Simulation of Controller Pilot Data Link Communications over VHF Digital Link Mode 3

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Abstract

The Federal Aviation Administration (FAA) has established an operational plan for the future Air Traffic Management (ATM) system, in which the Controller Pilot Data Link Communications (CPDLC) is envisioned to evolve into digital messaging that will take on an ever increasing role in controller to pilot communications, significantly changing the way the National Airspace System (NAS) is operating. According to FAA, CPDLC represents the first phase of the transition from the current analog voice system to an International Civil Aviation Organization (ICAO) compliant system in which digital communication becomes the alternate and perhaps primary method of routine communication. The CPDLC application is an Air Traffic Service (ATS) application in which pilots and controllers exchange messages via an addressed data link. CPDLC includes a set of clearance, information, and request message elements that correspond to existing phraseology employed by current Air Traffic Control (ATC) procedures. These message elements encompass altitude assignments, crossing constraints, lateral deviations, route changes and clearances, speed assignments, radio frequency assignments, and various requests for information. The pilot is provided with the capability to respond to messages, to request clearances and information, to report information, and to declare/rescind an emergency. A "free text" capability is also provided to exchange information not conforming to defined formats.

This paper presents simulated results of the aeronautical telecommunication application Controller Pilot Data Link Communications over VHF Digital Link Mode 3 (VDL Mode 3). The objective of this simulation study was to determine the impact of CPDLC traffic loads, in terms of timely message delivery and capacity of the VDL Mode 3 subnetwork. The traffic model is based on [1] and is used for generating air/ground messages with different priorities. Communication is modeled for the en route domain of the Cleveland Center air traffic (ZOB ARTCC).

Introduction

The current Air Traffic Control (ATC) system is insufficient, because it relies heavily on voice communications to relay control instructions and other information between air traffic controllers and pilots. The problem is, as air travel continues to increase, controller-pilot communication has increased to the saturation point during peak traffic periods at many locations. NASA, under the Advanced Air Transportation Technologies (AATT) Project, has been instituted to develop new technologies that enable free-flight, a safe and efficient flight regime under instrument flight rules (IFR) in which operators have the freedom to select their path and speed in real time [2].

To implement free flight or the new Air Traffic Management concepts, FAA has established an operational plan for the future ATM system, in which CPDLC is envisioned to evolve into digital messaging that will take on an ever-increasing role in controller-pilot communications, significantly changing the way the NAS is operating. According to FAA, CPDLC represents the first phase of transition from the current analog voice system to an ICAO compliant system in which digital communications becomes the alternate and perhaps primary method of routine communication.

This paper presents simulated results of the aeronautical telecommunication application Controller Pilot Data Link Communications over VHF Digital Link Mode 3 (VDL Mode 3). The objective of this simulation study was to determine the impact of CPDLC traffic loads, in terms of timely message delivery and capacity of the VDL Mode 3 subnetwork.

The traffic model is based on [1] and is used for generating air/ground messages with different priorities. Communication is modeled for the en route domain of the Cleveland Air Route Traffic Control Center (ZOB ARTCC).

VDL Mode 3 Subnetwork

VDL Mode 3 provides both Aeronautical Telecommunication Network (ATN) data and digital voice services. It was proposed to the International Civil Aviation Organization in 1994 by the United States Federal Aviation Administration as an alternative to using 8.33 KHz channel spacing to relieve VHF congestion. VDL Mode 3 works by providing four logical independent channels in a 25 kHz frequency assignment. Each channel can be used for voice or data transfer. The appealing capability of VDL Mode 3 is that it uses a frequency channel that can carry one analog voice transmission and turns it into three or four simultaneous transmissions using Time Division Multiple Access (TDMA). There are seven configurations defined for VDL Mode 3 in the ICAO VDL Mode 3 Standards and Recommended Practices (SARPs). The standard range or 4-slot configurations include 4V (four voice), 3V1D (three voice and one data), 2V2D (two voice and 2 data) and 3T (three trunked).

3T (which is used in this simulation) provides a trunked capability shared by all users in one 25 KHz channel in which one out of the four time slots is available for voice or data and two out of four time slots are available exclusively for data. The fourth time slot is used exclusively for channel management functions.

VDL Mode 3 uses the same modulation scheme as VDL Mode 2, which is Differential 8 Phase Shift Keying (D8PSK) at a data rate of 31.5 kbps [3].

VDL Mode 3 has the same subnetwork architecture for ATN communications as other VDL Modes, although in Mode 3 a different form of link layer protocol is employed, known as Acknowledged Connectionless Data Link (A-CLDL). VDL Mode 3 includes a Digital Communications Equipment (DCE) in the aircraft side of the subnetwork, which is not present in other modes.

CPDLC over VDL Mode 3

CPDLC or "Controller-Pilot Data Link Communications" is a digital application using Abstract Syntax Notation 1 (ASN.1) formatted messages to reduce congestion in the voice channels used for controller-pilot communications. CPDLC is an application envisioned to be carried over VHF Digital Link (VDL) modes. In this paper, the load of CPDLC over VDL Mode 3 is modeled and analyzed.

In the analog VHF communications environment, currently used by pilots and controllers, many commands and requests are issued using standard phraseology to ease communications. CPDLC works by assigning ASN.1 format codes to many of these standard message components. These ASN.1 message components are then assembled into data link messages by the pilots and controllers when communicating with the other party. Error checking can be incorporated in the transmission of ASN.1 CPDLC messages, ensuring that the information is displayed accurately at the other end of the link. The persistent textual display of the message ensures that the message is accurately interpreted and remembered, without the need for repetition.

Offloading routine formatted communications to CPDLC has the inherent advantage of freeing up the remaining voice slots or channels for more critical free text voice communications. Because the number of bits needed to transmit an ASN.1 formatted CPDLC message is fewer than the number of Vocoder bits needed to transmit a digital voice message, which in turn is more efficient than transmitting analog voice, the capacity of the VHF communications channel is significantly increased, reducing congestion. Various configurations of voice and data slots exist in VDL Mode 3 to allow the voice and data communications of one or more controllers managing groups of aircraft to be shared in TDMA format over a single frequency. This simulation examines the performance of CPDLC in the 3T configuration, where the first slot is used for data link management messages and the following three trunked slots in each frame can be used for either voice or data.

Simulation Overview

The simulations in this study are performed in OPNET version 10.0.A. OPNET is a discrete-event network simulation tool that models protocols as

finite-state machines. It provides a mechanism to implement custom protocols and interface these to a library of standard networking protocols to examine network performance.

The standard OPNET models for IP and UDP were combined with custom-written models for the application and VDL to create the aircraft and ground station for these simulations. The model for the aircraft and ground station is shown in Figure 1.
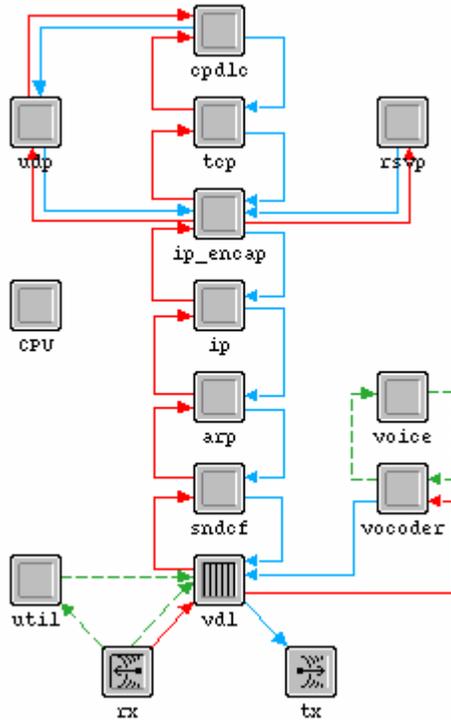
Figure 1. Aircraft and ground station model

In the model, the CPDLC process sends and receives empty CPDLC messages. User Datagram Protocol (UDP) is the transport protocol. IP is the network protocol, which is similar to the ATN Connection Less Network Protocol (CLNP). IP (version 4) provides packet addressing and routing functionality. The Address Resolution Protocol (ARP) converts the IP address into an address recognizable by the VDL process. No additional overhead is added to the simulation from the ARP protocol. The Sub-Network Dependent Convergence Function (SNDCF) provides interfacing between the network and data link layers, providing services including data compression. In this implementation, it assists in message priority assignment since IP does not support priority. The

VDL process implements the VDL Mode 3 media access control (MAC) and data link service (DLS) protocols in detail. The voice, voice encoder/decoder (Vocoder), Transport Control Protocol (TCP), and RSVP processes are not used in these simulations.

For these simulations, the UDP protocol is used instead of TCP. This is required in our implementation to correctly communicate message priority between CPDLC and VDL because the TCP/IP protocol suite does not support prioritized messages. Since these protocols are used in place of the ATN protocols only because of their availability in OPNET, our mechanism of reading priority directly from the CPDLC message is acceptable. Using TCP with this implementation, however, would cause inaccuracies since the TCP control packets, such as acknowledgements, would not contain priority information. To model the overhead from the ATN-specified connection-oriented TP4 protocol, additional traffic was added to the simulations to represent the TP4 acknowledgements.

The CPDLC message traffic used for this study is defined in [4]. The messages are defined in terms of messages per flight and messages per sector. To convert this data to messages per second (required for our implementation of the CPDLC model), the sector and flight durations were calculated from the ZOB flight data [5]. For sector-based messages, the inter-arrival time is set to the mean duration per sector (387 seconds). For flight-based messages, the inter-arrival time is set to the median duration per flight (5700 seconds). The median flight duration was used instead of the mean because a small percentage of the flights was very long (i.e. overseas) and skewed the data. The CPDLC message traffic used for the simulation is shown in Table I. To simulate explicit acknowledgements, a 34-byte packet (including transport layer overhead) is sent for each message using the same message rates.

Table I. CPDLC Traffic Profile

Priority	Uplink Size (bits)	Downlink Size (bits)	Mean Inter-Arrival Time (s)
High	72	12	2850
High	13	12	5700
High	68	12	5700
Medium	691	690	774
Medium	36	676	5700

Medium	13	12	5700
Low	13	120	387
Low	300	43	2850

Simulation Scenarios

For this study, two simulation scenarios were considered. The first scenario assumes a frequency assigned to a single sector and models the traffic for just one sector. The second scenario examines a denser traffic load by modeling all traffic within range of the VDL ground station, irrespective of sector and control center. Both of these scenarios consider CPDLC messages only; other messages and voice traffic are not modeled.

Scenario 1: Sector-Based Communications

The sector-based scenario model is similar to current ATC operations, where each sector is assigned its own frequency for analog voice. Since the 3T configuration only provides one voice channel, only a single sector may use a given frequency while maintaining today's policy of a dedicated voice channel per sector. The benefit of using VDL Mode 3 in this scenario is the ability to send both voice and data in one single frequency, instead of just analog voice.

This scenario looks at ZOB sector 27, which contained the greatest number of aircraft. The simulation covered a period of 4 hours during which time up to 12 aircraft were in the sector. The number of aircraft in the sector over the course of the simulation is shown in Figure 2.
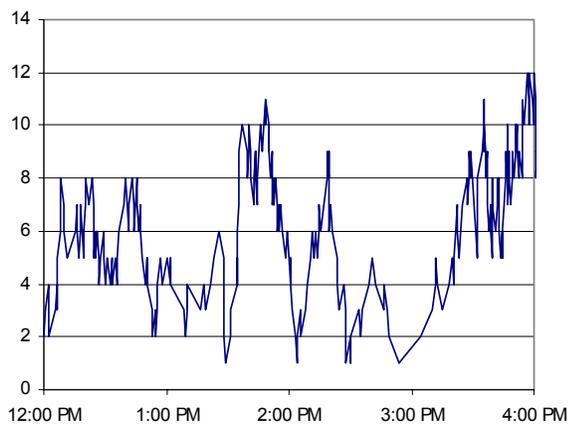
Figure 2. Flights in ZOB Sector 27

Scenario 2: Range-Based Communications

Since the sector-based communications scenario had so few aircraft compared to the limit of VDL Mode 3, this scenario is modeled to observe the datalink under higher-load conditions. To create the largest aircraft load possible, all aircraft within range of the ground station are assumed to share a single frequency. Note that the dedicated voice channel per sector requirement is ignored for this scenario.

In this scenario, all aircraft within range of the ground station are modeled. The aircraft within range are determined by radio line-of-sight as well as the VDL-defined limit of 200 nautical miles between the aircraft and ground station. The simulation examines a 2-hour period during which up to 120 aircraft are communicating with the VDL ground station. The number of aircraft in range of the ground station is shown in Figure 3.
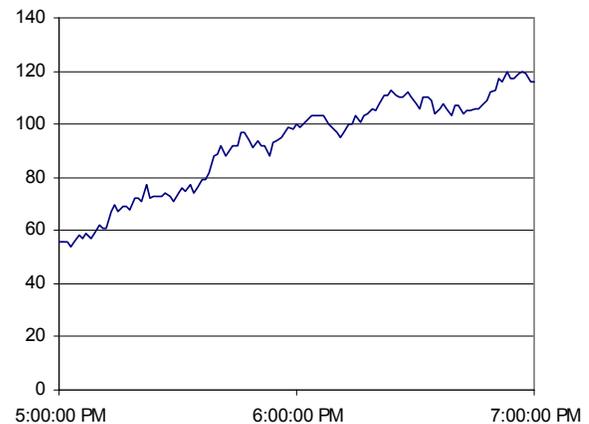
Figure 3. Flights in Range of Ground Station

Simulation Results

The delay results for the sector-based scenario are shown in Table II. Note that the downlink delays are greater than the uplink due to the slot request process. Comparing the delays for the high priority messages to the VDL Mode 3 requirements, we find that the delays are within specifications [1].

Table II. Delays for Sector-Based Communications

Priority	95th Percentile		99th Percentile	
	Uplink	Downlink	Uplink	Downlink
High	0.08	0.64	0.12	0.66
Medium	0.11	0.73	0.11	0.77
Low	0.08	0.72	0.11	0.94

The delay results for the range-based scenario are shown in Table III. In these simulations, the subnetwork was not able to meet the 95th percentile delay requirement for high priority messages in the downlink direction.

Table III. Delays for Range-Based Communications

Priority	95th Percentile		99th Percentile	
	Uplink	Downlink	Uplink	Downlink
High	0.11	1.34	0.23	1.90
Medium	0.28	1.34	0.40	2.13
Low	0.34	1.36	0.54	2.30

Conclusions

One thing is clear from this simulation study and from elsewhere [6] that VDL Mode 3 can easily accommodate the CPDLC traffic loads in a single sector. From our study, the simulation showed that the amount of CPDLC traffic that can be handled with a single VDL Mode 3 frequency using the 3T configuration is much larger than the traffic produced by a single sector. One exception is the 95th percentile downlink delays for CPDLC high priority messages in the range-based scenario. From Table III, these delays for the range-based communications are not met, however, in the current ATC or in the foreseeable future it is most unlikely that we will see a single controller handle such a large number of aircraft at one time. It is also difficult to speculate what implementation possibilities may exist to make efficient use of the available spectrum based on the results of this study alone. This difficulty is due to the fact that we only used the 3T configuration in our study. More simulation studies are needed to examine the effect of the CPDLC traffic loads on a VDL Mode 3 frequency using different configurations. There are, however, some implementation possibilities that we may conjecture based on the general understanding of data link for CPDLC in Mode 3.

The first possibility is that there may be one frequency per sector with multiple applications sharing the Mode 3 data link instead of just CPDLC. This approach would improve the utilization efficiency of the link, but does little to reduce the total number of VHF frequencies required in the NAS. The second possibility is that several sectors may share a single frequency. This would greatly reduce the spectrum congestion present in the current system. However, this implementation would require all controllers to share the one voice channel, a major departure from the current communications infrastructure and likely to receive resistance from the controllers.

References

[1] [1] ICAO Doc 9805, "Manual on VHF Digital Link (VDL) Mode 3," First Edition, 2002.

[2] RTCA Task Force 3, October 26, 1995, "Final Report of RTCA Task Force 3 on Free flight Implementation."

[3] AMCP/WG-D, February 1999, "VHF Digital Link (VDL) TDMA Mode 3 Standards and Recommended Practices," Draft Version 1.8.

[4] "DAG CNS Services Information Requirements Document," NASA AATT Project, December 29, 2003.

[5] Flight data set provided by Rafael Apaza, Federal Aviation Administration.

[6] Kabaservice, Thomas, June 2003, "Technical and Economic Benefits of VHF Digital Link Mode 3 Integrated Voice and Data Link for Air Traffic Control Communications," NEXTCOM White Paper, Harris Corporation.

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Funded by the Advanced Communications for Air Traffic Management project at NASA. The AC/ATM project is tasked with researching systems to provide the improved performance and increased capacity required for future air traffic management concepts.

Objectives:

- To determine the impact of Controller-Pilot Data Link Communications traffic loads on the VDL Mode 3 subnetwork in the en route domain.

- To determine the delay CPDLC messages experience from the VDL Mode 3 subnetwork

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Cleveland State University

- VHF Digital Link (VDL)

- Provides reliable data communication with an acknowledged connection-less data link protocol

- Supports voice and data communications

- Medium access by Time Division Multiple Access (TDMA)

- Uses the Aeronautical VHF Band (118 - 137 MHz)

- D8PSK modulation, 31.5 kbps data rate
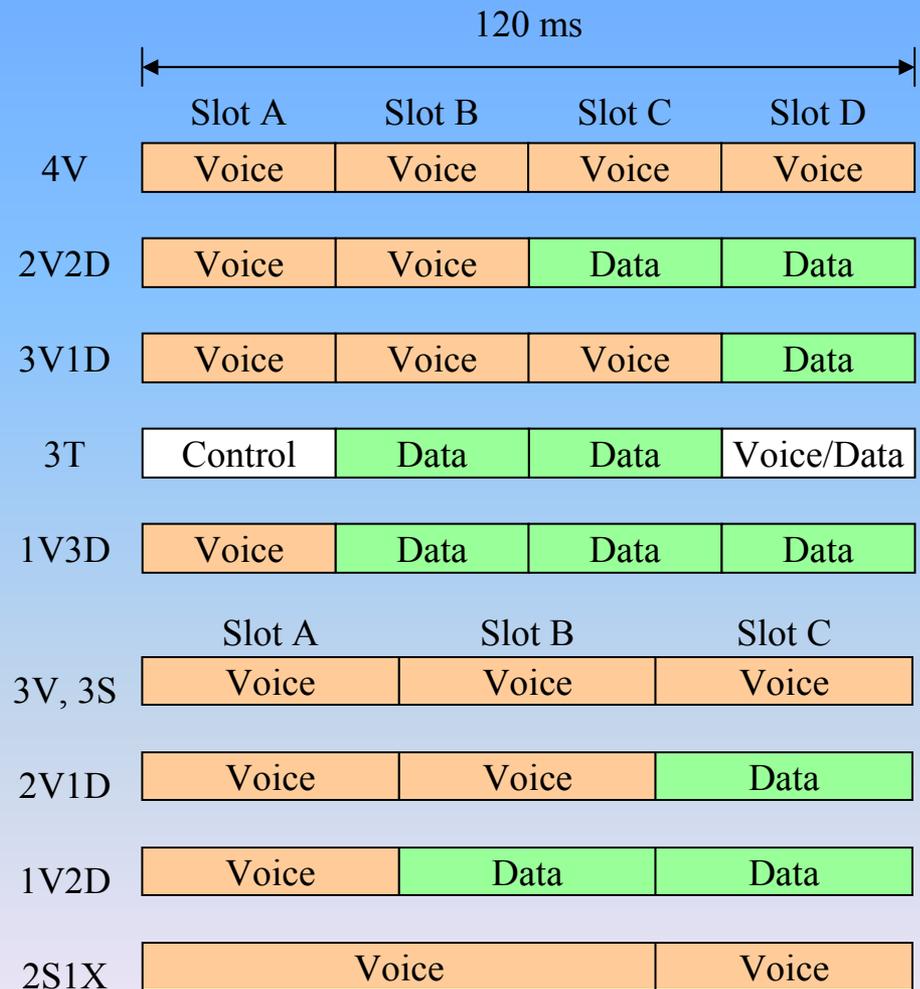
VDL Mode 3
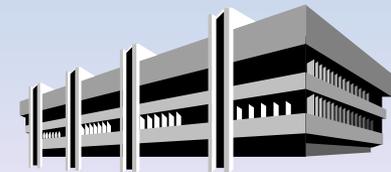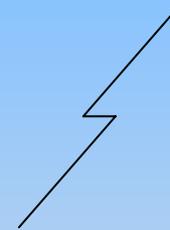
Standard range configurations
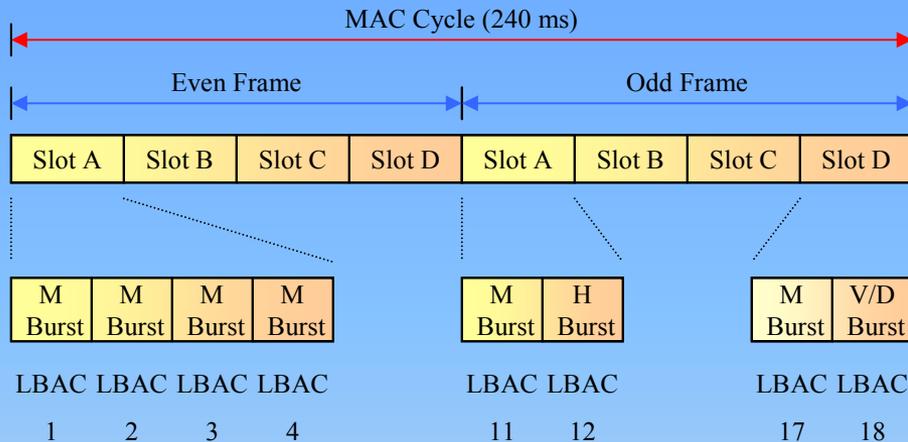
- 4 30 ms slots per frame

- Up to 200 nautical mile range

Extended range configurations

- 3 40 ms slots per frame

- Up to 600 nautical mile range

In this study we look at 3T only; future work will consider other configurations

- 2V2D

- 3V1D

	120 ms			
	Slot A	Slot B	Slot C	Slot D
4V	Voice	Voice	Voice	Voice
2V2D	Voice	Voice	Data	Data
3V1D	Voice	Voice	Voice	Data
3T	Control	Data	Data	Voice/Data
1V3D	Voice	Data	Data	Data

	Slot A	Slot B	Slot C
3V, 3S	Voice	Voice	Voice
2V1D	Voice	Voice	Data
1V2D	Voice	Data	Data
2S1X	Voice		Voice

VDL Mode 3 (3T)

MAC Cycle (240 ms)

Even Frame				Odd Frame			
Slot A	Slot B	Slot C	Slot D	Slot A	Slot B	Slot C	Slot D

| M Burst | M Burst | M Burst | M Burst | | M Burst | H Burst | | M Burst | V/D Burst |

LBAC LBAC LBAC LBAC   LBAC LBAC   LBAC LBAC

1   2   3   4   11   12   17   18

In both frames, Slots B and C are the same as Slot D

Slot A – Management

Slot B and C – Data

Slot D – Voice or Data

Composed of 18 Logical Burst Access Channels (LBAC)

   M – Management

   H – Handoff check

   V/D – Voice or Data

- Protocol supports up to 180 aircraft
- Each data slot can contain 496 bits of data
- Theoretical maximum data throughput: 12.4 kbps
- Useful in situations which contain predominately data and occasional voice

Controller-Pilot Data Link Communications replaces voice commands and requests with small digital messages

- Uses Abstract Syntax Notation 1 (ASN.1) format

Benefits of CPDLC:

- CPDLC messages are more efficient than analog or digitized voice

- Error-checking is incorporated into transmission of messages, ensures messages are received accurately

- Text display of messages, allows messages to be reviewed at a later time without repetition
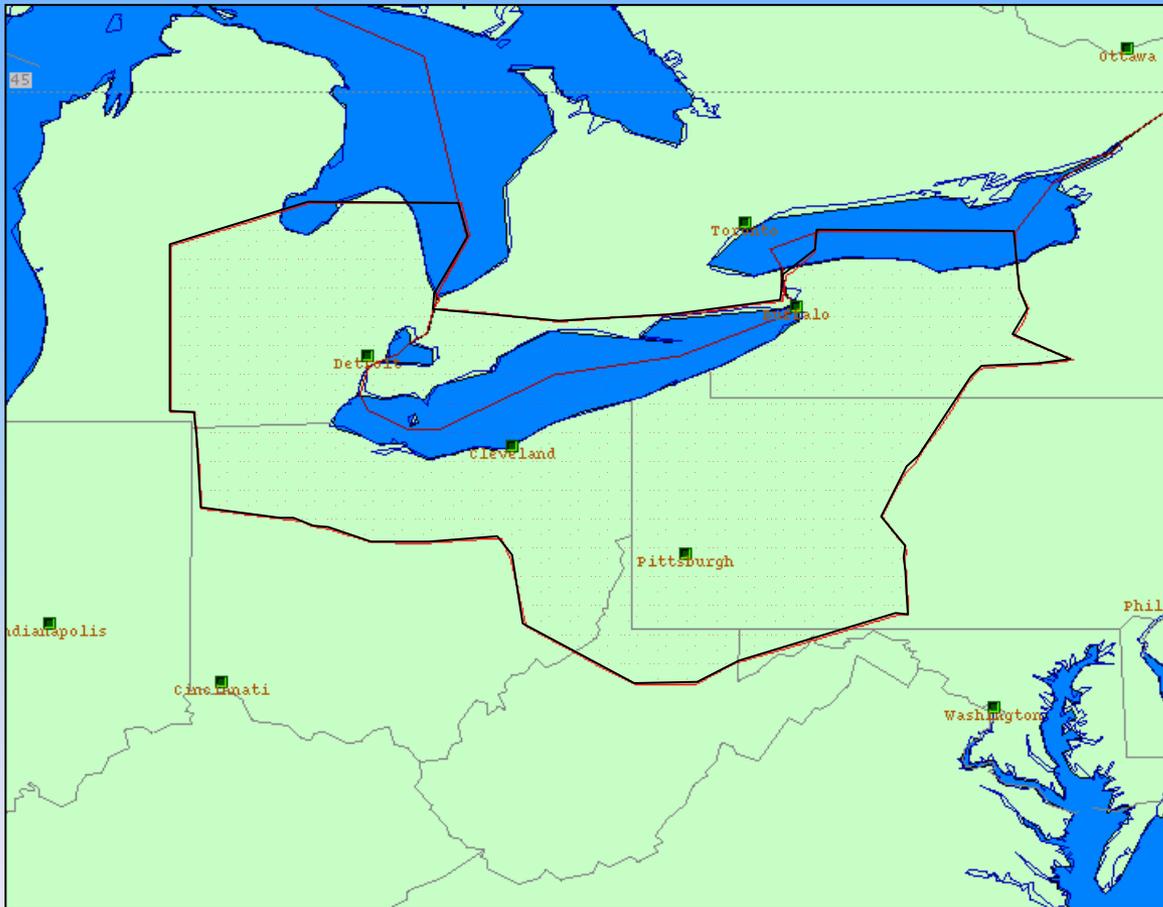
Simulation Model
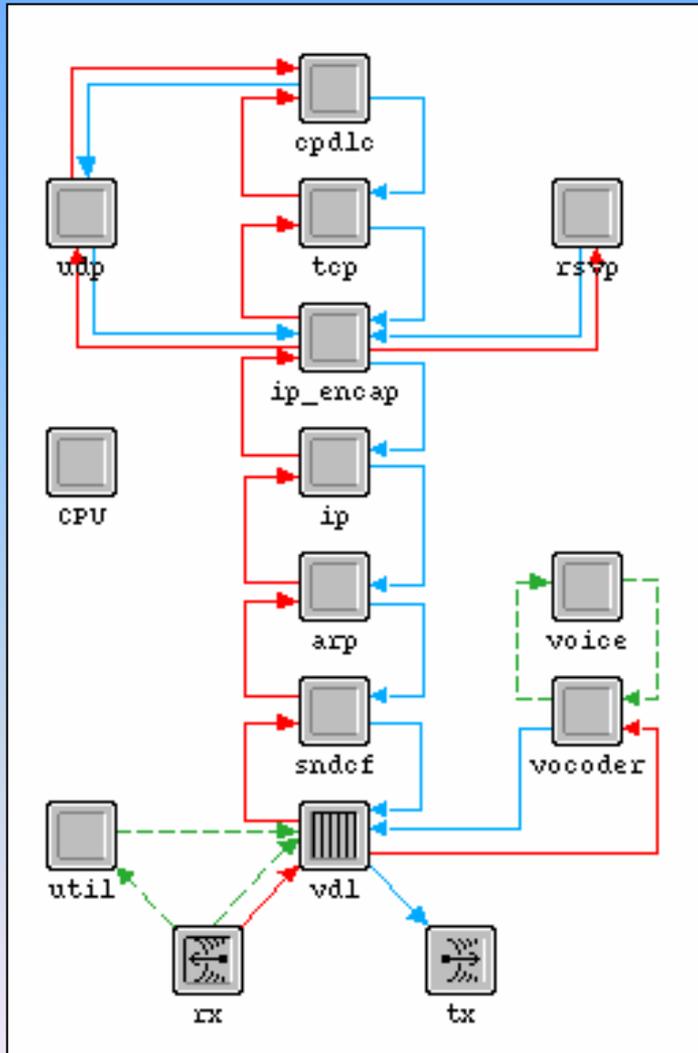
Aircraft and ground node model

Combination of OPNET-supplied and custom models

Uses IP protocol stack in place of ATN protocols

Models CPDLC by statistical generation of message sizes and inter-arrival times

Models VDL MAC and DLS sublayers in detail

Does not simulate aircraft or ground-based networks

Actual flight traffic data from Cleveland Air Route Traffic Control Center (ZOB ARTCC) used for simulations

Data covers all flights that pass through ZOB from takeoff to landing

Data taken over a 24 hour period

CPDLC Messages

Priority	Uplink Size (bits)	Downlink Size (bits)	Mean Inter-Arrival Time (s)
High	72	12	2850
High	13	12	5700
High	68	12	5700
Medium	691	690	774
Medium	36	676	5700
Medium	13	12	5700
Low	13	120	387
Low	300	43	2850

Messages are based on RTCA documents

Inter-arrival times are converted from messages per flight and messages per sector to messages per second

Times based on average time per sector/flight

Source: "Distributed Air/Ground Concept Element 5, 6, and 11. CNS Services Information Requirements Document" prepared by Analex for NASA Glenn.

2 simulations performed

- Sector-based CPDLC communications

- Range-based CPDLC communications

Subnetwork delays compared to the VDL MASPS requirements

- 95th percentile delay for high-priority messages of 192 application bits or less shall be less than 1 second

- 99.9[th] percentile delay for high priority messages of 192 application bits or less shall be less than 5 seconds

Sector-Based

Represents an implementation with 1 VDL channel per sector.

Simulation includes all aircraft within a busy sector.
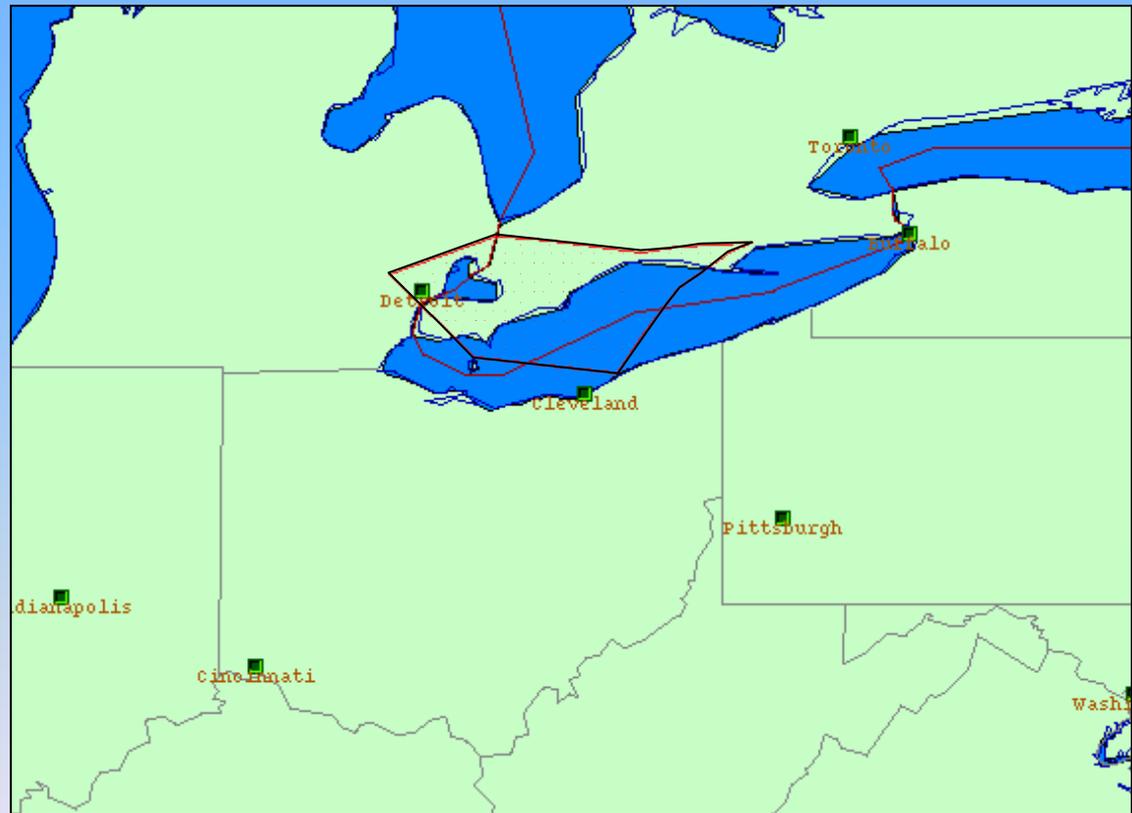
Sector-Based Flights
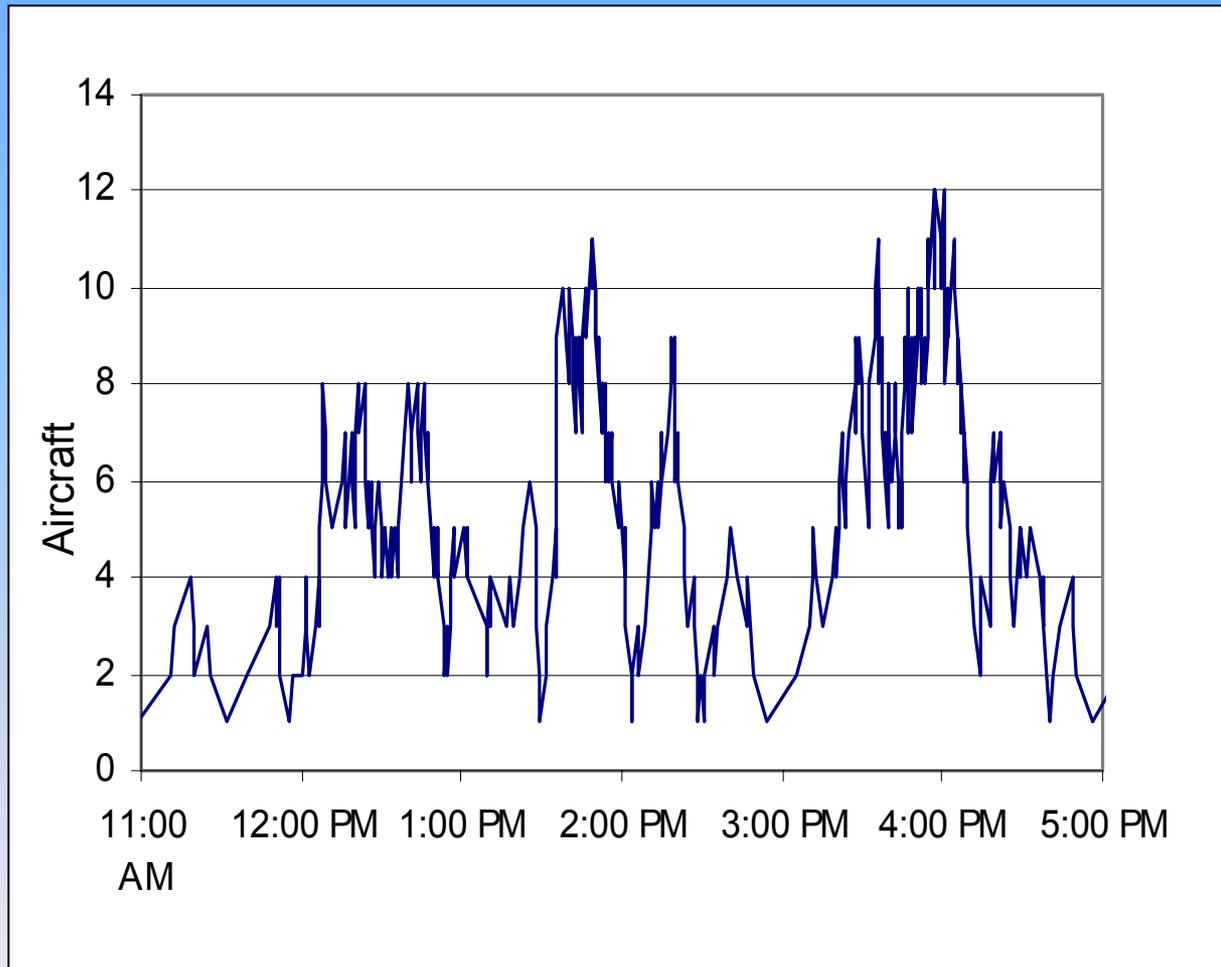
Uses flight data from 12:00 PM to 4:00 PM

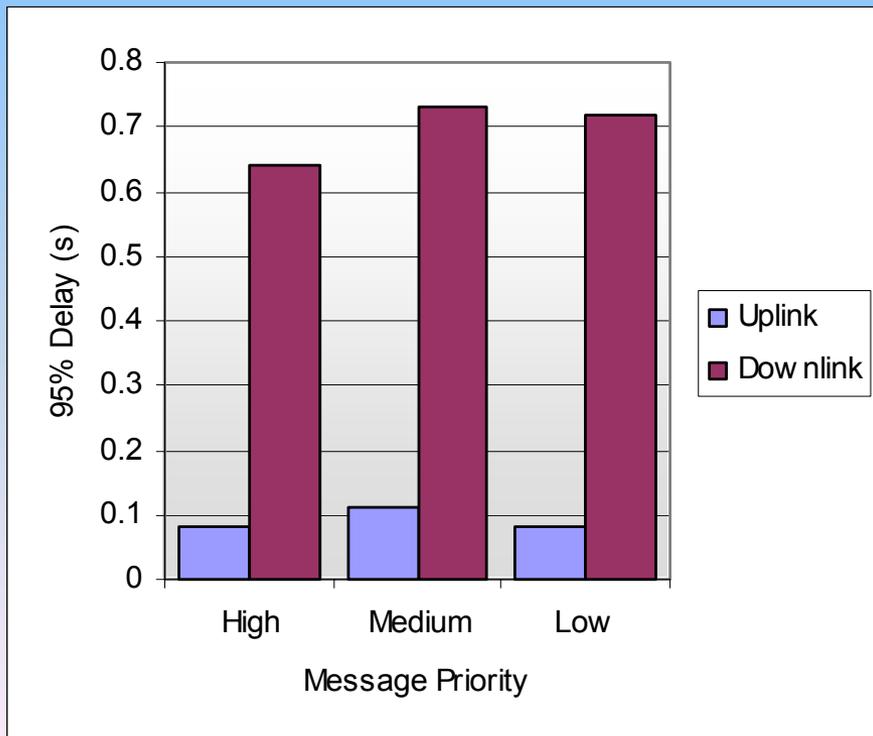155 total aircraft during the simulated 4-hour simulation

Area contains up to 12 aircraft at a time

Sector-Based Results

Sent a total of 584 CPDLC messages

95th and 99.9th percentile delays are within limits
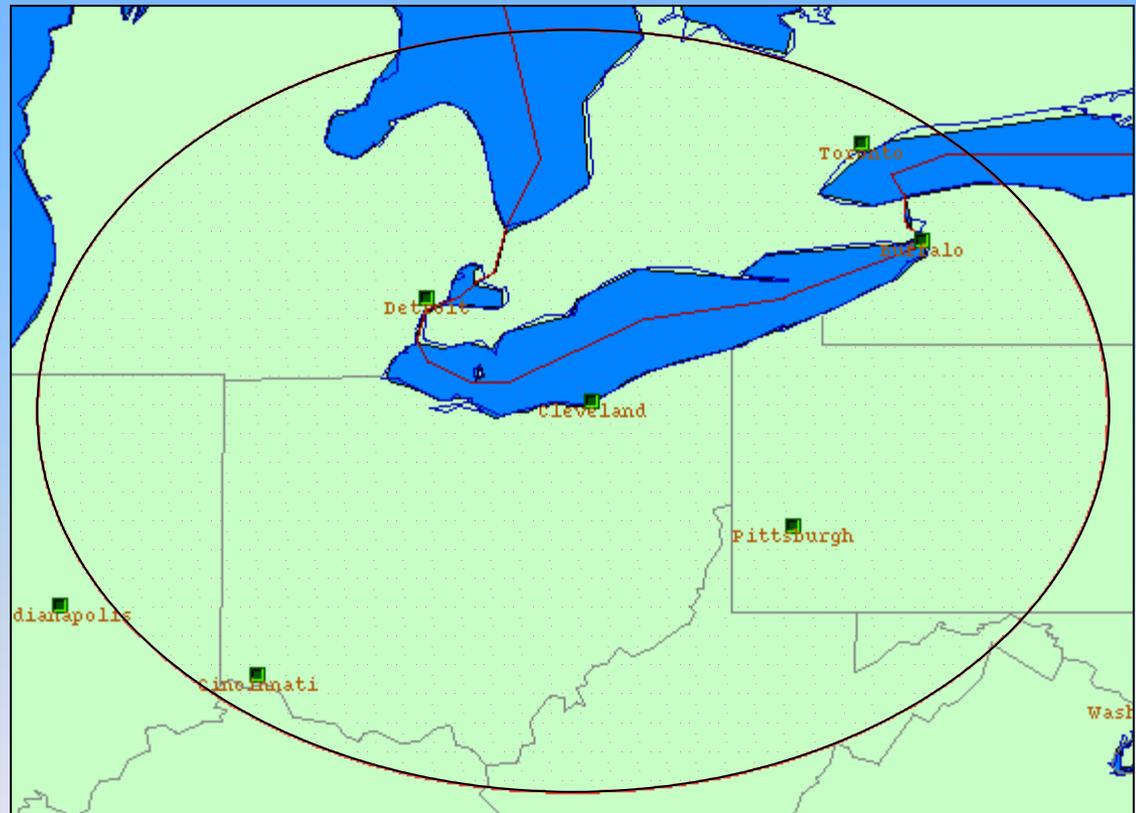
Low loading on VDL Mode 3 subnetwork
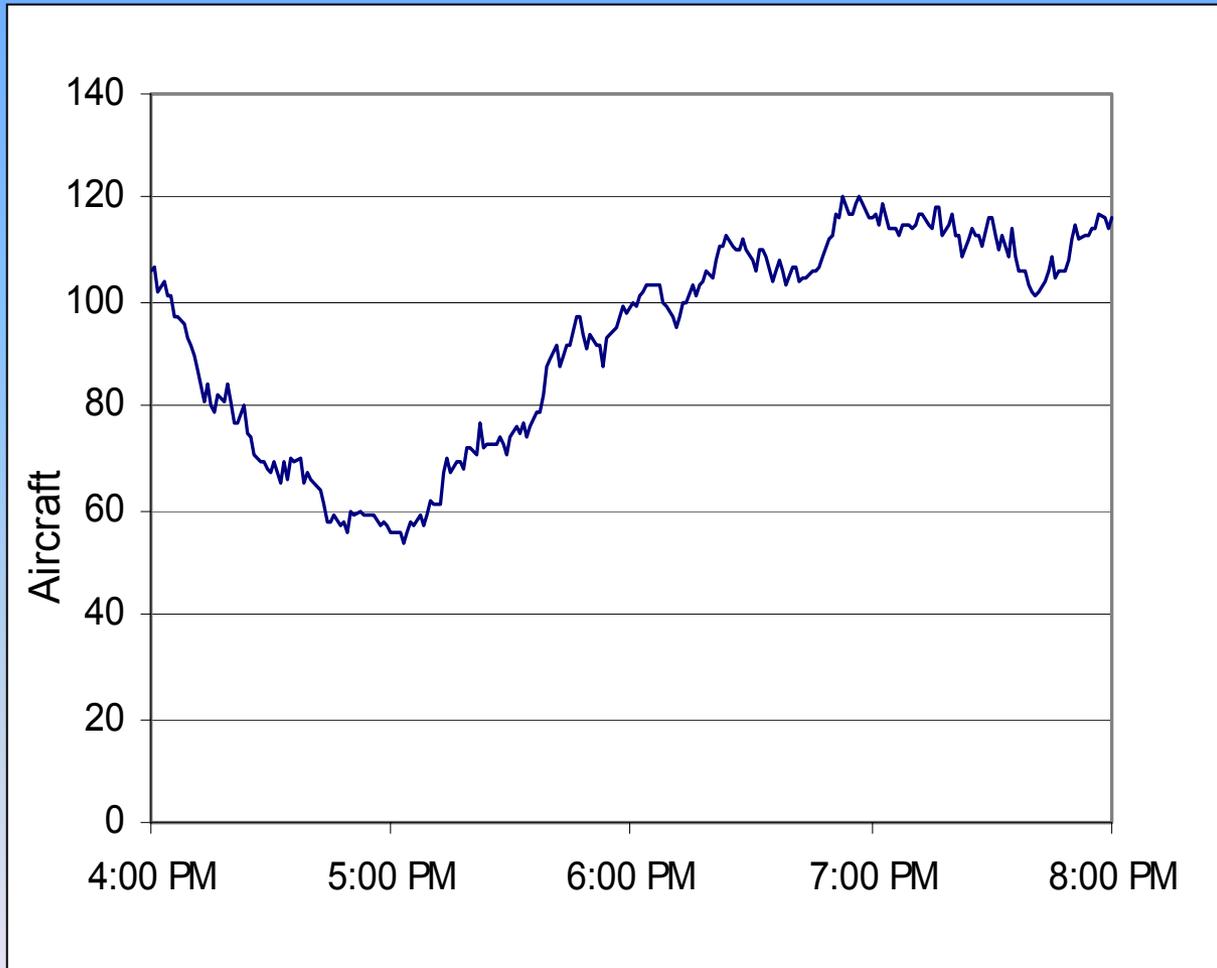
Downlink delays much higher than the uplink delays
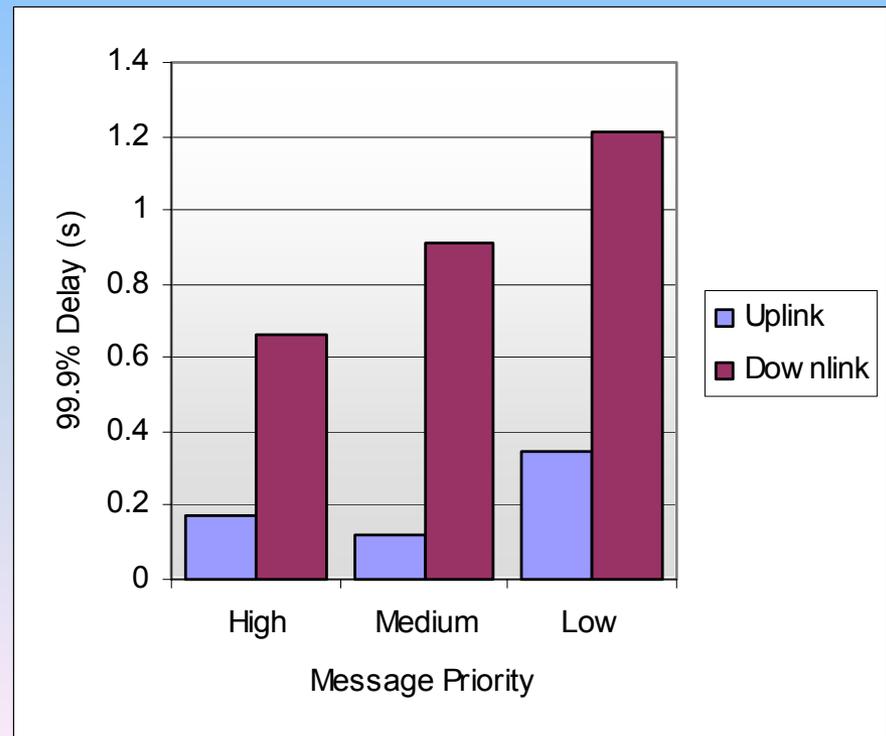
Represents an implementation with multiple sectors per channel resulting in denser traffic load

Simulation includes all aircraft within range of the ground station (up to 200 nmi) that pass through ZOB

Coverage area includes parts of adjoining ARTCCs

Range-Based Flights

Uses flight data from 5:00 PM to 7:00 PM

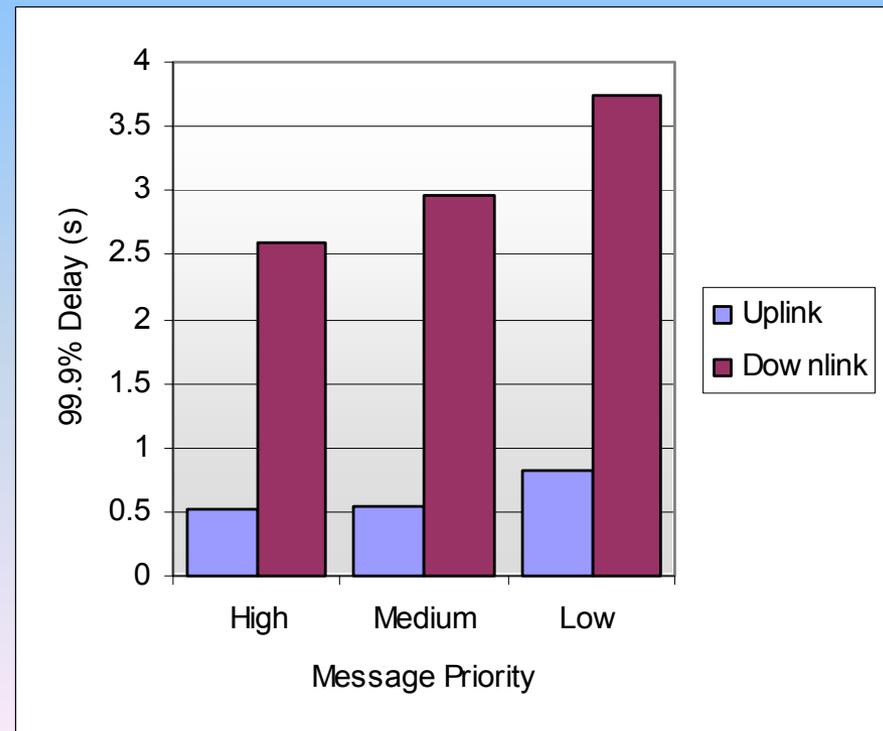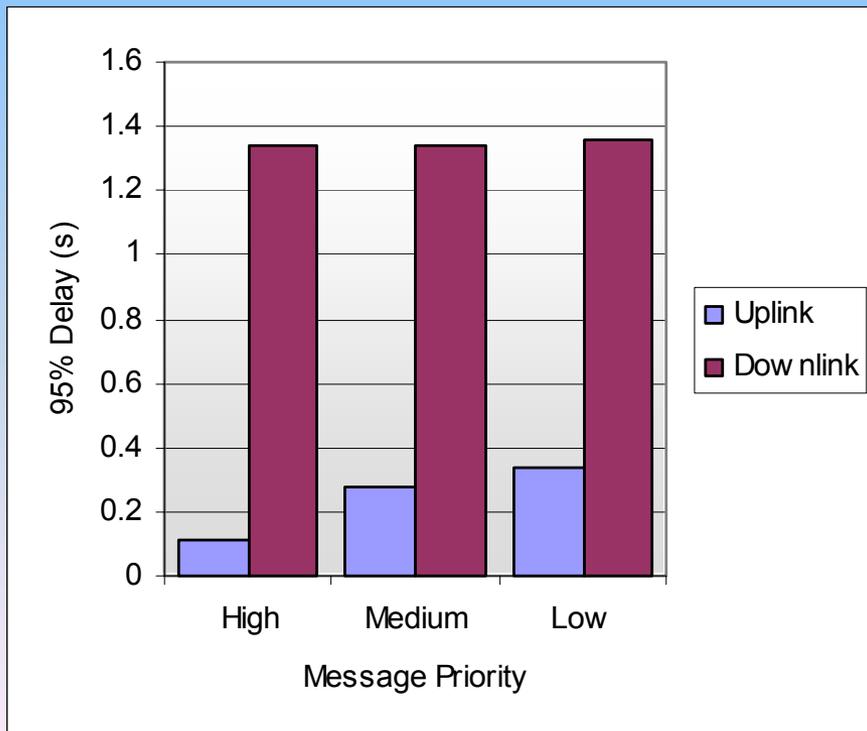297 total aircraft during the simulated 2-hour period

Area contains up to 120 aircraft at a time

Range-Based Results

Sent a total of 4590 CPDLC messages

95th percentile downlink delay is above limit

All other delays within limits

3T could not support the entire area, possibly support several sectors

Conclusions

VDL Mode 3 3T can be used to handle CPDLC traffic for a single sector

- Advantage: Provides voice and data communications

- Disadvantage: Will not reduce the total number of VHF frequencies required in the NAS

VDL Mode 3 3T could support more than 1 sector

- Advantage: Reduces spectrum congestion in the current system

- Disadvantage: Requires several sectors to share a single voice channel

Other configurations provide other possibilities

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Perform CPDLC simulations with other VDL Mode 3 configurations

- 2V2D

- 3V1D