintf(fdExtraBytes, "%d, %d\n", id2, extraBytes);
       }
       else sameBlock = false;
     } while (sameBlock);
// if sameblock = false then a new block will start
// printf("PDUId: %5ld %-12s length: %4d #PDUs: %2d extraBytes: \
// %4d diffLabel: %4d timeSpan: %lf\n",
// id1, type1, len1, blockCount, sumExtraBytes, sumDiffLbl, timeSpan);
// printf("%5d, %-20s, %4d, %2d, %4d, %4d, %lf\n",
// id1, type1, len1, blockCount, sumExtraBytes, sumDiffLbl, timeSpan);
  }

  fclose(fdO1);
  fclose(fdO2);
  fclose(fdS);
  fclose(fdExtraBytes);
  return 0;
}

// ------------------------------------------------------------------
```

```
int PDUcompareOK (FILE *fd1, FILE *fd2, long int p1, long int p2,
    int len1, float threshold, int *extraBytes, int *diffLbl) {
  int diff, diffLabel, eof1, eof2, diffFields;
  float percentSimilar;
    fseek(fd1, p1, SEEK_SET);
    fseek(fd2, p2, SEEK_SET);
    diff = 0;
    diffLabel = 0;
    readStr(fd1, a1, b1, c1, d1);
    readStr(fd2, a2, b2, c2, d2);
    assert(strncmp(a1, "dis204", 6)==0 && strncmp(a2, "dis204", 6)==0);
    eof1 = readStr(fd1, a1, b1, c1, d1);
    eof2 = readStr(fd2, a2, b2, c2, d2);
    while (eof1 != EOF && eof2 != EOF &&
           strncmp(a1, "dis204", 6) != 0 &&
           strncmp(a2, "dis204", 6) != 0) {
       diffFields = (strcmp(a1, a2) != 0);
       if (diffFields)
            diffLabel++;
       if (diffFields || strcmp(c1, c2) != 0 || strcmp(d1, d2) != 0 )
            diff += (d1[0]=='\0') ? strlen(c1)/2 - 1 : strlen(d1)/2 - 1;
       eof1 = readStr(fd1, a1, b1, c1, d1);
       eof2 = readStr(fd2, a2, b2, c2, d2);
    }
    percentSimilar = (float)(len1 - diff) / (float)len1;
    *extraBytes = diff;
    *diffLbl = diffLabel;
    return (diffLabel == 0 || percentSimilar > threshold);
}

// ------------------------------------------------
int readStr(FILE *fd, char a[], char b[], char c[], char d[]) {
    a[0] = b[0] = c[0] = d[0] = '\0';
    if (fgets(buffer, MAXstring*4, fd) == NULL) return EOF;
    if (buffer[0] == '\n') return !EOF;
    if (buffer[0] == '<') { sscanf(buffer, "<%[^>]>", a);
                            return !EOF;
    }
    if (strchr(buffer, '=') == NULL) {
           fgets(buffer2, MAXstring*4, fd);
           strcat(buffer, buffer2);
    }
    if (strchr(buffer,'"') != NULL)
        sscanf(buffer, "%s = \"%[^\"]\" = %s", a, b, c);
    else sscanf(buffer, "%s = %s = %s = %s", a, b, c, d);
```

```
    return !EOF;
}

//==========================================================================


//--------------------------------------------------------------------
// file: generator.cpp
//--------------------------------------------------------------------

#include <omnetpp.h>
#include <stdio.h>

// Generator simple module class
//
class Generator : public cSimpleModule
{
    // variables used
    FILE *fd, *fdextra, *fdLog;
    char filename[50], msgname[50], pduIniType[50], pduType[50],
         firstCh, c[6], predictedAction;
    char comments[200];
    int commentCount, bundling;
    double dataRateBps, hour_equiv, percentPosSlack;
    simtime_t startTime, gapTime, transmissionTime, schedTimeSec,
              slack, generatorServiceTime, blockWaitTime;
    long pduIniLength, byteFrame_length, bitFrame_length, file_pos;
    unsigned int  eof, num_frames, numNodes, sendTime;
    int pduextra[70000], extralength, pduLenIni, pduLenCurr;
    int frames_sent, frame_counter, pdu_counter, positiveSlack,
        my_address, toAddr, pduID;
    bool firstTime, emptyBlock, blockTimedout, busy;
    cMessage *readyToSend, *blockTimeout, *msg1;
    cOutVector slackTime;

    // member functions
    Module_Class_Members(Generator,cSimpleModule,0)
    virtual void initialize();
    virtual void handleMessage(cMessage *msg);
    virtual void finish();

private:
    void PDUrecord1();
    void PDUrecord2();
};
```

```
Define_Module( Generator );

//==============================================================
void Generator::initialize()
{
    commentCount = 0;
    for (pduID=0; pduID<70000; pduID++)
        pduextra[pduID] = 0;
    fdextra = fopen("juanTgz\\juanTgz3\\extrab.txt", "r");
    fdLog = fopen("juanTgz\\juanTgz4\\PDUlog.txt", "w");
    int counterextra = 0;
    while (fscanf(fdextra, "%d, %d", &pduID, &extralength) != EOF) {
          pduextra[pduID] = extralength;
          counterextra++;
    }
    startTime = par("startTime");
    blockWaitTime = par("blockWaitTime");
    generatorServiceTime = par("generatorServiceTime");
    gapTime = gate("out")->toGate()->toGate()->ownerModule()
              ->par("gapTime");
    my_address = par("fromAddr");
    c[4] = 'W'; c[5] = 'S';
    bundling = par("bundling"); printf("bundling = %d\n", bundling);
    if (bundling < 1 || bundling > 6 )
        {printf("Error in generator %d, bundling = %d\n",
                 my_address, bundling);
         return;}
    numNodes = par("totalNodes");
    dataRateBps = (double)gate("out")->toGate()->toGate()->ownerModule()
                  ->par("dataRateBps");
    printf("Generator my_address=%d, numNodes=%d startTime=%lf "
           "blockWaitTime=%lf generatorServiceTime=%lf gapTime=%lf\n",
           my_address, numNodes, startTime, blockWaitTime,
           generatorServiceTime, gapTime);

    hour_equiv = (pow(2.0, 31.0) - 1.0);
    frames_sent = 0;
    frame_counter = 0;
    pdu_counter = 0;
    positiveSlack = 0;
    toAddr = -1;            // all packets are broadcasted

    slackTime.setName("Slack Time to Send Next Message");
```

```
    firstTime = true;
    emptyBlock = true;
    blockTimedout = false;
    busy = false;
    readyToSend =   new cMessage("readyToSend");
    blockTimeout =  new cMessage("blockTimeout");

    sprintf(filename, "juanTgz\\juanTgz4\\dataNew%d.txt", my_address);
    if ((fd = fopen(filename, "r")) != NULL)
    {
        scheduleAt (startTime, readyToSend);     // schedule first event
//      printf("Generator my_address=%d scheduled readyToSend.\
 Initialization completed.\n", my_address);
    }
}


//=====================================================================
void Generator::handleMessage(cMessage *msg)
{
    if(msg == blockTimeout)
    {
        if (busy) {
           blockTimedout = true; //block is sent at next readyToSend
           return;
        }  // end of busy status
        //- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
        // status is idle (not busy)
        msg1->setTimestamp();    // block will be sent immediately
        transmissionTime = (double)msg1->length() / dataRateBps;
        send(msg1,"out");
        frames_sent++;
        PDUrecord2();
        emptyBlock = true;
        blockTimedout = false;  // block was just sent
        busy =  true;
        if (eof != EOF) {    // if EOF and block not empty,
                             // then readyToSend was not scheduled
           cancelEvent(readyToSend);  //remove previous (future time)
                                      // readyToSend
        }
        scheduleAt(simTime() + transmissionTime + gapTime +
                  generatorServiceTime, readyToSend);
        return;
    }  //end of msg == blockTimeout
```

```
//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

// msg is not blockTimeout, should be readyToSend
    if (msg == readyToSend)
    {
        if (blockTimedout) { //current block has priority over new PDUs
           msg1->setTimestamp();   // block will be sent immediately
           transmissionTime = (double)msg1->length() / dataRateBps;
           send(msg1,"out");
           frames_sent++;
           PDUrecord2();
           emptyBlock = true;
           blockTimedout = false;  // block was just sent
           busy =  true;
           scheduleAt(simTime() + transmissionTime + gapTime +
                      generatorServiceTime, readyToSend);
           return;
        }  //end of blockTimedout
//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

// msg is readyToSend & not blockTimedout
        firstCh = getc(fd);     //skips over comments indicated by
                                // '%' in first char
        while (firstCh == '#') {
            fgets(comments, 200, fd);
            commentCount++;
            printf("Comments # %d in %s are: %s\n",
                    commentCount, filename, comments);
            firstCh = getc(fd);
        }
        ungetc(firstCh, fd);
        file_pos = ftell(fd);
        eof = fscanf(fd,
              "%x %ld | %*s %*d <dis204 %s PDU>: %d %c %c %c %c",
              &sendTime, &byteFrame_length, pduType, &pduID,
              &c[0],&c[1],&c[2],&c[3]);
            // c[0] is neural network (column 1)
            // c[1] is type (column 2)
            // c[2] is type and length (column 3)
            // c[3] is type, length and timestamp (column 4)
            // c[4] = W always wait
            // c[5] = S always send
        predictedAction = c[bundling-1];
        if (eof == EOF)  {
           if (emptyBlock) {       // end of generator simulation
```

```
            percentPosSlack = (double)positiveSlack *
                              100.0 / (double)pdu_counter;
            printf("EOF in file %11s at time %lf, positive slack "
            "frames=%6d(%5.2lf%%), total PDUs=%6d, total frames"
            " built=%6d, total frames sent=%6d\n",
            filename, simTime(), positiveSlack, percentPosSlack,
            pdu_counter, frame_counter, frames_sent);
            fclose(fdLog);
         }  // end of emptyBlock
         else {        // block is not empty
            busy = false;
            cancelEvent(blockTimeout);
            scheduleAt(simTime(), blockTimeout);
         }
         return;
      }  // end eof == EOF
// - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

//      msg = readyToSend  & not blockTimedout & not EOF
//      we read a new PDU from the summary file.
       //conversion from OTB units to seconds
       schedTimeSec = (double)(sendTime/2) * 3600.0 / hour_equiv;
       bitFrame_length = byteFrame_length * 8;
       slack = schedTimeSec - simTime();
       if (firstTime)  {           // first time this particular PDU
                                   // was read from the input file.
           pdu_counter++;
           slackTime.record(slack);
           if (slack >= 0) positiveSlack++;
           firstTime = false;   // this particular PDU
                                //won't be recorded again.
       }
       if (slack > 0.)  {
          busy = false;   // we will be idle for a while
          if (fseek(fd, file_pos, SEEK_SET)) perror( "Fseek failed" );
          // next packet is scheduled at timestamp in PDU
          scheduleAt(schedTimeSec, readyToSend);
          return;
       }  // end of slack > 0.
// - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

//  msg = readyToSend & not blockTimedout & not EOF & slack <= 0.
// This PDU must be grouped for replication
       firstTime = true; // to record slack for next PDU.
       if (emptyBlock) { //This PDU will be the first in the new block
```

```
            sprintf(msgname,"Data%d F%d T%d",
                    ++frame_counter, my_address, toAddr);
            msg1 = new cMessage(msgname);
            msg1->setLength(bitFrame_length);
            PDUrecord1();
            strcpy(pduIniType,pduType);
            pduIniLength = byteFrame_length;
            if (predictedAction == 's' || predictedAction == 'S')
            {  // predicted action = send
               msg1->setTimestamp();
               transmissionTime = (double)msg1->length() / dataRateBps;
               send(msg1,"out");
               frames_sent++;
               PDUrecord2();
               busy = true;
               scheduleAt(simTime() + transmissionTime + gapTime +
                          generatorServiceTime, readyToSend);
            }
            else {                // predicted action = wait
               scheduleAt(simTime() + blockWaitTime, blockTimeout);
               busy = false;
               emptyBlock = false;
               scheduleAt(simTime() + generatorServiceTime, readyToSend);
            }
            return;
          }  // end of emptyBlock
// - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

// msg = readyToSend & not blockTimedout &
// not EOF & slack <= 0. & not emptyBlock
          if ((strcmp(pduIniType,pduType)==0) &&
             (pduIniLength==byteFrame_length)) { //compatible PDU
//grouping (bundling)
             msg1->setLength(msg1->length()+(pduextra[pduID]*8));
             PDUrecord1();
             if (predictedAction == 's' || predictedAction == 'S') {
                msg1->setTimestamp();   // predicted action = send
                transmissionTime = (double)msg1->length() / dataRateBps;
                send(msg1,"out");
                frames_sent++;
                PDUrecord2();
                cancelEvent(blockTimeout);
                emptyBlock = true;
                busy = true;
                scheduleAt(simTime() + transmissionTime + gapTime +
```

```
                        generatorServiceTime, readyToSend);
            }          // end of predictedAction = send
            else {     // predicted action = wait
               busy = true;
               scheduleAt(simTime() + generatorServiceTime, readyToSend);
            }          // end of predicted action = wait
            return;
         } //  end of compatible PDU
// - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

// msg = readyToSend & not blockTimedout &
// not EOF & slack <= 0. & not emptyBlock & PDU not compatible
         msg1->setTimestamp();
         transmissionTime = (double)msg1->length() / dataRateBps;
         send(msg1,"out");
         frames_sent++;
         PDUrecord2();
         cancelEvent(blockTimeout);
         sprintf(msgname,"Data%d F%d T%d",
         ++frame_counter, my_address, toAddr);
         msg1 = new cMessage(msgname);
         msg1->setLength(bitFrame_length);
         PDUrecord1();
         strcpy(pduIniType,pduType);
         pduIniLength = byteFrame_length;
         if (predictedAction == 's' || predictedAction == 'S')
         {  // predicted action = send
            // this 1-PDU block is considered to have timedout
            blockTimedout = true;
         }
         else {        // predicted action = wait
            scheduleAt(simTime() + blockWaitTime +
                       generatorServiceTime, blockTimeout);
         }             // end of predicted action = wait
         busy = true;
         scheduleAt(simTime() + transmissionTime + gapTime +
                    generatorServiceTime, readyToSend);
         return;  //  msg = readyToSend & not EOF & slack <= 0.
    } // end msg == readyToSend
//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

    printf("Generator %d: Unrecognized message\n", my_address);
    return;
}
```

```
//==================================================================
void Generator::finish()  {
  ev << "Generator " << my_address << ": No of frames sent = "
     << frame_counter << endl;
}

//==================================================================
void Generator::PDUrecord1()  {
  if (my_address == 24) fprintf(fdLog, "%d ", pduID);
}

//==================================================================
void Generator::PDUrecord2()  {
  double t, seconds;
  int minutes;
  t = simTime();
  minutes = (int) t/60.;
  seconds = t - minutes*60.;

  if (my_address == 24) {
      double t, seconds;
      int minutes;
      t = simTime();
      minutes = (int) (t/60.);
      seconds = t - minutes*60.;
      fprintf(fdLog, ": %lf (:%d:%.3lf) | \tframes:%d\n",
              t, minutes, seconds, frames_sent);
  }
}

//-----------------------------------------------------------
// file: sink.cpp
//-----------------------------------------------------------

#include <omnetpp.h>


//
// Sink simple module class
//
class Sink : public cSimpleModule
{
    int my_address, from, to, collisionCounter, framesReceived,
        unrecognized, wrongAddress;
    double travelTime;
```

```
    cMessage *collision;
    char *p;

    // member functions
    Module_Class_Members(Sink,cSimpleModule,0)
    virtual void initialize();
    virtual void handleMessage(cMessage *msg);
    virtual void finish();

    cDoubleHistogram *travelDist;
    cOutVector travelHist;
    cStdDev travelStats;

    cOutVector collHistAccum;

};

Define_Module( Sink );

void Sink::initialize()
{
    collisionCounter = 0;
    my_address = parentModule()->par("nodeID");
    collision = new cMessage("collision");
    travelDist = new cDoubleHistogram(
                 "Travel Time Distribution at destination", 100);
    travelDist->setRange(0, 100);
    travelHist.setName("Travel Time History");
    travelStats.setName("travel Stats");
    collHistAccum.setName("Collision Accumulation");
    framesReceived = 0;
    unrecognized = 0;
    wrongAddress = 0;
}

void Sink::handleMessage(cMessage *msg)
{
    // msg == collision
    if (strcmp(msg->name(), collision->name()) == 0)
    {
        collisionCounter++;
        collHistAccum.record (collisionCounter);
        delete msg;
        return;
    }
```

```
    p = strchr(msg->name(),'F');

    if (p == NULL)
    {   ev<<"Sink["<<my_address<<"] unrecognized deleted "
          <<msg->name()<<endl;
        delete msg;     // unrecognized message, considered an error
        unrecognized++;
    }
    else                    // p != NULL, this is a regular message
    sscanf(p, "F%d T%d", &from, &to);

    if (to == -1 || to == my_address)
    {
//      ev << "Sink[" << my_address << "] Frame " << msg->name()
           <<" at T = " << simTime() << endl;
        travelTime = simTime() - msg->timestamp();
        // travel time travelStatsistics collection
        travelDist->collect (travelTime);
        travelHist.record(travelTime);
        travelStats.collect(travelTime);
        framesReceived++;
    }
    else wrongAddress++;

    delete msg;
}

void Sink::finish()
{
    long num_samples;
    double smallest, largest, mean,
           standard_deviation, variance;

    ev << endl << endl<< "*** Module: " << fullPath() << "***" << endl;
    ev << "Total arrivals: " << travelDist->samples() << endl;
    ev << "Estimation of the travel stationary \
    distribution of travel time.\n";
    ev << "Travel time, # of messages, estimated \
    probability density function.\n";
    for(int i=0; i<travelDist->cells(); ++i)
    {   if(travelDist->cell(i) > 0)
        {   ev << i << ":\t" << travelDist->cell(i);
            ev << "\t" << travelDist->cellPDF(i) << endl;
        }
```

```
    }
    recordStats("Travel Time Distribution Statistics", travelDist);
    ev << "Travel Time Statistics" << endl;
    num_samples = travelStats.samples();
    smallest = travelStats.min();
    largest = travelStats.max();
    mean = travelStats.mean();
    standard_deviation = travelStats.stddev(),
    variance = travelStats.variance();
    ev << "Number of samples: " << num_samples          << endl;
    ev << "Smallest time: "     << smallest             << endl;
    ev << "Largest time: "      << largest              << endl;
    ev << "Mean value: "        << mean                 << endl;
    ev << "Standard Dev: "      << standard_deviation   << endl;
    ev << "Variance: "          << variance             << endl;
    printf("Sink %d: Total frames received=%d, total collisions \
    detected=%d total unrecognized=%d wrong address=%d\n",
           my_address, framesReceived, collisionCounter,
           unrecognized, wrongAddress);
}

//---------------------------------------------------------------
// file: router.cpp
//---------------------------------------------------------------

#include <omnetpp.h>
#include <string.h>

//
// Router simple module class
//
class Router : public cSimpleModule
{
    int routerID, nodesPerPlane, totalNodes;
    int inf, sup;
    int from, to, inGate, outGate;
    // 3 communication channels.
    int collisionCount[3], collisionCountNonReset[3];
    double  startTime, routerServiceTime, transmissionTime,
            collInterval, gapTime[4], dataRate[4];
    int fromLan, toLan, fromSP, toSP, fromPP, toPP;  // frame counters

    cQueue queue;
    cMessage *sendNow, *readyToSend, *collision,
             *collStatsNow, *msg1, *msg2;
```

```
    cDoubleHistogram *jobDist;
    cOutVector jobsInSys;
    cStdDev stat;

    cDoubleHistogram *collDist[3];
    cOutVector collInSys[3];

    cOutVector collHistAccum;

    // member functions
    Module_Class_Members (Router, cSimpleModule,0)
    virtual void initialize ();
    virtual void finish ();
    virtual void handleMessage (cMessage *msg);
    void serveMessage();
    int outputGate (int inGate, int from, int to);
};

Define_Module( Router );



//=============================================================
void Router::initialize()
{
    int i;
    startTime = par("startTime");
    routerID        = par("routerID");
    nodesPerPlane   = par("nodesPerPlane");
    totalNodes      = par("totalNodes");
    routerServiceTime = par("routerServiceTime");

    gapTime[0]  = gate("outToLocal")->toGate()->ownerModule()
                  ->par("gapTime");
    gapTime[1]  = gate("outToWirelessPP")->toGate()->toGate()
                  ->ownerModule()->par("gapTime");
    gapTime[2]  = gate("outToWirelessSP")->toGate()->toGate()
                  ->ownerModule()->par("gapTime");
    gapTime[3]  = gapTime[1] > gapTime[2] ? gapTime[1] : gapTime[2];

    dataRate[0] = (double)gate("outToLocal")     ->toGate()
                  ->ownerModule()->par("dataRateBps");
    dataRate[1] = (double)gate("outToWirelessPP")->toGate()->toGate()->ownerModule()
                  ->par("dataRateBps");
```

```
    dataRate[2] = (double)gate("outToWirelessSP")->toGate()->toGate()->ownerModule()
                  ->par("dataRateBps");
    dataRate[3] = dataRate[1] < dataRate[2] ? dataRate[1] : dataRate[2];

    collision    = new cMessage("collision");
    collStatsNow = new cMessage("collStatsNow");
    readyToSend  = new cMessage("readyToSend");
    sendNow      = new cMessage("sendNow");

    inf = nodesPerPlane * routerID;
    sup = inf + nodesPerPlane - 1;
    // msg1 = NULL because initial state is "readyToSend"
    msg1 = NULL;

    jobDist = new cDoubleHistogram(
              "Queue Message Distribution (router)", 100);
    jobDist->setRange(0, 100);
    jobsInSys.setName("Messages in System (router)");
    stat.setName("stat");

    {   char *titles[3] =   { "Collisions at inFromLocal (Ethernet)",
                              "Collisions at inFromWirelessPP",
                              "Collisions at inFromWirelessSP" };
        for (i = 0; i<3; i++)
        {   collisionCount[i] = 0;
            collisionCountNonReset[i] = 0;
            collDist[i] = new cDoubleHistogram(titles[i], 100);
            collDist[i]->setRange(0, 100);
            collInSys[i].setName(titles[i]);
        }
    }
    collHistAccum.setName("Collision Accumulation");

    // count collisions in 1-second intervals
    collInterval = 1.;
    // frame counters set to 0
    fromLan = toLan = fromSP = toSP = fromPP = toPP = 0;
    // first event to request collision statistics.
    scheduleAt(collInterval+startTime, collStatsNow);
}


//==============================================================
void Router::handleMessage(cMessage *msg)
{
```

```
    if (strcmp(msg->name(), collision->name()) == 0) // msg == collision
    {   inGate = msg->arrivalGate()->id() /2;    // inGate = 0 or 1 or 2
        collisionCount[inGate]++;
        collisionCountNonReset[inGate]++;
        collHistAccum.record (collisionCountNonReset[0] +
                              collisionCountNonReset[1] +
                              collisionCountNonReset[2]);
        delete msg;
        return;
    }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    // Statistics collection requested now
    else if (msg == collStatsNow)
    {   for (int i=0; i<3; i++)
        {   collDist[i]->collect (collisionCount[i]);
            collInSys[i].record(collisionCount[i]);
    // starts a new count for the next interval
            collisionCount[i] = 0;
        }
        scheduleAt(simTime()+collInterval, collStatsNow);
        return;
    }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    else if (msg == sendNow)
    {
        switch (outGate)
        {
            case 0:
                send(msg1, "outToLocal");
                toLan++;
                break;

            case 1:
                send(msg1, "outToWirelessPP");
                toPP++;
                break;

            case 2:
                send(msg1, "outToWirelessSP");
                toSP++;
                break;

            case 3:
```

```
                msg2 = (cMessage *) msg1->dup();
                send(msg1, "outToWirelessPP");
                toPP++;
                send(msg2, "outToWirelessSP");
                toSP++;
                break;
        }
    }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    else if (msg == readyToSend) // last gapTime has elapsed
    {
        if ( queue.empty() ) // There are no remaining messages in queue
        {
            msg1 = NULL;
        }

        else
        {
            msg1 = (cMessage *) queue.pop();
// schedules a sendNow and readyToSend for msg1
            serveMessage();
        }
    }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    else       // msg == regular message || unrecognized
    {
// to ignore messages sent to satellite from other planes
      char *p = strchr(msg->name(),'F');
      sscanf(p, "F%d T%d", &from, &to);
      inGate = msg->arrivalGate()->id();
// gate #4: inFromWirelessSP
      if ((inGate == 4) && (from != totalNodes))
      {
          delete msg;
          return;
      }

// msg arrived while server is idle, current state is "readyToSend"
      if (msg1 == NULL)
// Statistics collection: queue length was 0
      {   jobDist->collect(0);
          jobsInSys.record(0);
          stat.collect(0.);
```

```
          msg1 = msg;     //msg will be serviced immediately
          serveMessage(); //schedules a sendNow and readyToSend for msg1
      }

      else                            // Arrival while server is busy
      {
// n msgs in queue + 1 being serviced
          jobDist->collect(queue.length()+1);
          jobsInSys.record(queue.length()+1);
          stat.collect(queue.length()+1.);
          queue.insert( msg );
      }
    }   // end of regular message

}       // end handleMessage


//=============================================================
void Router::serveMessage()
{
    char *p = strchr(msg1->name(),'F');
    if (p == NULL)         // unrecognized message, considered an error
    {
        ev<<"Router["<<routerID<<"] unrecognized deleted "
          <<msg1->name()<<endl;
        delete msg1;
        scheduleAt( simTime(), readyToSend );
        return;
    }

    sscanf(p, "F%d T%d", &from, &to);
// inGate: 0/2 = 0, 2/2 = 1 or 4/2 = 2
    inGate = (msg1->arrivalGate()->id()) / 2;
    if (inGate==0)fromLan++;
    if (inGate==1)fromPP++;
    if (inGate==2)fromSP++;
// outGate = -1, 0, 1, 2, 3
    outGate = outputGate(inGate, from, to);
    if (outGate < 0)
    {
        delete msg1;
        scheduleAt( simTime(), readyToSend );
        return;
    }
```

```
    transmissionTime = msg1->length() / dataRate[outGate];
    scheduleAt( simTime() + routerServiceTime, sendNow );
    scheduleAt( simTime() + routerServiceTime + transmissionTime
              + gapTime[outGate], readyToSend );

}


//=======================================================
int Router::outputGate(int inGate, int from, int to)
{
    switch (inGate)
    {
        case 0:                                         // inFromLocal
            if (to == -1)               return 3;   // outToWirelessSP
                                                    // and outToWirelessPP
            if (to == totalNodes)       return 2;   // outToWirelessSP
            if (to < inf || to > sup)   return 1;   // outToWirelessPP
            return -1;                              // delete message
            break;

        case 1:                                         // inFromWirelessPP
            if (to == -1)               return 0;   // outToLocal
// delete, this case shoud not occur
            if (to == totalNodes)       return -1;
            if (inf <= to && to <= sup) return 0;   // outToLocal
            return -1;                              // delete message
            break;

        case 2:                                         // inFromWirelessSP
            if (
                 (from == totalNodes) &&
                 ((to == -1) || (inf <= to && to <= sup))
// from satellite (groundStation) to local broadcast
               ) return 0;
            return -1;                              // delete message
            break;
    }
    return -2;      // unreachable code to eliminate C++ warning.
}


//=======================================================
void Router::finish()
{
```

```
    long num_samples;
    double smallest, largest, mean, standard_deviation, variance;

    ev << endl << endl<< "*** Module: " << fullPath() << "***" << endl;
    ev << "Total arrivals:\t" << jobDist->samples() << endl;
    ev << "Total collisions detected:"<<endl;
    ev << "At inFromLocal: " << collisionCountNonReset[0]<<endl;
    ev << "At wirelessPP: "  << collisionCountNonReset[1]<<endl;
    ev << "At wirelessSP: "  << collisionCountNonReset[2]<<endl<<endl;

    ev << "Estimation of the stationary  distribution of messages \
    as observed by an arrival.\n";
    ev << "Queue length, # arrivals that saw n messages in queue, \
    estimated probability density function.\n";
    for(int i=0; i<jobDist->cells(); ++i)
    {   if(jobDist->cell(i) > 0)
        {   ev << i << ":\t" << jobDist->cell(i);
            ev << "\t" << jobDist->cellPDF(i) << endl;
        }
    }
    recordStats("Message Distribution Statistics", jobDist);
    ev << "Queue length statistics" << endl;
    num_samples = stat.samples();
    smallest = stat.min();
    largest = stat.max();
    mean = stat.mean();
    standard_deviation = stat.stddev(),
    variance = stat.variance();
    ev << "Number of samples: " << num_samples          << endl;
    ev << "Smallest queue: "    << smallest             << endl;
    ev << "Largest queue: "     << largest              << endl;
    ev << "Mean value: "        << mean                 << endl;
    ev << "Standar Dev: "       << standard_deviation   << endl;
    ev << "Variance: "          << variance             << endl;
    printf("Router %d: frames fromLan=%d, toLan=%d, fromSP=%d, \
    toSP=%d, fromPP=%d, toPP=%d, in queue=%d\n",
    routerID, fromLan, toLan, fromSP, toSP, fromPP,
    toPP, queue.length());
}

//---------------------------------------------------------------
// file: satellite.cpp
//---------------------------------------------------------------

#include <omnetpp.h>
```

```
#include <string.h>

//
// Satellite simple module class
//
class Satellite : public cSimpleModule
{
    // arrays are of length 2 because of the 2 communication channels.
    int satelliteID, totalNodes;
    double startTime, satServiceTime, transmissionTime,
           gapTime[2], dataRate[2];
    double WSPposition, WGSposition, collInterval;
    int from, to, inGate, outGate, numGate;
    int collisionCount[2], collisionCountNonReset[2], byteCount,
        framesToGS, framesToPlanes, framesReceivedFromGS,
        framesReceivedFromSP, unrecognized;
    char *p;

    cQueue queue;
    cMessage *sendNow, *readyToSend, *collision, *collStatsNow, *msg1;
    cDoubleHistogram *jobDist, *byteDist;
    cOutVector jobsInSys, bytesInSys;
    cStdDev msgStat, byteStat;
    cDoubleHistogram *collDist[2];
    cOutVector collInSys[2];

    // member functions
    Module_Class_Members(Satellite, cSimpleModule,0)
    virtual void initialize();
    virtual void finish();
    virtual void handleMessage(cMessage *msg);
    void serveMessage();
    int outputGate (int inGate, int from, int to);


};

Define_Module( Satellite );

//==============================================================
void Satellite::initialize()
{
    int i;
    startTime = par("startTime");
    satServiceTime = par("satServiceTime");
```

```
    sendNow = new cMessage("sendNow");
    collision = new cMessage("collision");
    collStatsNow = new cMessage("collStatsNow");
    readyToSend  = new cMessage("readyToSend");

    gapTime[0]  = gate("outBus1")->toGate()->ownerModule()
                  ->par("gapTime");
    gapTime[1]  = gate("outBus2")->toGate()->ownerModule()
                  ->par("gapTime");

    dataRate[0] = (double)gate("outBus1")->toGate()->ownerModule()
                  ->par("dataRateBps");
    dataRate[1] = (double)gate("outBus2")->toGate()->ownerModule()
                  ->par("dataRateBps");

    satelliteID = par("satelliteID");
// totalNodes = 3*8 = 24, but 0,...,24 = 25 nodes
    totalNodes = par("totalNodes");
//  WSPposition  = par("WSPposition");
//  WGSposition  = par("WGSposition");
    msg1 = NULL;

    jobDist = new cDoubleHistogram(
              "Queue Message Distribution (satellite)", 100);
    jobDist->setRange(0, 100);
    jobsInSys.setName("Messages in System (satellite)");
    byteDist = new cDoubleHistogram(
              "Queue Byte Distribution (satellite)", 100);
    byteDist->setRange(0, 100);
    bytesInSys.setName("Bytes in System (satellite)");

    {   char *titles[2] =   { "Collisions at wirelessGS",
                              "Collisions at wirelessSP" };

        for (i = 0; i<2; i++)
        {   collisionCount[i] = 0;
            collisionCountNonReset[i] = 0;
            collDist[i] = new cDoubleHistogram(titles[i], 100);
            collDist[i]->setRange(0, 100);
            collInSys[i].setName(titles[i]);
        }
    }
    framesToGS = 0;      // to count frames sent to Ground Station
    framesToPlanes = 0;
    framesReceivedFromGS = 0;
```

```
    framesReceivedFromSP = 0;
    unrecognized = 0;
    byteCount = 0;                      // counts bytes in queue.
    collInterval = 1.;     // count collisions in 1-second intervals
// first event to request collision statistics.
    scheduleAt(collInterval+startTime, collStatsNow);

}

//==============================================================
void Satellite::handleMessage(cMessage *msg)
{
    if (strcmp(msg->name(), collision->name()) == 0) //msg == collision
    {
        inGate = msg->arrivalGate()->id() /2;        //inGate = 0 or 1
        collisionCount[inGate]++;
        collisionCountNonReset[inGate]++;
        delete msg;
        return;
    }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    else if (msg == collStatsNow)   // Statistics collection requested now
    {   for (int i=0; i<2; i++)
        {   collDist[i]->collect (collisionCount[i]);
            collInSys[i].record(collisionCount[i]);
// starts a new count for the next interval
            collisionCount[i] = 0;
        }
        scheduleAt(simTime()+collInterval, collStatsNow);
        return;
    }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    else if (msg == sendNow)
    {
        switch (outGate)
        {
            case 0:
                send(msg1, "outBus1");  // wirelessGS
                framesToGS++;
                break;

            case 1:
                send(msg1, "outBus2");  // wirelessSP
```

```
                framesToPlanes++;
                break;
            }
        }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
        else if (msg == readyToSend)    // last gapTime has elapsed
        {
            if ( queue.empty() ) // There are no remaining messages in queue
            {
                msg1 = NULL;
                if (byteCount != 0)
                printf("Satellite: Error, empty queue has byteCount = %d\n",
                        byteCount);
            }

            else
            {
                msg1 = (cMessage *) queue.pop();
// subtracts # bytes taken from the queue
                byteCount -= msg1->length()/8;
// schedules a sendNow and readyToSend for msg1
                serveMessage();
            }
        }

//- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
        else           // msg == regular message or unrecognized
        {
// msg arrived while server is idle, current state is "readyToSend"
          if (msg1 == NULL)
          {
// Statistics collection: queue length was 0
             jobDist->collect(0);
             jobsInSys.record(0);
             msgStat.collect(0.);
// Statistics collection: queue length was 0
             byteDist->collect(0);
             bytesInSys.record(0);
             byteStat.collect(0.);
             msg1 = msg;           // msg will be serviced immediately
// schedules a sendNow and readyToSend for msg1
             serveMessage();
          }
          else                 // Arrival while server is busy
```

```
      {
// n msgs in queue + 1 being serviced
          jobDist->collect(queue.length()+1);
          jobsInSys.record(queue.length()+1);
          msgStat.collect(queue.length()+1.);
// accumulates # bytes in new message
          byteCount += msg->length()/8;
// n msgs in queue + 1 being serviced
          byteDist->collect(byteCount);
          bytesInSys.record(byteCount);
          byteStat.collect(byteCount);
          queue.insert( msg );
      }
    }   // end of regular message

}       // end handleMessage


//=============================================================
void Satellite::serveMessage()
{
    char *p = strchr(msg1->name(),'F');
    if (p == NULL)    // unrecognized message, considered an error
    {
        ev<<"Satellite: unrecognized message deleted "<<endl;
        delete msg1;
        unrecognized++;
        scheduleAt( simTime(), readyToSend );
        return;
    }

    sscanf(p, "F%d T%d", &from, &to);
    inGate = (msg1->arrivalGate()->id()) / 2; //inGate: 0/2=0, 2/2=1
    if (inGate==0) framesReceivedFromGS++;
    else framesReceivedFromSP++;
    outGate = outputGate(inGate, from, to);   // outGate = -1, 0, 1
    if (outGate < 0)
    {
        delete msg1;
        unrecognized++;
        scheduleAt( simTime(), readyToSend );
        return;
    }

    transmissionTime = msg1->length() / dataRate[outGate];
```

```
    scheduleAt( simTime() + satServiceTime, sendNow );
    scheduleAt( simTime() + satServiceTime + transmissionTime +
                gapTime[outGate], readyToSend );

}


//=============================================================
int Satellite::outputGate(int inGate, int from, int to)
{
    switch (inGate)
    {
        case 0:                             // inBus1 (wirelessGS)
            if (to < totalNodes) return 1;  // WirelessSP
            return -1;                        // delete message
            break;

        case 1:                                     // inBus2 (wirelessSP)
            if (to == -1 || to == totalNodes)
                 return 0; // inBus1 wirelessGS
            return -1;                              // delete message
            break;
    }

    return -2;      // unreachable code to eliminate C++ warning.
}


//=========================================================
void Satellite::finish()
{
    long num_samples;
    double smallest, largest, mean, standard_deviation, variance;

    ev << endl << endl<< "*** Module: " << fullPath()
       << "***" << endl;
    ev << "Total arrivals:\t" << jobDist->samples() << endl;
    ev << "Total collisions detected:"<<endl;
    ev << "At wirelessGS: " << collisionCountNonReset[0]
       <<endl;
    ev << "At wirelessSP: " << collisionCountNonReset[1]
       <<endl<<endl;
    ev << "Estimation of the stationary  distribution of \
    messages as observed by an arrival.\n";
    ev << "Queue length, # arrivals that saw n messages in \
```

```
    queue, estimated probability density function.\n";
    for(int i=0; i<jobDist->cells(); ++i)
    {   if(jobDist->cell(i) > 0)
        {   ev << i << ":\t" << jobDist->cell(i);
            ev << "\t" << jobDist->cellPDF(i) << endl;
        }
    }
    recordStats("Message Distribution Statistics", jobDist);
    ev << "Queue length statistics" << endl;
    num_samples = msgStat.samples();
    smallest = msgStat.min();
    largest = msgStat.max();
    mean = msgStat.mean();
    standard_deviation = msgStat.stddev(),
    variance = msgStat.variance();
    ev << "Number of samples: " << num_samples          << endl;
    ev << "Smallest queue: "    << smallest             << endl;
    ev << "Largest queue: "     << largest              << endl;
    ev << "Mean value: "        << mean                 << endl;
    ev << "Standar Dev: "       << standard_deviation   << endl;
    ev << "Variance: "          << variance             << endl;
    printf("Satellite: total frames received from GS=%d, \
    sent to SP=%d\n",
           framesReceivedFromGS, framesToPlanes);
    printf("Satellite: received from SP=%d, sent to GS=%d, \
    unrecognized=%d, in queue=%d\n",
    framesReceivedFromSP, framesToGS, unrecognized, queue.length());
}


//---------------------------------------------------------------
// File: simplebus.cc
// Based on an example by Andras Varga, author of OMNeT++.
//---------------------------------------------------------------

#include <assert.h>
#include <omnetpp.h>

#define MAX_NUM_TAPS  50

class SimpleBus : public cSimpleModule
{
    struct sTransmission
    {
        int tap, channel;
```

```
        bool upstream;
        bool isCollision;
        simtime_t busyStart, busyEnd;
        cMessage *endEvent;
        cMessage *frame;
    };

int prueba;
    Module_Class_Members(SimpleBus,cSimpleModule,0);
    virtual void initialize();
    virtual void handleMessage(cMessage *msg);

    cMessage *createMessage();
    sTransmission *createTransmission();
    void recycleMessage(cMessage *msg);
    void recycleTransmission(sTransmission *tr);

  private:
    int numTaps;
    int numChannels;

    bool wantCollisionModeling;
    bool wantCollisionSignal;
    bool isFullDuplex;
    double delaySecPerMeter;
    double dataRateBps;

    char busTypePosition[20];
    double tapPositions[MAX_NUM_TAPS];
    cArray tapStates;

    cHead recycledMessages;
    cLinkedList recycledTransmissions;
};

Define_Module(SimpleBus);


void SimpleBus::initialize()
{
    // get parameters
// collision modeling flag
    wantCollisionModeling = par("wantCollisionModeling");
// "send collision signals" flag
    wantCollisionSignal = par("wantCollisionSignal");
```

```
// number of independent channels
    numChannels = par("numChannels");
// channel mode
    isFullDuplex = par("isFullDuplex");
// delay of the bus
    delaySecPerMeter = par("delaySecPerMeter");
// data rate of the bus
    dataRateBps = par("dataRateBps");
    strcpy(busTypePosition, par("busType").stringValue());
    strcat(busTypePosition, "position");
//  busTypePosition = LANposition, WPPposition, WSPposition,
//  or WGSposition

    // query the number of taps and the their positions (in meters)
    numTaps = gate("out")->size();
    assert(numTaps < MAX_NUM_TAPS);
    for (int k=0; k<numTaps; k++)
    {
        tapPositions[k] = gate("out",k)->toGate()->ownerModule()
        ->par(busTypePosition);
    }

    // create linked lists that will hold channel states at taps
    // (sTransmission structs)
    tapStates.setName("tapStates");
    for (int i=0; i<numTaps; i++)
    {
        for (int j=0; j<numChannels; j++)
        {
           char listname[64];
           sprintf(listname,"tap%dchannel%d",i,j);
           cLinkedList *list = new cLinkedList(listname);
           tapStates.addAt(i*numChannels+j, list);
        }
    }

    recycledMessages.setName("recycledMessages");
    recycledTransmissions.setName("recycledTransmissions");
}

cMessage *SimpleBus::createMessage()
{
    return new cMessage;
}
```

```
SimpleBus::sTransmission *SimpleBus::createTransmission()
{
    return new sTransmission;
}

void SimpleBus::recycleMessage(cMessage *msg)
{
    delete msg;
}

void SimpleBus::recycleTransmission(sTransmission *tr)
{
    delete tr;
}

void SimpleBus::handleMessage(cMessage *msg)
{
    cMessage *msg_new;

    // is msg a frame to be transmitted on the bus?
    if (!msg->isSelfMessage())
    {
        // get position where packet dropped in
        double packetPos = tapPositions[msg->arrivalGate()->index()];

        // get channel and direction of packet
        int channel = 0;
        if (msg->findPar("channel")>=0)
            channel = msg->par("channel");
        bool upstream = true;
        if (msg->findPar("upstream")>=0)
            upstream = msg->par("upstream");

        // duration of packet transmission
        double duration = msg->length() / dataRateBps;

        // check for collisions and schedule events at different taps
        for (int tap=0; tap<numTaps; tap++)
        {
// frame doesn't reach originating tap (J.V.)
// if channel is full duplex, frames propagate in only one
// direction, so maybe this frame won't reach this tap at all
            if ((packetPos == tapPositions[tap]) || isFullDuplex &&
               ((upstream && packetPos>tapPositions[tap]) ||
               (!upstream && packetPos<tapPositions[tap])))
```

```
            continue;

        // determine when frame head and tail will reach this tap
        double distance = fabs(packetPos-tapPositions[tap]);
        double delay = distance * delaySecPerMeter;

        simtime_t start = simTime() + delay;
        simtime_t end = start + duration;

        #ifdef WANT_DEBUG
          ev << "Start receive " << msg->name() << " at tap "
          << tap << " at T = " << start << endl;
          ev << "Complete receive " << msg->name() << "at tap "
          << tap << " at T = " << end << endl;
        #endif

        bool hasCollision = false;
        sTransmission *collisionTr = NULL;
        cLinkedList *list =
            (cLinkedList *)tapStates[tap*numChannels+channel];

        // if needed, do collision resolution at tap[tap]
        if (wantCollisionModeling)
        {
            for (cLinkedListIterator i(*list); !i.end(); i++)
            {
                sTransmission *tr = (sTransmission *) i();

                // does frame overlap with this transmission?
                if (channel==tr->channel && (!isFullDuplex ||
                    upstream==tr->upstream) &&
                    end>tr->busyStart && start<tr->busyEnd)
                {
// this is a collision; if we already had one, merge this transmission
// structure into the one already holding the collision, and discard
// this transmission struct.
                    if (hasCollision && tr!=collisionTr)
                    {
                        // extend (start,end) interval
                        if (start>tr->busyStart)
                            start = tr->busyStart;
                        if (end<tr->busyEnd)
                            end = tr->busyEnd;

                        // recycle this transmission
```

```
                            recycleMessage(cancelEvent(tr->endEvent));
                            if (tr->frame)
                                delete tr->frame;
                            list->remove(tr);
                            recycleTransmission(tr);

                            // adjust collisionTr afterwards...
                            tr = collisionTr;
                        }
                        else
                        {
                            // set collision flags
                            hasCollision = true;
                            collisionTr = tr;
                            tr->isCollision = true;

// if this transmission collided, don't need frame any more
                            if (tr->frame)
                            {
                                delete tr->frame;
                                tr->frame = NULL;
                            }
                        }

// adjust start and end times and reschedule events
                        if (tr->busyStart > start)
                            tr->busyStart = start;
                        else
                            start = tr->busyStart;

                        if (tr->busyEnd < end)
                        {
                            tr->busyEnd = end;
                            scheduleAt(end, cancelEvent(tr->endEvent));
                        }
                        else
                            end = tr->busyEnd;

                        #ifdef WANT_DEBUG
  ev << "*****CONTENT OF STRANSMISSION STRUCT AT TAP " << tap
     << " ******" << endl;
  ev << "channel = " << tr->channel << endl;
  ev << "tap = " << tr->tap << endl;
  ev << "busyStart = " << tr->busyStart << endl;
  ev << "busyEnd = " << tr->busyEnd << endl;
```

```
  ev << "************************************************" << endl;
                        #endif
                    }
                }
            }

// if no collision, add transmission structure and schedule
// associated events
            if (!hasCollision)
            {
                // create and fill in transmission structure
                sTransmission *tr = createTransmission();
                tr->tap = tap;
                tr->channel = channel;
                tr->upstream = upstream;
                tr->isCollision = false;
                tr->busyStart = start;
                tr->busyEnd = end;
                tr->frame = (cMessage *) msg->dup();

                // schedule event at end of transmission
                tr->endEvent = createMessage();
                char msgName[64];
                sprintf(msgName,"tap%dchannel%d-e",tap,channel);
                tr->endEvent->setName(msgName);
                tr->endEvent->setContextPointer(tr);
                scheduleAt(end, tr->endEvent);

                // add to list
                list->insertHead(tr);
            }
        }
        // don't need original frame any more
        delete msg;
    }

    else // msg->isSelfMessage() is true
    {
// this is a scheduled message, obtain associated
// transmission structure
        sTransmission *tr = (sTransmission *)msg->contextPointer();
        assert(msg==tr->endEvent);

// remove transmission structure from list
        cLinkedList *list = (cLinkedList *) tapStates[tr->
```

```
        tap*numChannels+tr->channel];
        list->remove(tr);

// send frame or collision signal on the corresponding tap
//this section changed so that collisions can be monitored
        if (tr->isCollision)
        {
             ev << "a collision signal output" << endl;
             if (wantCollisionSignal)
             {
                 msg_new= new cMessage("collision");
                 msg_new->setKind(1);
                 send(msg_new,"out",tr->tap);
                 ev<<busTypePosition[0]<<busTypePosition[1]<<
                 busTypePosition[2]<<"bus:"<<simTime()<<" THE MESSAGE "<<
                 msg->name()<<" caused a collision"<<endl;
             }
        }
        else
        {
//              ev << "a signal output" << endl;
             msg_new=tr->frame;
             msg_new->setKind(2);
             send(msg_new, "out", tr->tap);
        }
        recycleTransmission(tr);
        recycleMessage(msg);
    }

}
```

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