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Characteristics and Capacity of VDL Mode 2, 3, and 4 Subnetworks

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In the current National Airspace System (NAS), voice communications for Air Traffic Services (ATS) are transmitted by analog VHF radios. Aeronautical Operational Communications (AOC) use a character-oriented system operating in the VHF band known as Aircraft Communications Addressing and Reporting System (ACARS). These radios are neither capable of supporting the growth in air traffic expected in the near future, nor are they capable of enabling new services under development. Three bit-oriented digital VHF radios, VDL Modes 2, 3, and 4, have been proposed as solutions to frequency congestion in the aeronautical VHF band. In this paper each mode is investigated through simulations which explore their individual characteristics under variable loads. The three modes are also tested in realistic terminal and en route domain scenarios. The capacity of each mode is estimated based on the subnetwork delays specified in the standards. The results indicate that VDL Mode 2 can support the highest traffic load, but cannot provide deterministic delays for critical applications. Mode 3 supports the least load due to large downlink delays, but provides the required mechanisms for critical information transfer. Mode 4 has a marginally higher capacity than Mode 3 with similar prioritization capabilities.

Nomenclature

a	ratio of propagation delay to packet transmission time
G	offered load
LF	load factor
p	persistence value for random access
Q5	retransmission timer and parameters (Mode 4)
r	number of retransmissions
S	throughput
T1	retransmission timer (Modes 2 and 3)
TM1	random-access backoff delay

I. Introduction

THE Aeronautical Telecommunications Network (ATN) is envisioned as a global network which will increase the safety of air traffic and the capacity while reducing operating costs and delays. The ATN will introduce new or enhanced services for aircraft, such as Controller Pilot Data Link Communication (CPDLC), Flight Information Service (FIS), and Automatic Dependent Surveillance—Broadcast (ADS-B). In order to achieve its goals, the ATN

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requires advancements in the areas of communication, navigation, and surveillance. VDL Modes 2, 3, and 4 support the communication aspect of the ATN. Additionally, Mode 4 supports surveillance as a data link for ADS-B.

Much research has already been performed on VDL. Hung[1,2] and Wang[3] have performed VDL simulation research on Modes 2 and 3 to determine capacity. Hung[4] has also identified a performance issue in VDL Mode 3 along with a suggested improvement. ARINC has investigated Mode 2 through simulations for current-day use for both ATS and AOC.[5] The Aeronautical Mobile Communications Panel (AMCP)[6] explored all three modes and reported maximum useful throughput rates for each based on several independent studies. VDL Mode 4 has also been investigated as a surveillance system.[7] Physical layer evaluations have been performed on the D8PSK modulation scheme for VDL Mode 2.[8,9] The two modulation schemes, D8PSK and GFSK, have also been compared for use with VDL Mode 4.[10]

The simulation models of VDL used in this paper have been used previously in other related research. Mode 2 has been evaluated for Air Traffic Services (ATS) and Aeronautical Operational Communications (AOC) in general[11,12] and specifically for the AOC and the Automated Meteorological Transmission (AUTOMET) services in multiple domains.[13] Several Mode 3 configurations have been compared for combined voice and data with the Controller/Pilot Data Link Communications (CPDLC) service.[14] Modes 2, 3, and 4 have been briefly examined in the terminal[15] and en route[16] domains.

This paper presents research and simulated results on VDL Modes 2, 3, and 4 in supporting ATS and AOC communications. Most previous research cited previously has focused on just one mode at a time. These results are not as useful for comparing the three modes because of different testing conditions and different services. In the research reported in this paper three modes are tested under identical conditions such that the results can be compared directly.

This paper is organized as follows: section II begins with a description of the ATN architecture and the role of VDL. It describes the general architecture of VDL systems. Section III describes the simulation scenario used for all three modes. It contains the data traffic profile and identifies the assumptions which are common to all simulations. Section IV begins with an overview of VDL Mode 2 and its specific protocols. The Mode 2 simulations and analysis of the results are described therein. Section V contains a description of the VDL Mode 3 protocols and functionality as well as the analysis of the VDL Mode 3 simulations. Section VI discusses the VDL Mode 4 protocols and functionality and concludes with the VDL Mode 4 simulation analysis. Section VII compares the VDL modes in the terminal and en route domains with actual traffic profiles. Section VIII provides a summary of the research and simulation results. The protocols for the VDL modes are only briefly described in this paper; the detailed descriptions are documented in the respective standards.[17,18]

II. System Architecture

A. ATN CNS Architecture

The ATN architecture creates a network over which information can be transferred between aircraft and ground systems. A global ground network connects systems together. Aircraft communicate to the ground network through terrestrial radio links such as VDL and HF data links. In areas where these radio links are unavailable, such as in oceanic regions or remote areas, satellite communication is used. Some components of the ATN architecture are illustrated in Fig. 1.

In the aircraft, data from avionics systems are passed through the avionics bus to the Communications Management Unit (CMU), which contains an ATN air/ground router. The CMU will then route the data to the VHF Digital Radio (VDR), or to one of the other air/ground data links such as a satellite-based system. Additionally, the CMU supports other systems such as ACARS.

To achieve interoperability over diverse subnetworks, the ATN uses the ISO Transport Protocol 4 (TP4) and Connection-Less Network Protocol (CLNP), which are functionally similar to the TCP/IP protocols used in the Internet. A Sub-Network Dependent Convergence Function (SNDCF) is contained within the ATN routers to adapt the CLNP protocol to each of the subnetworks, as CLNP expects a simple connection-less underlying network whereas many of the subnetworks have connection mode services. The air-to-ground subnetworks require some special features for mobility, which are contained in the mobile SNDCF.

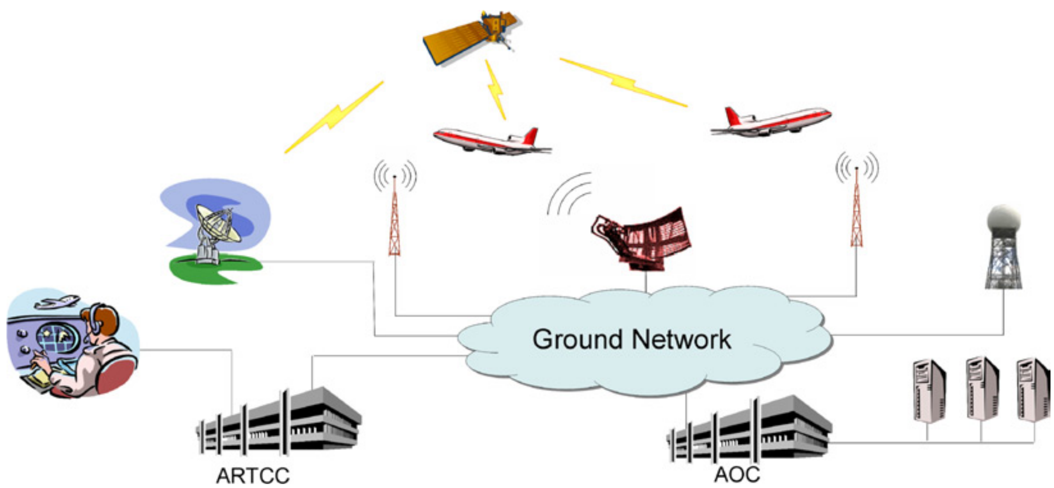

Fig. 1 General ATN architecture.

B. VDL Architecture

The VDL specifications encompass the subnetwork, data link, and physical layers. The architecture is shown in Fig. 2. The Mode 4 architecture is slightly different than that of Modes 2 and 3 in that it additionally has the VDL Mode 4 Specific Services (VSS) sublayer interfacing between the MAC and the DLE and LME. External to the VDL architecture are the ATN and other non-ATN applications which require transmission over VDL, such as ACARS-over-AVLC (AOA) and ADS-B.

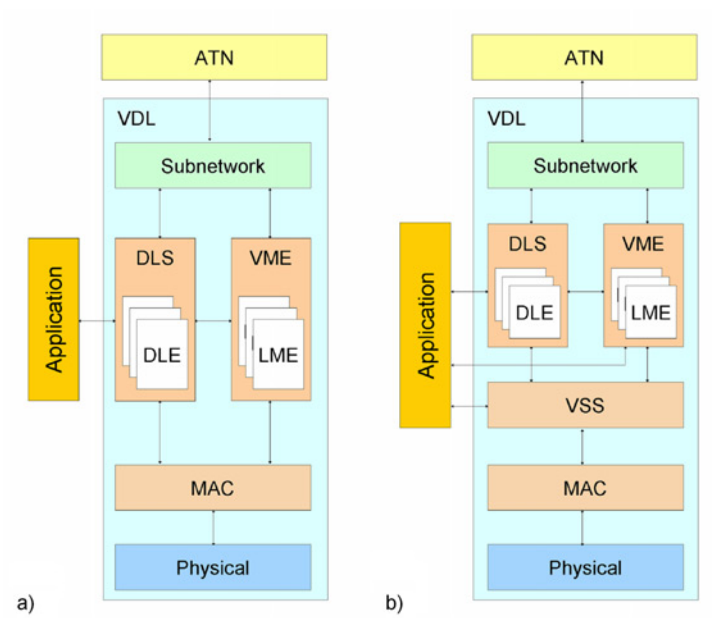

Fig. 2 VDL architecture for (a) Modes 2 and 3 and (b) Mode 4.

1. Subnetwork Layer

The subnetwork layer provides the interface to the ATN routers. X.25 is the subnetwork layer for VDL Modes 2 and 3 in accordance with the standards. Mode 3 additionally supports direct use of CLNP in ‘frame mode’, eliminating the overhead of establishing connections at the subnetwork layer.

2. Data Link Layer

In the VDL architecture, the data link layer is divided into a set of sublayers: the VDL Management Entity (VME), the Data Link Service (DLS), and the Media Access Control (MAC). Additionally, VDL Mode 4 contains a VDL Mode 4 Specific Services (VSS) sublayer.

The VME is responsible for link connection management. A Link Management Entity (LME) is created for each air-ground connection. The LMEs are responsible for link initialization, connection, modification, and handoff. The DLS is responsible for data transfer between the aircraft and ground. A Data Link Entity (DLE) is created for each air-ground connection. The DLEs provide addressing, error detection, and flow control. The MAC layer controls link access, and determines when a station may transmit on the link. For VDL Mode 4, the VSS provides additional services specific to the Mode 4 MAC and DLS.

3. Physical Layer

The physical layer defines the burst format that will be transmitted. The modulation scheme and data rate are specified for each of the modes. The physical layer also describes additional information appended to all transmissions known as the training sequence. The training sequence is used to synchronize the transmitter and receiver so that communication may take place.

III. Simulation

VDL simulations were performed using OPNET Modeler version 10.5.A. OPNET is a discrete-event network simulation package that allows modeling of protocols as finite state machines. Each state in the FSM contains C code to perform the protocol functionality. Models for the VDL protocols were created in OPNET and integrated with the standard protocols and links in OPNET to form the VDL radios and an application data stream. These models are the basis for the aircraft and ground station.

A. Traffic Model

The traffic model used for the simulations is specified in the Mode 2 and 3 system performance standards[17] and represents terminal domain traffic projected for the year 2015. This is a standardized model for VDL capacity simulations. The parameters in Table 1 is the data traffic model with a load factor (LF) of 1. The LF is modified by proportionally adjusting the average message rate.

The standard specifies that simulations for a subnetwork model should be performed by varying LF from 0.2 to 8, and for an integrated model the LF should be 1 and 2. The simulations performed here are single subnetwork simulations, but also include simulation of the upper layers in the protocol stack with the appropriate overhead for frame headers and routing. As such, the LF specification for the integrated model was used with an additional set using a LF of 3.

Table 1 Traffic model.

	Uplink		Downlink	
Priority	Average rate (msg/s)	Average size (bits)	Average rate (msg/s)	Average size (bits)
High	0.017	137	0.024	110
Medium	0.0017	198	0.0008	100
Low	0.001	2400	0.002	2400
Low	0.0017	3325	0.0033	1760

B. Simulation Scenario

The simulation scenario used to test the VDL modes consisted of a single ground station communicating with a variable number of aircraft. Separate simulations were performed with the number of aircraft ranging from 10 to 180, in increments of 10. All aircraft were randomly placed within 200 nautical miles of the ground station at a fixed altitude of 30,000 feet. For simplicity, the aircraft positions in these simulations were static.

All aircraft were tuned to a frequency of 130.000 MHz to match the ground station. Aircraft transmitter power was 16 watts while the ground transmitter power was 25 watts, which matched to the VDL equipment used in Ref. 8. All VDL parameters were set to the default values specified in the standards.

During the simulation, aircraft were in continuous contact with the ground station. The first ten minutes of simulation were reserved for connection setup between aircraft and ground stations to bring the simulation to a steady-state condition. During this time the aircraft connect to the subnetwork one by one at evenly distributed intervals. Statistics are not collected during this period. Aircraft typically spend only about 10 minutes in the terminal domain. However, these simulations increased that duration to 50 minutes because of the low rate of arrival of data traffic. When only 10 minutes of simulation time was used, a small number of samples were generated for each aircraft. However, by increasing the simulation time a larger set of samples was collected.

C. Network Modeling Assumptions

The ground and aircraft network characteristics and their performances are outside the scope of this research. Delays induced by these networks are not significant to the results reported herein, and as such are not modeled.

TP4 connections are established before the start of the simulations and the connections are never closed during the simulation. The protocol adds 9 bytes of header information to data packets. The acknowledgement is 34 bytes in length and is sent immediately upon reception of a data packet. The window size is large enough compared to the traffic load to allow immediate transmission of all frames. The VDL link will successfully transmit the frame before a TP4 retransmission can take place. Since TP4 keep-alive messages occur infrequently, they are not modeled. These assumptions were made to simplify the transport protocol and are based upon the parameter values for the transport protocol described in Ref. 19.

The CLNP protocol adds 60 bytes of header information to each data packet. No other overhead occurs from the CLNP protocol. Inter-Domain Routing Protocol (IDRP) updates occur prior to the simulation of the data traffic and aircraft traffic models. During the simulation, IDRP keep-alive messages are transmitted every 400 seconds and these messages are 126 bytes in length.[19]

Compression is performed at the Mobile SNDCF on all frames. The compression scheme is identical for all VDL Modes. From the results reported in Ref. 20, a static compression ratio of 3.6:1 was used. This ratio included the combination of Local Reference (LREF) header compression and Lempel-Ziv-Welch (LZW) data compression schemes.

Each VDL Mode has mechanisms to identify subnetwork congestion and link failure. When congestion or failure is encountered, the aircraft LME is informed so that a handoff may occur. In our simulations, the aircraft will disconnect from the subnetwork during these conditions. To keep the network loaded, the aircraft will attempt to reconnect to the network using the network entry procedures and continue transmissions. Any frames queued when the network disconnection occurs or transmitted before the aircraft finishes connecting to the VDL subnetwork are lost.

The physical communications channel is simplified. A bit error rate based on the signal-to-noise ratio is sufficient for this research, and the distance is limited by line-of-sight. Channel effects such as fading, multipath, and Doppler frequency shifts are not included in this research.

IV. Mode 2

VDL Mode 2, along with the unimplemented VDL Mode 1, was originally intended to be an upgrade to ACARS under the name Aviation VHF Packet Communications (AVPAC). It was proposed to ICAO in May of 1994 to be a subnetwork for the ATN. The ICAO standards on Mode 2 were completed and published in 1997.

A. Mode 2 Protocol Description

For Mode 2, the standards specify a Differential 8 Phase Shift Keying (D8PSK) modulation scheme operating at a bit rate of 31.5 kbps. All transmitted frames contain a 108 bit training sequence. The first 5 symbols of the

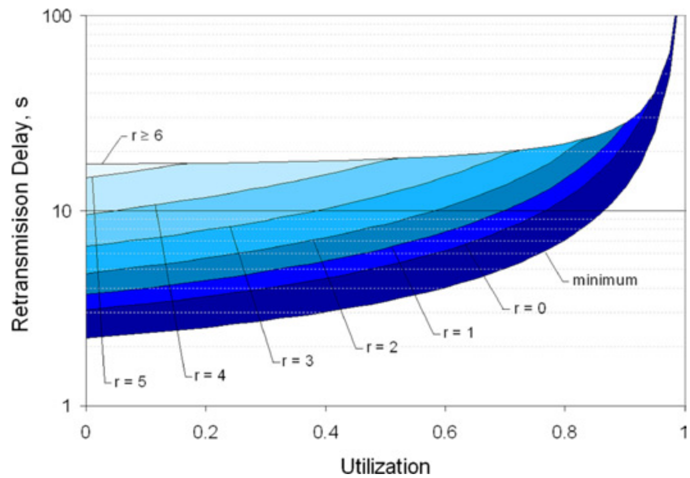

Fig. 3 Range of values for retransmission delay T1 using the default parameters.

training sequence are for transmitter power ramp up and stabilization. The rest of the training sequence includes a synchronization code, the transmission length, and Forward Error Correction (FEC) for the header.

Medium access is governed by a p-persistent Carrier Sense Multiple Access (CSMA) protocol, in which access attempts are only made when the channel is sensed idle. During an access attempt the station will transmit with probability p or back off for TM1 seconds with probability $(1 - p)$. The maximum number of access attempts is bounded, and after a maximum number of failed access attempts, the MAC will transmit the packet as soon as the channel becomes idle. This algorithm attempts to reduce the number of collisions while minimizing the medium access delay.

The DLS employs a Connection-Oriented Protocol (COP) known as Aviation VHF Link Control (AVLC). The AVLC protocol is a sliding window protocol with multi-selective reject functionality. It uses a dynamically calculated retransmission delay T1 based on the channel utilization and the number of retransmissions. The range of values of T1 as a function of the utilization using the default parameters is plotted in Fig. 3. The value of T1 is randomly set between a minimum and maximum value, where the maximum is determined by the number of retransmissions.

All frames sent from the DLEs are placed in an active DLS queue. The queue processes frames for acknowledgement and redundancy. The queue guarantees that redundant or duplicate packets are not contained in the queue. When a frame is queued, its acknowledgement is checked and all other frames to the same destination are updated to reflect that acknowledgement. Incoming frames are also checked, and any queued frames that the incoming frame acknowledges are removed. When the access to the medium is successful, link control frames are transmitted in preference to user data. When the channel is accessed, more than one DLE frame may be included in a single physical layer transmission.

B. Mode 2 Modeling Assumptions

The DLS queue implements all the optional active features described in the standards, including the acknowledgement update and redundant frame removal. By employing frame grouping, in our simulations multiple frames can be transmitted during a single MAC channel access.

The values for the VDL Mode 2 parameters used in the simulations were the default values and are shown in Table 2.

C. Mode 2 Simulation Analysis

A common parameter used when evaluating system performance of networks is the ratio of propagation delay to the packet transmission time, denoted by "a". In general, the maximum utilization varies inversely with a, with the

Table 2 VDL Mode 2 parameters.

Sublayer	Parameter	Description	Default value
MAC	p	Persistence	13/256
	TM1	Inter-access delay	4.5 ms
	M1	Maximum access attempts	135
DLS	$T1_{min}$	Retransmission minimum	1 s
	$T1_{max}$	Retransmission maximum	15 s
	$T1_{mult}$	Retransmission multiplier	1.45
	$T1_{exp}$	Retransmission exponent	1.7
	T2	Acknowledgment delay	0.5 s
	k	Window size	4

upper bound of the system occurring at $1 / (1 + a)$.[21] In the Mode 2 simulations, the mean frame size measured at the physical layer varied with the number of aircraft and the LF. The mean frame size for the calculation of “a” is 544 bits, obtained from the simulation with 180 aircraft at a LF of 1. This yielded a maximum “a” of 0.07 for the farthest aircraft in this simulation.

The link throughput S compared to the offered load G is shown in Fig. 4. Both the throughput and offered load are normalized to the data rate. In order to account for all the overhead from VDL Mode 2 which is not observable at the subnetwork layer, the offered load and link throughput are measured at the link layer. The peak throughput for the subnetwork was not achieved during these simulations. Comparing the simulated results to the corresponding theoretical curves for p-persistent CSMA,[22] the curves are similar in shape. However, as noted in Ref. 1, the load at which the peak throughput is attained is much lower than the prediction from the theoretical model.

The subnetwork delay is shown in Fig. 5. The VDL Mode 2 MASPS state that the 95th percentile subnetwork delay should be no more than 3.5 seconds for Mode 2. The subnetwork capacity by this requirement is limited by the downlink at approximately 3.3 kbps. The downlink delay exhibits a stepped increase around 2.0 kbps. In Ref. 12 this was noted to be due to the influence of the retransmission delay on the 95th percentile subnetwork delay, which is caused by the retransmission rate reaching 5%. For the uplink, this step occurs at a higher load, between 2.5 and 3 kbps. The differing slopes among the LF are caused by the resolution of data points. Increasing the LF tends to lower the load at which the step occurs.

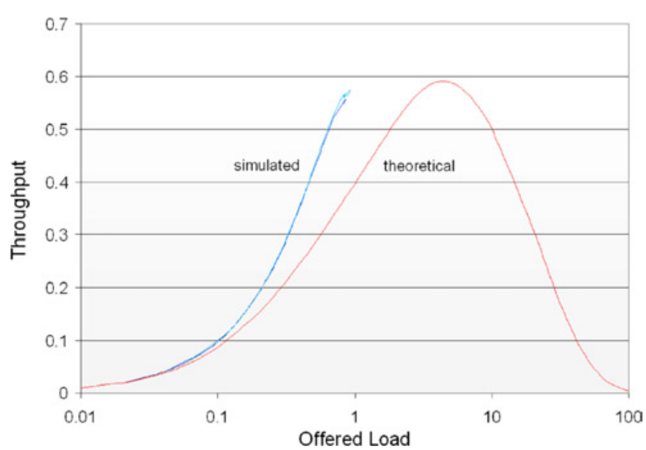

Fig. 4 Simulated and theoretical curves comparing the throughput S to the offered load G.

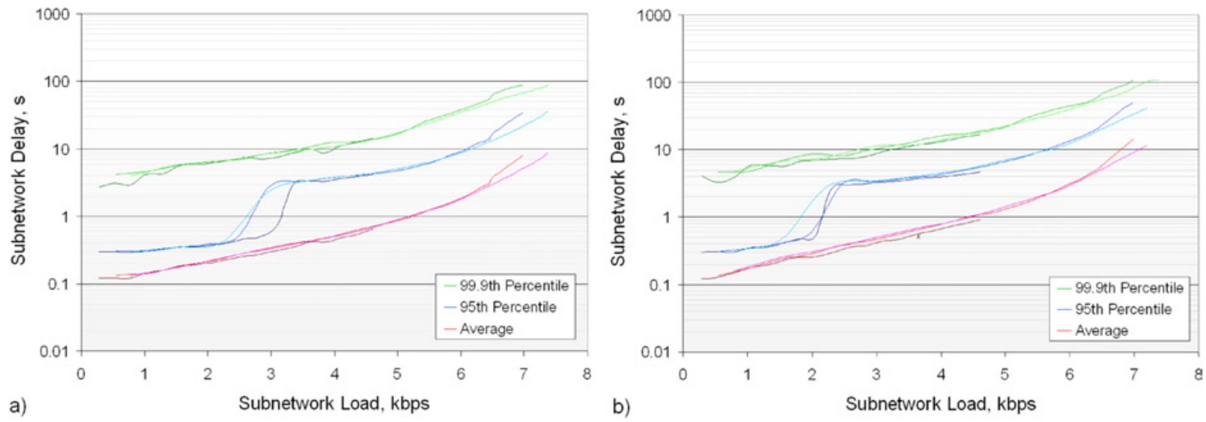

Fig. 5 Subnetwork delays for the (a) uplink and (b) downlink.

V. Mode 3

VDL Mode 3 was proposed by the FAA to ICAO in May 1994 as an alternative to moving to 8.33 kHz channel spacing. It provides both data and voice access to the channel. Mode 3 was approved as an ATN subnetwork in 2001.

A. Mode 3 Protocol Description

Mode 3 specifies a D8SPK modulation scheme operating at 31.5 kbps, the same as Mode 2. Mode 3 uses a 63 bit training sequence consisting of transmitter power ramp up and stabilization sequence lasting 5 symbol periods followed by a 48 bit synchronization sequence.

The VDL Mode 3 MAC sublayer uses Time Division Multiple Access (TDMA) in which slot usage for data transmission is controlled by the ground station. Several configurations exist using the standard 4-slot per frame and long-range 3-slot per frame timing structure to accommodate different amounts of voice and data traffic. In the standard range configurations, four 30 ms time slots, denoted as A, B, C, and D, make up a MAC frame. A MAC cycle consists of two MAC frames, even and odd, with a duration of 240 ms. The slots are subdivided into Logical Burst Access Channels (LBACs) to provide management capabilities in the voice and data slots. VDL Mode 3 supports 4 levels of priority.

In this paper the 3T configuration is investigated. This is a standard-range 4-slot configuration which allows for assigned data and voice access and supports up to 180 aircraft. In the 3T configuration, slot A is dedicated to management, slots B and C are dedicated data slots, and slot D can contain either voice or data. The 3T configuration provides the most allotted slots for data and best data communications performance.[14]

Aircraft request slots for transmission from the ground by placing a reservation request burst by random access (RA) in a LBAC available for that purpose. When an aircraft has a reservation to transmit by random access, it will skip a random number of unused RA slots between 0 and RR, and then transmit on the next RA opportunity. The request identifies the number of slots required and the priority of the data that is to be transferred. The ground will also poll individual aircraft to determine reservations, allowing aircraft fixed access for requests. The rate at which polling occurs is determined by the number of aircraft in the subnetwork. The aircraft will respond to these polls in an LBAC in slot A of the even frame. The exact LBAC used by an aircraft to transmit the response is determined by the group that the aircraft selected before entry into the network.

Based on priority, the ground determines when to grant access to the link. Reservation responses are sent in the uplink management (M) burst in slot A of the odd frame. If the ground is unable to immediately grant the request when it is received, it responds with a Request Acknowledgment (RACK). Otherwise it will indicate which slot in the next MAC cycle may be used to begin the transfer, as well as whether slot D may be used or if it is reserved for voice. Up to 12 responses may be placed in a single uplink M burst in the 3T configuration.

Once access has been granted to the link, a station will transmit starting in the indicated slot and use consecutive data slots until the transmission is completed. Transmissions are limited to a maximum of 15 consecutive slots;

frames requiring more slots to transmit are not permitted. In the event that a voice reservation is also granted, only slots B and C will be used for data transmission.

The DLE uses an Acknowledged Connection-Less Protocol (ACLP) which adds only 6 bytes of header information to each network frame. Upon sending a frame, the DLE waits for an acknowledgement before sending the next frame. The MAC sublayer notifies the DLE when an ACK is not received at the expected time. Frame grouping is allowed at the DLS sublayer, in which frames of the same priority and destination may be sent together. Optionally, a frame of lower priority may also be included in the group as long as it does not require additional slots to transmit. An ACK will acknowledge all frames in the group. If the T1 timer expires before an acknowledgment is received and retransmission occurs, and a higher priority packet is queued, the retransmission of the unacknowledged group will be delayed.

Downlink acknowledgements created by the DLE are automatically converted into an ACK burst and scheduled for transmission in the M burst LBAC one MAC cycle after the last data segment is sent. The ground station recreates the DLE ACK from the ACK burst and passes it to the DLE. Uplink acknowledgments are sent in normal data bursts, but with an expedited priority that takes precedence over any ungranted data transmission.

B. Mode 3 Modeling Assumptions

The simulations assume that all aircraft VDL radios are continuously in the normal timing state and receive all the uplink M bursts. Since voice traffic is not included, slot D will always be available for data.

Frame grouping was employed at the DLE, allowing frames of the same priority to the same destination to be grouped together for transmission. Frames of lower priority were also grouped, as long as their inclusion did not increase the number of slots required. Although it is permissible by the standards, grouping of unacknowledged frames to different destinations was not performed. This eliminates the possibility of sending multiple uplink acknowledgments in a single burst.

The MASPS specify that the VDL DLS shall not send a new frame group to the MAC until an acknowledgement has been received for the previous transmitted frame group. In the ground station this is interpreted to be one frame group per DLE, not the DLS as a whole. Otherwise, only a single uplink frame could be transmitted per MAC cycle. This can cause a bottleneck condition at the ground station even with relatively few aircraft, resulting in long delays and wasted slots.

The uplink M burst only includes normal messages which contain reservation responses. The only downlink messages sent in M bursts are reservation request, poll response, and acknowledgment messages.

The parameters for VDL Mode 3 in the 3T configuration used in the simulations are shown in Table 3.

C. Mode 3 Simulation Analysis

The slot usage for each individual slot in the MAC cycle is shown in Fig. 6. The TDMA structure of Mode 3 favors slot B of the even frame, as it is the first assigned slot in each MAC cycle. At the highest load level attained by these simulations, slot B of the even frame approaches 100% usage. Slot D of the odd frame, the last assigned slot, is used approximately 90% of the time. Overall slot usage is approximately 96% at the highest subnetwork loads.

Although the percentage of slots used is high, the slots are used inefficiently. The maximum number of data bits which can be accommodated in one slot is 496. At loads of up to about 3.5 kbps, the simulations showed an average of about 208 bits per slot. At subnetwork loads of 3.5 kbps and higher, frame grouping increases the average number of bits. The uplink acknowledgements, which are only 48 bits, are transmitted in individual data slots since acknowledgment grouping was not employed in these simulations. Conceivably, since the majority of

Table 3 VDL Mode 3 parameters.

Sublayer	Parameter	Description		Default value
MAC	RR	Reservation request randomizer	(aircraft)	8
	T1	Delay before retransmission	(aircraft)	10 MAC cycles
			(ground)	2 MAC cycles
	T_ack	Maximum ACK delay	(ground)	9 MAC cycles
DLS	N1	Maximum frame group size		930 octets

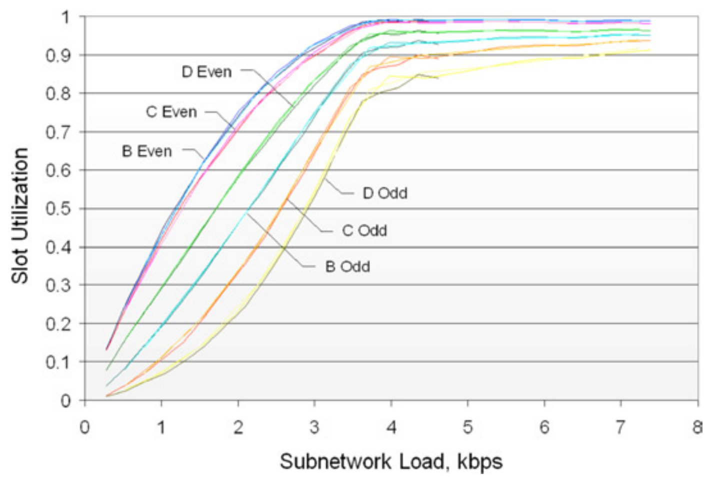

Fig. 6 TDMA slot usage for Mode 3 as a function of network load.

messages require a single slot for transmission, up to six acknowledgements may be generated for a single MAC cycle, requiring six slots to transmit in the simulation. All six of these could be placed into a single slot if acknowledgement grouping were performed, thereby increasing the average bits per slot and reducing the number of slots used.

The capacity is not just limited by the slot use, however. It is also dependent upon the slotted Aloha access mechanism for the downlink reservation requests. The percent of all used random-access slots that result in a collision is shown in Fig. 7. The fact that separate curves result from the differing LF shows that the percentage of collisions is dependent on the number of aircraft, as fewer aircraft are required to achieve the same subnetwork load with a higher LF. At higher loads, the percentage of collisions begins to decrease. This is due to the aircraft reaching the maximum number of retransmission attempts and ceasing to transmit via slotted aloha, which reduces the contention for the random-access slots. In these cases reservations are made by the fixed-access polling mechanism.

The subnetwork delays for the uplink and downlink are shown in Fig. 8. The delays increase at an approximately steady rate until the load reaches 3.5 kbps. For the uplink, the delays from the differing LF are similar until the stepped increase, at which point the higher LF have lower delays due to increased frame grouping. The downlink delays are larger than the uplink since a reservation must be transmitted before a slot can be assigned. The downlink delays also show more dependence on the LF than the uplink. The differing LF create similar but distinct traces at

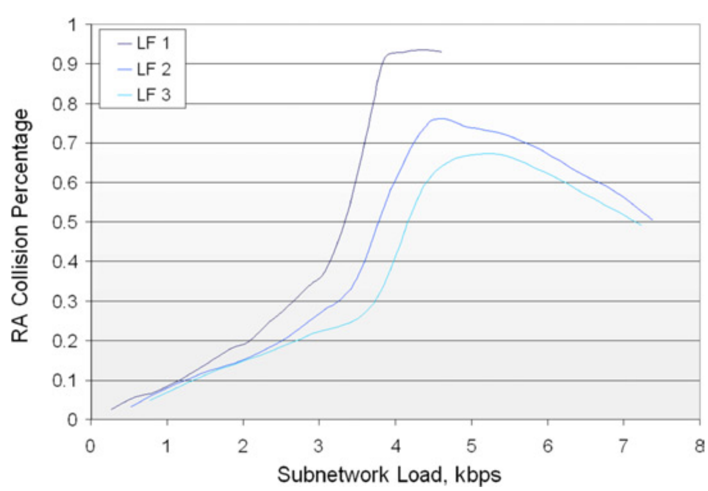

Fig. 7 Random-access LBAC collision percentage.

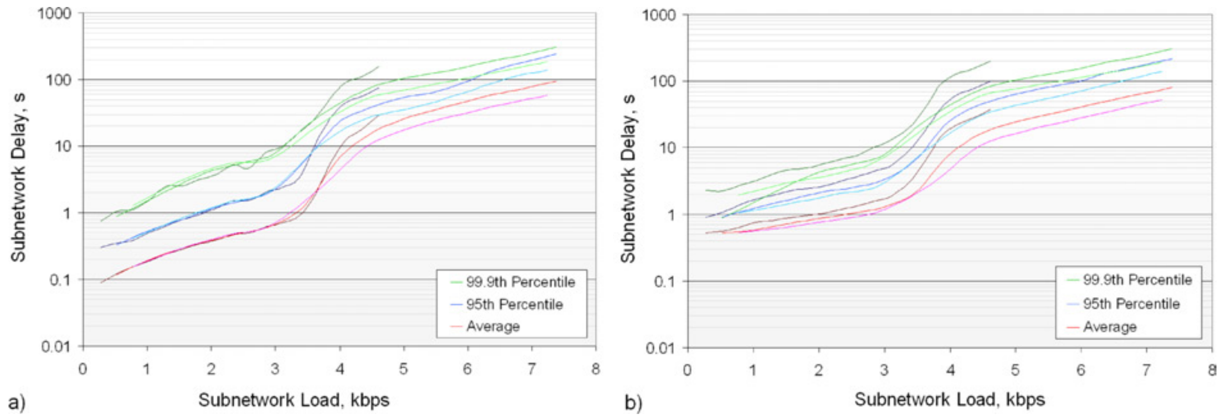

Fig. 8 Subnetwork delays for the (a) uplink and (b) downlink.

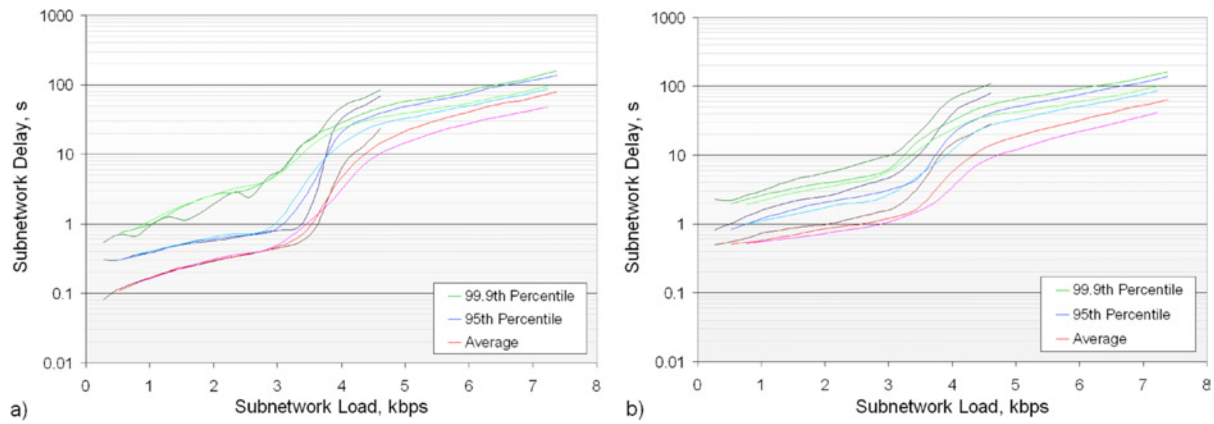

Fig. 9 High-priority subnetwork delays for the (a) uplink and (b) downlink.

all loads in the downlink plot, with the lower LF having higher delays at a given load due to increased contention from more aircraft and less use of frame grouping.

The VDL standard specifies two timing constraints on the subnetwork for VDL Mode 3. The maximum 95^{th} percentile subnetwork delay for high priority traffic of 192 bits or less is 1 second, and the maximum 99.9^{th} percentile subnetwork delay is 5 seconds. The delays for the high priority messages, shown in Fig. 9, exceed the 95^{th} percentile limit with a subnetwork load of 0.5 kbps for the downlink with a LF of 1. The 99.9^{th} percentile delays do not exceed the requirements until a load of 1.8 kbps with LF 1. The requirements can be met with higher loads when a larger LF is used.

The VDL Mode 3 downlink is dependent upon the random-access mechanism for slot reservation. In Ref. 4, the random access algorithm of VDL Mode 3 was investigated and improved upon, such that slot reservation requests may be transmitted in less time. By incorporating these improvements, the downlink subnetwork delays were decreased. For our simulation scenarios, the improved algorithm may allow for Mode 3 to support higher traffic loads while meeting the subnetwork delay requirements, however it should be noted that Ref. 4 used a non-default value of 16 for RR which should produce higher delays than the default in the non-optimized algorithm.

VI. Mode 4

VDL Mode 4 is based on the Swedish STDMA datalink which supports navigation and surveillance applications and it was proposed to the ICAO in May, 1994. Mode 4 had originally been included in the ICAO SARPs for surveillance only, although the protocols provided communications functionality. In February 2004, ICAO approved the deletion of the surveillance-only limitation.

A. Mode 4 Protocol Description

The VDL Mode 4 physical layer uses a Gaussian-filtered Frequency Shift Keying (GFSK) modulation operating at 19.2 kbps. The training sequence for Mode 4 consists of periods for transmitter power ramp-up and bit synchronization. The Mode 4 training sequence is 40 bits in length.[23]

The MAC uses a Self-organizing Time Division Multiple Access (STDMA) mechanism. Time is segmented into 13.3 ms timeslots, with 75 slots per second. A superframe lasts for 60 seconds and contains 4500 slots. Aircraft timing is primarily based on Global Navigation Satellite System (GNSS), but alternatively timing can be derived from ground stations or other sources, including other aircraft. This allows the system to continue operating even when communication with the primary source fails.

The MAC burst for Mode 4 requires more information to be contained within it than the other modes. Mode 4 bursts contain a start and end flag, reservation information, source address, message, and a Cyclic Redundancy Check (CRC). The size of the burst header depends on the type of message being transmitted and the type of reservation being placed.

VDL Mode 4 receivers are intended to be multi-channel. Two Global Signaling Channels (GSCs) are defined for Mode 4. Aircraft are expected to transmit position information, such as in ADS-B messages, alternately on these two channels. In areas where traffic levels are high, the aircraft can be directed to local channels for use.

VDL Mode 4 has two operational modes: autonomous reporting and directed reporting. When operating under autonomous reporting, each aircraft chooses its own slots for transmission, whereas in directed reporting, the ground station determines which slots aircraft may use.

Slot selection is handled by the VSS. When a reservation is to be placed, the VSS identifies the first Q4 available slots in the range specified by the application that meet the length requirement. In the event that less than Q4 available slots are found in the specified range, a mechanism exists to select previously reserved frames from distant aircraft communicating with distant stations. This ‘Robin Hood’ protocol allows for slot reuse if certain conditions are met. From the available list of slots, the VSS randomly selects one for use.

Several reservation mechanisms exist for VDL Mode 4, such as periodic broadcast, incremental broadcast, unicast request, information transfer request, directed request, superframe block, and second block reservation protocols. The unicast request and information transfer request protocols are used for DLS data transfers, and are briefly described below because of their pertinence to our research results. The unicast reservation allows for a one-way transfer. A station can reserve a block of slots on behalf of another station. The information transfer protocol, however, is a two-way communication. A station reserves slots for another station to use, and it also reserves a single slot for itself to send an acknowledgment.

The Unicast reservation utilizes a VSS-based retransmission mechanism. If a response is not received from the peer in the slot reserved for the transfer, the retransmission procedures will be invoked. Retransmitted frames access the link by random-access. The retransmission delay is dynamically calculated based on slot utilization and number of retransmission attempts. The range of values possible for Q5 when using the default parameters is shown in Fig. 10 against the slot utilization. The value of Q5 is randomly set, according to the standards, between a minimum and maximum value, where the maximum is determined by the number of retransmissions and the minimum by default is 0.

Information transfers do not use the VSS for retransmission; the retransmission is the responsibility of the DLS sublayer. Upon indication that an information transfer was not successful, a DLE will restart the transmission process.

The DLE uses a Negotiated Setup Connection-Oriented Protocol (NSCOP) for air-to-ground communications and a Zero Overhead Connection-Oriented Protocol (ZOCOP) for air-to-air communications. The DLS supports 16 levels of priority, enough to map each of the 15 levels of priority specified by the ATN. The larger burst format at the MAC sublayer allows for a small DLE frame header to be used. For data packets, the header is only 2 bytes in length.

The DLS will use either the short or long transmission procedures depending on the length of a frame. In the short procedure, the DLS sends a data frame to the VSS with instructions to include a unicast reservation for a single slot with the transmission. The VSS will place a reservation for the data frame in an existing transmission, if possible;

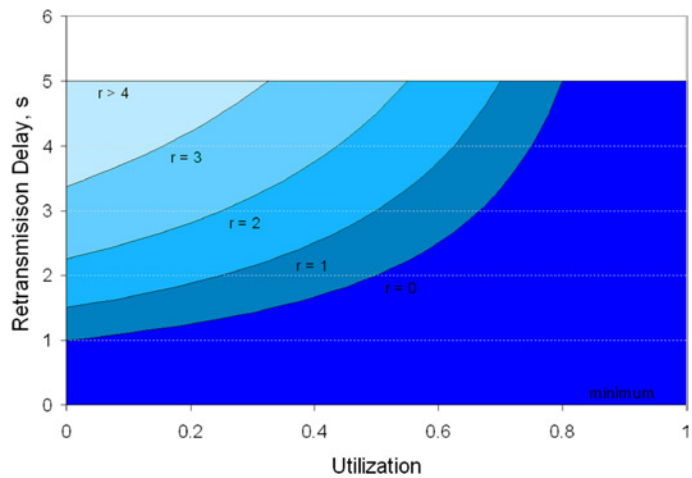

Fig. 10 Range of values for retransmission delay Q5 using the default parameters.

otherwise it will specify that the frame be transmitted by random access. When the frame is received by the peer DLS, an acknowledgement is created and transmitted back to the source. The acknowledgement will be placed in the slot reserved by the unicast reservation.

For a long transmission, the DLS issues a Request-To-Send (RTS) frame that includes the length of the data transmission. The RTS is sent similarly to the data frame of the short transmission, with a unicast reservation for a single slot for the peer. The peer, upon receiving an RTS, responds with a Clear-To-Send (CTS). The CTS is sent in the frame reserved for it and includes an information transfer reservation for the data length specified in the RTS. The information transfer reservation reserves slots for the data frame as well as a slot for the acknowledgement. The DLS will send the frame when it receives the CTS, and the peer will respond with an acknowledgement.

The DLE allows linking of transmissions such that data and RTS frames can be combined in a single transmission. In these cases the ACK and CTS responses will also be combined. When transmissions are linked in this way, all transmissions after the initial RTS will be by reserved access.

B. Mode 4 Modeling Assumptions

In these simulations, all aircraft can be seen as operating on a local channel. The aircraft would have been sent to this channel from a GSC prior to the beginning of the simulation. The channel does not contain ADS-B or air-to-air transmissions. The ZOCOP protocol is not necessary for air-to-ground communications, and was not included in the models.

The subnetwork operates under autonomous reporting because the frame arrival times are not known a priori by the ground station. Ground quarantined slots are not provided in the simulations.

The Robin Hood protocol was also not included because it is not required for a single ground station for the following reason. Since the protocol relies on a minimum distance between the reserved receiver and transmitter and the new receiver and transmitter, and all communications involve the single ground station as either the receiver or transmitter, the conditions for slot reuse can never be satisfied.

The only reservation protocols implemented in the research reported in this paper were the unicast and information transfer protocols. These two reservation protocols, along with the random access protocol, are sufficient for DLS messages. Other protocols, such as periodic broadcast, are better suited for non-DLS communications such as ADS-B.

The values for the VDL Mode 4 parameters used in the simulations are shown in Table 4.

C. Mode 4 Simulation Analysis

Mode 4 simulations cannot support the subnetwork loads attained by the Modes 2 and 3 simulations. The largest load attained was 2.75 kbps. This was due to aircraft considering the link to be congested and initiating handoff

Table 4 VDL Mode 4 parameters.

Sublayer	Name	Description	Default value
MAC	p	Random-access persistence	64/256
	VS3	Maximum access attempts	24
VSS	Q4	Number of available slots	3
	$Q5_{min}$	Retransmission minimum	0 s
	$Q5_{max}$	Retransmission maximum	5 s
	$Q5_{mult}$	Retransmission multiplier	1
	$Q5_{exp}$	Retransmission exponent	1.5
	$Q5_{num}$	Retransmission count	4

procedures, caused by the retransmission count reaching $Q5_{num}$. The results indicate that frames sent by random-access were colliding. In Fig. 11 the percent of all transmissions made by random access for both the uplink and the downlink is shown. For the uplink, the percentage of random access transmissions decreases at an almost constant rate, since the large number of transmissions provides opportunities to place reservations for frames normally sent by random access. The aircraft, however, do not have enough frames in the transmit queue to make effective use of adding reservations for random access frames, and as a result use a high number of random-access transmissions. The percentage increases with the load due to retransmissions, since the retransmissions use random-access. These retransmissions are the result of collisions from random access. Increasing the LF marginally improves the situation by decreasing the number of aircraft contending for a slot at a given load. As documented in Ref. 24, reducing the persistence value may help mitigate the problem.

The subnetwork delays are shown in Fig 12. The uplinks tend to have lower delays than the downlinks because the uplinks piggyback reservations onto data transmissions and thereby reduce the number of random access transmissions.

The subnetwork delays for high-priority traffic are shown in Fig. 13. Since Mode 4 has only been standardized for use in the ATN for surveillance, and not as a communications datalink, a maximum limit does not exist to determine capacity. By using the limits defined for Mode 3, the maximum subnetwork load is approximately 0.8 kbps with LF = 1 due to the 95th percentile requirement. Ref. 24 demonstrated that lower delays could be attained by adjusting the reservation parameters, leaving open the possibility that higher loads may be supported by tuning the relevant parameters.

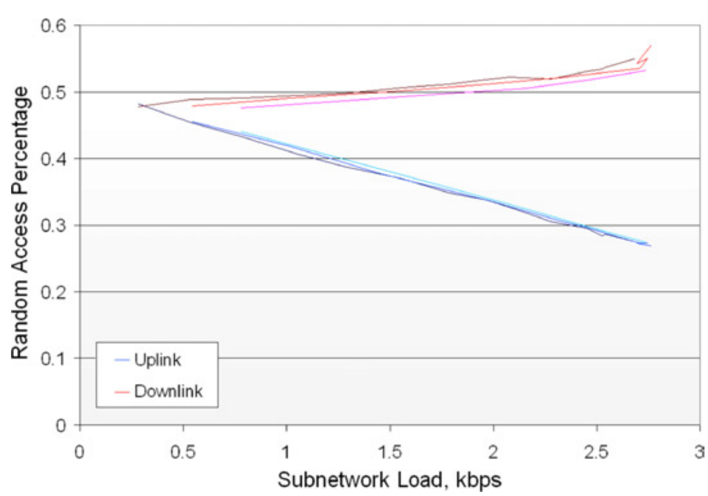

Fig. 11 Percentage of all transmissions that are made by random access.

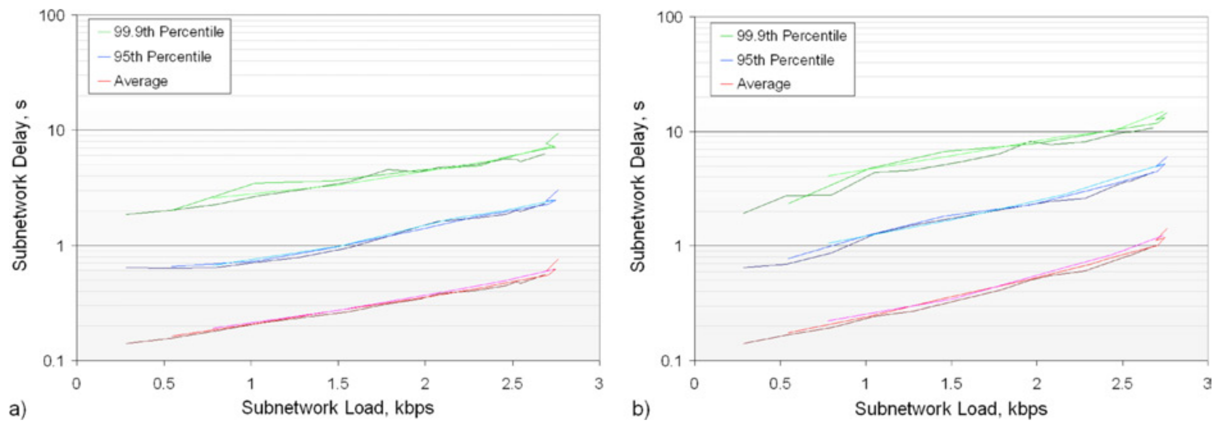

Fig. 12 Subnetwork delays for the (a) uplink and (b) downlink.

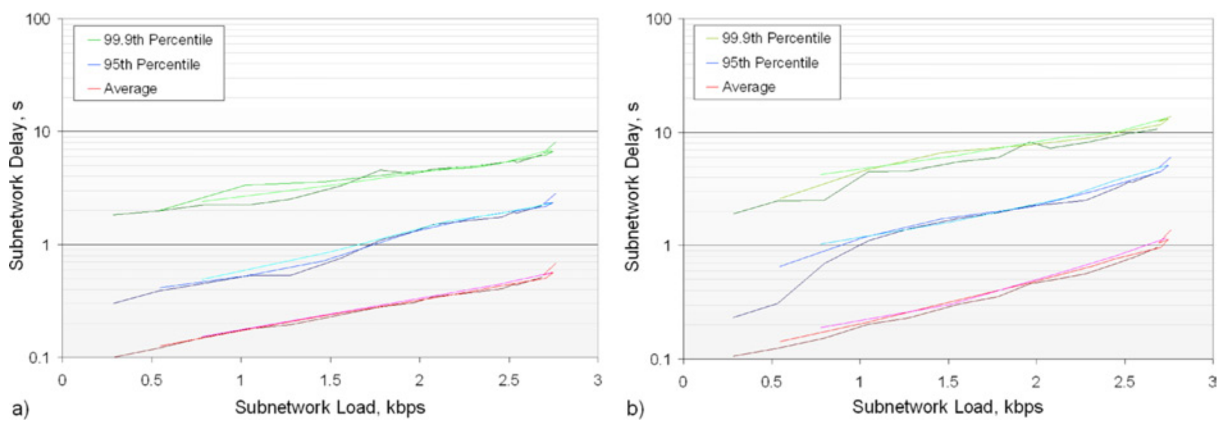

Fig. 13 High priority subnetwork delays for the (a) uplink and (b) downlink.

VII. Evaluation of VDL in the NAS

The previous simulations were conducted to test the capacity of the VDL Modes under constant conditions. The National Airspace System (NAS) however is quite dynamic. To evaluate the VDL Modes under typical operating conditions, aircraft movement into and out of the coverage area of a ground station was simulated. These simulations are based on actual flight trajectories obtained from the FAA. Two scenarios were considered, the first using VDL in the terminal domain and the second using VDL in the en route domain. These simulations are an extension of previous research.[15,16] Some optimization of the VDL parameters was performed to determine if tuning the network would improve performance. Previous research has shown that the performance of Mode 2 could be improved with the proper optimizations.[12,13]

A. Terminal Domain

The aircraft flight trajectories were derived from FAA radar tracking data from the Detroit Metropolitan Wayne County Airport (DTW). The aircraft trajectories were restricted to a range of five to forty nautical miles and an altitude of 18,000 feet or less. During the one hour of flight simulation, a total of 254 aircraft traverse the simulation area. The number of aircraft used in the terminal scenario as a function of the time of day is shown in Fig. 14.

For this simulation, the traffic profile from Ref. 25 is used. This is the basis of the standard model specified in the standards and includes both ATS and AOC traffic. The reference includes traffic profiles specific to each domain, and, therefore, is used here in place of the standard model. The traffic profile used for the terminal domain simulation is shown in Table 5.

Fig. 14 Number of aircraft in terminal simulation.

Table 5 Terminal traffic model.

		Uplink		Downlink	
Service name	Priority	Average rate (msg/s)	Average size (bits)	Average rate (msg/s)	Average size (bits)
Pilot/Controller communications	High	0.016	123	0.022	32
Traffic Flight Management Information	Medium	0.00083	800	0.00083	100
FIS Planning Services	Medium	0.017	3325	—	—
Aircraft Originated Meteorological Obs.	Medium	0.0017	56	0.0033	1760
Advanced Air Traffic Management	High	0.0017	40	0.0017	960
Route Deviation Warnings	High	0.00033	800	0.00033	800

The results for the subnetwork delays from the terminal domain simulations for all three VDL modes with the default parameters are shown in Fig. 15a. For Mode 2, the 95th percentile delays are substantially below the 3.5 second maximum limit stated in the standards. The 99.9th percentile delay ranges from about 3 to 3.5 seconds, which is to be expected for any frame requiring retransmission due to collisions. The Mode 3 subnetwork delay in the downlink direction is 1.2 seconds, which is inappreciably more than the 95th percentile requirement of 1 second for

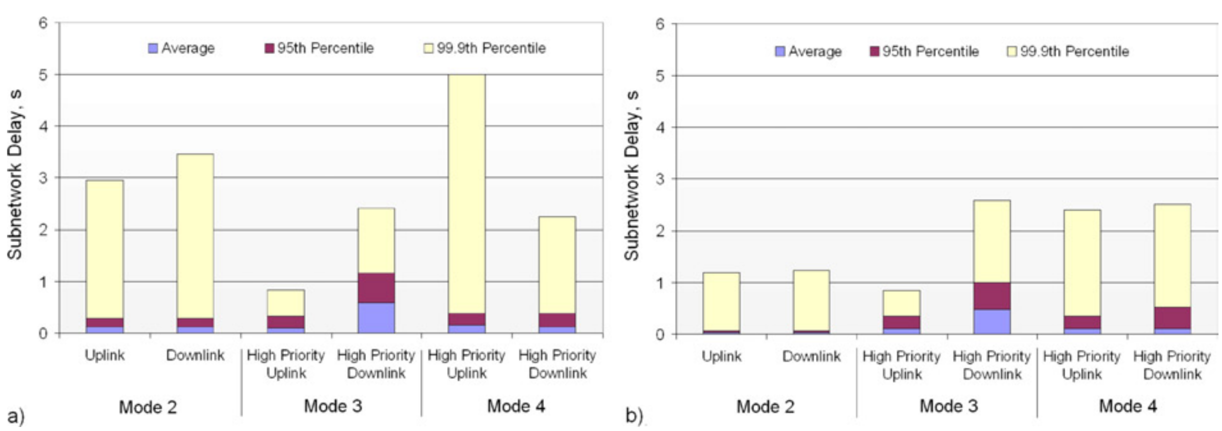

Fig. 15 Terminal subnetwork delays using (a) default and (b) optimized parameters.

high priority traffic. This is due to the delays from the downlink random access mechanism noted in section V. Mode 4 had the highest 99.9th percentile delay in the uplink direction, but the average 95th percentile delays were similar to Mode 2.

To further investigate the performance, some basic parameter optimizations were performed on the VDL subnetworks and the corresponding results are shown in Fig. 15b. For Mode 2, the backoff delay TM1 was reduced from 4.5 to 0.5 ms. Since all aircraft were within 40 nautical miles of the ground station, the longest time required for one aircraft to determine that another is transmitting is the propagation delay from the two aircraft with the largest distance between them. This occurs with two aircraft located 40 nautical miles from the ground station in opposite directions, with a propagation delay of approximately 0.5 ms. The persistence was also decreased from 13/256 to 10/256. As a result of these optimizations, the delays for Mode 2 were significantly reduced, with a 95th percentile of 0.06 seconds and 99.9th percentile delay of 1.2 seconds. For Mode 3, optimization of the downlink is necessary to meet the delay requirements and so the reservation request randomizer RR was reduced from 8 to 3. This allows the aircraft to transmit reservation requests earlier to reserve slots with less delay, but can also increase collisions in more heavily loaded subnetworks. This optimization reduced the 95th percentile delay to 1 second, allowing Mode 3 to meet its requirement. However, this increased the 99.9th percentile delay marginally due to the higher probability of collision on the random access M bursts. For Mode 4, the persistence for random-access was increased from 64/256 to 80/256 to allow faster access, and the retransmission maximum delay $Q5_{max}$ reduced from 5 to 2.5 and $Q5_{exp}$ from 1.5 to 1.25 to reduce retransmission delays. This provided an improvement to the 99.9th percentile delay in the uplink direction, but slightly degraded the 95th and 99.9th percentile delay in the downlink direction.

B. En Route Domain

For the en route domain, three busy sectors were modeled based on flight data from the Cleveland ARTCC. Sectors ZOB20 and ZOB21 are low altitude sectors which serve aircraft up to altitudes of 23,950 feet. Sector ZOB27 is a high altitude sector between 23,951 and 34,950 feet and is located above sectors ZOB20 and ZOB21. These three sectors are modeled such that Mode 3 for each sector has its own group. For this scenario, four hours of traffic were simulated with a total of 301 aircraft. The number of aircraft simulated as a function of the time of day is shown in Fig. 16.

In the en route domain simulations, the traffic profile for the en route domain[25] is used and it includes both ATS and AOC traffic. This model has the same services as those in the terminal domain. The traffic profile used for the en route domain simulations is shown in Table 6.

The subnetwork delay results from the en route simulations for all three VDL modes with the default parameters are shown in Fig. 17a. All three modes meet the delay requirements. Mode 2 had the highest 99.9th percentile delays due to retransmissions.

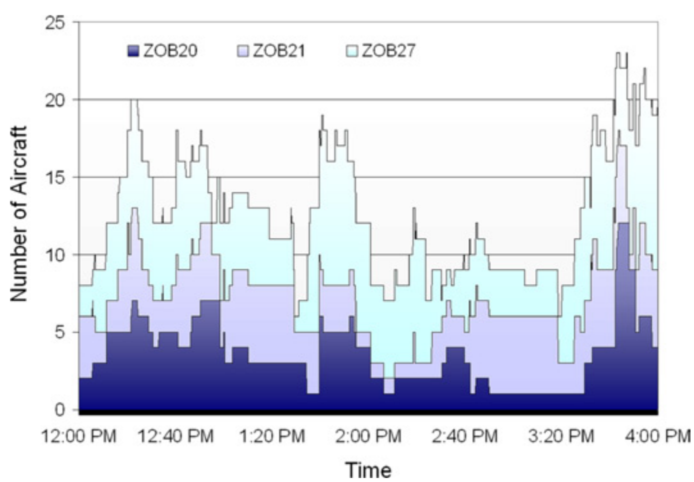

Fig. 16 Number of aircraft in en route simulation.

Table 6 En route traffic model.

		Uplink		Downlink	
Service name	Priority	Average rate (msg/s)	Average size (bits)	Average rate (msg/s)	Average size (bits)
Pilot/Controller communications	High	0.0068	118	0.012	34
Traffic Flight Management Information	Medium	0.00067	800	0.00067	100
FIS Planning Services	Medium	0.002	1624	0.002	64
Aircraft Originated Meteorological Obs.	Medium	0.00067	56	0.0033	1760
Advanced Air Traffic Management	High	0.00067	40	0.00067	960
Route Deviation Warnings	High	0.00013	800	0.00013	800
Aeronautical Operational Communications	Low	0.001	2400	0.0017	2400

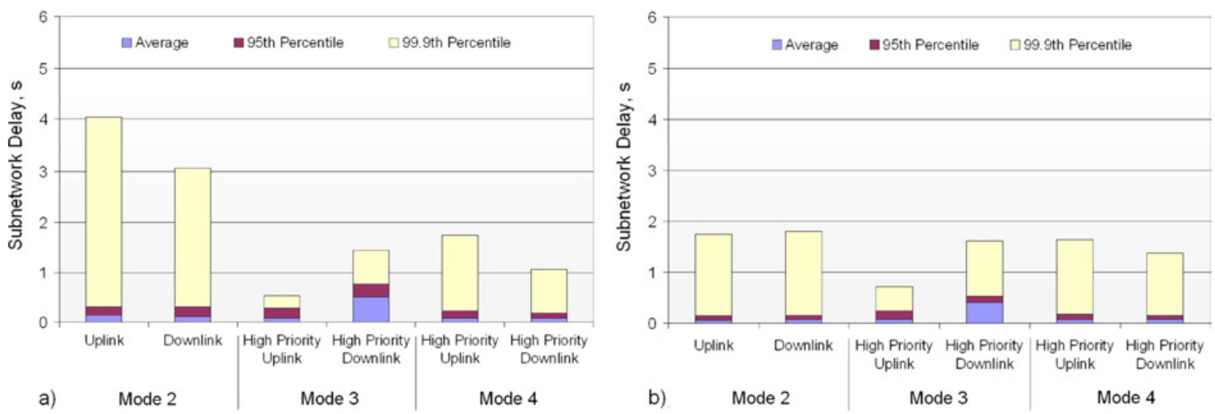

Fig. 17 En route subnetwork delays using (a) default and (b) optimized parameters.

The subnetwork delays using optimized parameters are shown in Fig. 17b. The same optimizations that were used in the terminal simulations were used for en route, with the exception of the Mode 2 backoff delay TM1. For the en route domain, this parameter was set to 1.5 ms to allow for a larger range of up to 120 nautical miles. Although the simulations did not require the additional range, this permitted us to cover larger sectors. Mode 2 still showed a substantial improvement in the subnetwork delay. As with the terminal domain simulations, Mode 3 improved upon the 95th percentile downlink delay but the 99.9th percentile delay increased. There was no change exhibited by Mode 4. The modifications recommended by Ref. 24 actually degraded the delays (not shown), and may only help under considerable loading conditions.

VIII. Conclusions

The protocols for VDL Modes 2, 3, and 4 were reviewed and investigated for data communications through simulation. The performance of each mode was individually analyzed. The capacity, in terms of the number of aircraft supported on a single frequency, was defined based on the FAA specifications for subnetwork delay for modes 2 and 3. The VDL Modes are summarized in Table 7.

The simulations determined that VDL Mode 2 is capable of a subnetwork load of 3.3 kbps, equivalent to the load from approximately 130 aircraft when using the suggested traffic load. Modes 3 and 4 were not capable of supporting a comparable load, with Mode 3 supporting only 0.5 kbps and Mode 4 supporting 0.8 kbps. However, VDL Mode 2 is not intended for the same use as Modes 3 and 4. Mode 2, because of its CSMA implementation, cannot provide prioritized link access and is intended to communicate non-critical information. Modes 3 and 4 do support priority in their respective TDMA and STDMA protocols, and could be used for safety-of-flight messages. As such, Mode 3 has a stricter delay requirement than does Mode 2. Mode 4 seemed to have a limitation in that the subnetwork could not reach more than approximately 2.7 kbps because the protocol mechanisms forced aircraft to terminate

Table 7 VDL Modes summary.

	Mode 2	Mode 3	Mode 4
Data rate	31.5 kbps	31.5 kbps	19.2 kbps
Modulation	D8PSK	D8PSK	GFSK
Media access	CSMA	TDMA	STDMA
Transfer protocol	COP	ACLP	NSCOP ZOCOP
Priority levels	none	4	15
Benefits		Voice	Air-to-air ADS-B
Estimated max. load	3.3 kbps	0.5 kbps*	0.8 kbps**
Capacity (LF = 1)	130	20*	30**

*Using standard random-access algorithm.
**Assuming same delay requirements as Mode 3.

the link because of too many retransmissions. It should be noted that all simulations used the default values for all VDL parameters. Performance could likely be increased for all three modes by tuning the parameters for a specific scenario.

In the terminal and en route domain simulations with the default parameters, Modes 2, 3, and 4 resulted in similar average delays, with the exception of the Mode 3 downlink. In all three scenarios, Modes 2 and 4 provided lower average and 95th percentile subnetwork delays in the downlink than Mode 3, and comparable mean and 95th percentile delays for the uplink. Mode 3, however, had lower 99.9th percentile delays in both the downlink and uplink directions in most cases, again demonstrating that the Mode 2 CSMA protocol and its retransmission procedures may not be suitable for safety-of-flight messages. However, with the optimized parameters, Mode 2 had 99.9th percentile delays rivaling those of Modes 3 and 4 in the en route domain and was better than Modes 3 and 4 in the terminal domain. Mode 4 tended to have higher 99.9th percentile delays than Mode 3, and occasionally was worse than Mode 2, caused by use of the random-access mechanism when there is no opportunity to place reservations. The Mode 4 uplink proved to have higher delays than the downlink, possibly due to the ground station requiring more retransmissions. Furthermore, Mode 4 did not respond well to tuning of the parameters, indicating that the default parameters are perhaps optimal. The overall performance of Mode 4, nevertheless, may improve if more of the Mode 4 reservations, such as ground quarantine, are included in the simulations and this is a topic for further investigation.

Acknowledgments

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