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End-to-End Data Link Delays Using Mode S

SUMMARY

The U.S. has presented end-to-end delay requirements for ATN applications in [1]. A simulation study indicates that most delay requirements for CPDLC and ATIS in en route and terminal airspace can be met with Mode S for the expected level of application traffic. An exception is the 95th percentile uplink delay for CPDLC. Application message rates were varied to determine how much delays will change if the future message rates have been underestimated or if new applications are fielded.

REFERENCES

1. “U. S. Operational Requirements for ATN in CNS/ATM-1,” WG2/WP77, March 1995.

1.0 INTRODUCTION

CAASD has recently used its the simulation of the Aeronautical Telecommunications Network (ATN) to estimate the end-to-end delays in the Federal Aviation Administration’s (FAA’s) portion of the ATN assuming the use of Mode S. Work is in progress to add a VHF air/ground subnetwork to the model. When that development is complete, similar delay estimates can be made for the VHF subnetwork.

The simulation shows that most delay requirements for Automatic Terminal Information Service (ATIS) and Controller/Pilot Data Link Communication (CPDLC) stated in [1] and [2] can be met for the expected application message rates. Application message rates were varied to determine how much delays will change if the future message rates have been underestimated.

Delays in the real system may be longer than the results presented here because of a number of simplifying assumptions in the model. These assumptions are stated in section 2.2 below. The simulation did not include upper layer protocols or the Context Management Application (CMA), which may also contribute to longer delays.

2.0 MODEL DESCRIPTION AND ASSUMPTIONS

2.1 General

These experiments simulated a portion of the FAA’s ATN infrastructure. To keep simulation run times reasonable, the simulation included only aircraft with connections to Kansas City (ZKC), Denver (ZDV), Albuquerque (ZAB), Fort Worth (ZFW), and Houston (ZHU). One ATN router was located at each of these ARTCCs. (An ARTCC is an en route control facility, sometimes referred to as a “center.”) Each ARTCC was its own routing domain. The ground routers were interconnected by the NADIN Packet Switched Network (PSN), the FAA’s national X.25 network. The time to send a packet across the PSN was uniformly distributed between 200 and 500 milliseconds.

Two additional routers, Atlanta (ZTL) and Memphis (ZME), acted as “backbone” routers for the FAA’s ATN “island.” These routers were chosen to minimize the amount of routing updates in the overall network. Routes to aircraft were distributed using the Interdomain Routing Protocol (IDRP) [3] as described in the ATN Manual [4].

An average of 53 aircraft were in each domain's airspace[1]. Aircraft flight times in an ARTCC's airspace were exponentially distributed with a mean of 27 minutes, which reflects current flight times in the U. S. The minimum time in an ARTCC's airspace was 60 seconds. Transport connections were set up as soon as an IDRP connection was established after takeoff or after entering coverage of the next center. The applications were notified when a transport connect confirm was sent or received. The applications began generating messages upon receipt of this notification; therefore, the end-to-end delays for application messages were not affected by the time to set up transport connections. This may be an optimistic assumption in the real world. CLNP headers were compressed by the Subnetwork Dependent Convergence Function (SNDCF) as specified in the ATN Manual.

End-to-end delays were measured from the time an application sent a packet until it was received by the destination application. The model included a 30 millisecond delay from the time an application created a packet until it arrives at the Mode S transponder or sensor, and about 30 milliseconds from the time Mode S receives a packet until it is delivered to the application. This delay covers processing in the protocol stack and local communication on the ground or in the aircraft.

2.2 Mode S Model

Mode S was the air/ground ATN subnetwork in the simulation. The scan interval was 12 seconds for en route sensors and 4.8 seconds for terminal sensors. The Mode S model optimistically assumed each aircraft carried a level 4 transponder which can send and receive a 160-octet Extended Length Message (ELM) in each scan.[2] Of this 160 octets, a small number of octets were used by Mode S as frame header information. If a packet received by the Mode S sensor was 27 octets or fewer, it was transmitted as a Standard Length Message (SLM) rather than an ELM. The maximum SLM message size for a transponder was 26 octets. A maximum of one SLM and one ELM were transmitted in each scan.

No multiplexing was done over Mode S. Multiplexing is an option defined in the ICAO Mode S subnetwork Standards and Recommended Practices (SARPs). The Ground Data Link Processor (GDLP) will only multiplex after long queues have developed in the Mode S sensor. A sensor can buffer up to ten 16-segment ELMs per aircraft[3]. Only when this limit is exceeded does the GDLP begin to multiplex. The application message frequencies are low enough that the sensor buffer space will only be filled in extremely rare circumstances. In

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[1] The delays in our model are independent of the number of aircraft, so it is not important whether there will be more or fewer than 53 aircraft in each ARTCC's airspace in the real system.

[2] A level 4 transponder must be able to downlink a minimum 40 octets per scan; it is expected that implementations will be capable of 160 octets per scan.

[3] The sensor can also buffer up to two 4-segment standard length messages (SLMs) per aircraft.

order to multiplex efficiently, this function must be performed in the sensor. U.S. sensors are not planned to have this feature for CNS/ATM package 1, but could be enhanced to increase capacity. The downlink is somewhat different. The transponder will buffer only one ELM. The Aircraft DLP (ADLP) will queue and multiplex additional ELMs. Because the simulation did not model this multiplexing in the downlink direction, CPDLC delays reported to be 3 scans or longer might be sent in the second scan. This model simplification does not affect the major conclusions of these experiments.

The simulation assumed that applications do not attempt to send messages over a link until the router initiation process[4] is complete.

The model included a number of simplifying assumptions. Where these assumptions are not valid, the end-to-end delays will be longer than predicted by the simulation. The assumptions are as follows:

1. The model assumes there are no Mode S specific services. Proposals have been made to distribute some information, such as Terminal Weather Information for Pilots (TWIP) and the (Mode S) Traffic Information Service (TIS), over Mode S but outside the ATN framework. These so-called Mode S specific services may have priority over other data to be sent over Mode S depending on how priorities are assigned. Some Mode S specific services are intended for general aviation.

2. The model assumes reservations are not required. In one mode of operation, a Mode S sensor reserves a transponder when it has data to send. During the reservation period, if another sensor has data to send to that aircraft, it must wait until the reservation is cleared. This lockout situation will occur regularly in the ATN. When an aircraft is approaching an ARTCC airspace boundary, it will go through a router initiation sequence with the ATN router in the next center. During this sequence, if reservations are used, data from the current center to the aircraft will be delayed. No such delays are included in the simulation. The FAA is currently considering whether to modify the sensor software to close out a reservation in the same scan in which the data was transmitted. This modification would minimize the lockout problem.

3. The model assumes a Mode S transponder can recharge its transmitter instantaneously. In reality, the transmitter will take some time to recharge. When an transponder is in contact with multiple sensors in different cells (a cell being the coverage

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[4] The “router initiation process” is the process of getting routing information into the aircraft and ground routers when an aircraft establishes a new connection with a ground router. In this simulation, the process consisted of the exchange of ISO 9542 Intermediate System Hellos (ISHs) and establishment of an IDRP connection between aircraft and ground.

area of all sensors connected to a single ATN router), there could be cases where an aircraft sends an ELM to one sensor and cannot recharge fast enough to send to another sensor. An transponder may communicate with sensors in multiple cells even if the pilot is only communicating with a single ATC facility. For example, when an aircraft enters a new cell, the aircraft and ground routers initiate a connection.

4. The model assumes each Mode S frame is delivered successfully during the first scan in which it is sent. In reality, there will be some bit errors which will force some link level retransmissions. Most retransmissions will occur in the same beam dwell; however, those retransmissions that must wait until the next scan will increase end-to-end delay seen by the applications. Because coverage maps will not be used, data link messages will be sent when aircraft are at the very edge of coverage where bit errors are most likely.

5. The model assumes aircraft density is low enough that the delay across Mode S is independent between aircraft. Where aircraft are lined up, for example in the terminal area, this assumption may not be valid. When aircraft are clustered, the throughput to each aircraft will be less than in the model.

If these five assumptions are not true, end-to-end delays will be longer than predicted by the model; therefore, the optimistic delays presented here should be considered a lower bound on the actual delays.

2.3 Application Models

The model included the CPDLC and ATIS applications. For ATIS, the aircraft periodically sent a 7-byte request to a ground end system at the aircraft's destination. The ground end system sent a 270 byte response[5] back to the aircraft.

For CPDLC, either the ground or the aircraft could initiate a request/reply transaction. Each downlink message was 4 octets. Each uplink message was 15 octets. The CPDLC model included triangular distributions for pilot and controller response times. The parameters for these distributions are listed in Table 1. These response times, which are based on [5, 6], have a big impact on the end-to-end delays because they determine when during the Mode S scan the response is sent. For example, if a pilot in en route airspace takes an average of 9.3 seconds to respond, the response must wait an average of only (12 - 9.3) = 2.7 seconds before the sensor's antenna again rotates into position.

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[5] The mean ATIS message size is 300 bytes according to *DLP Weather Data Processing and Retrieval Requirements*, DOT/FAA/SA-90/2, 17 December 1990. A 10% smaller message was simulated as a conservative estimate of compressing the message for transmission.

Table 1. Pilot and Controller Response Times

Responder	Minimum (sec)	Mean (sec)	Maximum (sec)
Pilot	6.8	9.3	10.9
Controller	30	45	53

2.4 Priority

Table 2 shows the subnetwork priority of each type of data and how that priority is mapped into the two Mode S priorities.

Table 2. Priorities

Type of Data	Subnetwork Priority	Mode S Priority
IDRP	14	High
ES-IS	14	High
CPDLC	10	High
ATIS	9	Low

2.5 Transport Protocol

The simulation included a detailed model of the connection oriented transport protocol, ISO 8073 [6]. Parameters that affect end-to-end delays were set as shown in Table 3.

Table 3. Transport Parameters

Parameter	Value
Acknowledgment time (AL)	2 sec
Retransmission time (T1)	203 sec
Inactivity Time (IL)	600 sec
Expected Max Transit Delay (ELR, ERL)	100 sec
Max. Number of transmissions	3

The acknowledgment time defines how long a transport entity may wait before it must acknowledge a received packet.

A retransmission time of 203 seconds seems somewhat large but was necessary to prevent transport connections from timing out in the scenarios with heavier traffic loads. Somewhat smaller values may be better; further study would be needed to determine an optimal value. Since the model assumed no packet losses on the air/ground link, and packet losses due to mobile routing were rare, the long retransmission timer did not affect end-to-end delay statistics. In keeping with the current version of the ATN Manual, the transport model did not dynamically adjust the retransmission timer after a timeout. No congestion control mechanisms, such as responding to the Congestion Experienced (CE) bit were active.

Transport acknowledgments were sent as keepalives when a transport connection was idle for 297 seconds. Rather than using the window time to determine when to send keepalives, the acknowledgment time was calculated as

$$\text{Ack time} = IR - 3 * (ELR + 1)$$

where IR is the inactivity time of the remote transport entity and ELR is the expected one way transmission time from the local to the remote transport entity.

Selective acknowledgment was not used although it seemed to have little effect on delay statistics.

3.0 RESULTS

3.1 Delays for Expected Application Traffic

In 1994, CAASD, working with the FAA's Data Link Operational Requirements Team (DLORT), estimated future FAA data link traffic. The estimates are presented in [8]. The estimates were subsequently incorporated into the FAA's Data Link operational requirements document [2]. Traffic loads in the simulation were based on these estimates. Table 4 lists the average time between transactions for each application. A transaction is a request followed by a reply. CPDLC transaction frequencies in terminal airspace are approximately 2.5 times greater than in en route airspace. Transaction interarrival times in the simulation were exponentially distributed.

Table 4. Application Transaction Frequency

Application	Average Time Between Transactions (sec)	Transaction Frequency (msgs/hour)
ATIS	1628	2.2
CPDLC:		
en route, ground initiated	150	24
en route, aircraft initiated	1252	2.9
terminal, ground initiated	60	60
terminal, aircraft initiated	500	7.2

Table 5 presents delays for three cases:

a. an aircraft in coverage of a terminal sensor while in terminal airspace

b. an aircraft in coverage of a terminal sensor while in en route airspace

c. an aircraft in coverage of an en route sensor while in en route airspace.

The sensor type determines the antenna scan time (4.8 or 12 seconds) and the airspace determine the message frequency. For the FAA, most sensors are terminal sensors. All terminal airspace and most en route airspace is covered by terminal sensors. As was noted above, CPDLC message frequencies in terminal airspace are approximately 2.5 times greater than in en route airspace.

The “one way” delay statistics in Table 5 include all uplink and downlink samples. Uplink, downlink, and one way delays are all reported since it is not clear which of the three is meant where the requirements documents specify “end-to-end delay.” Bordered cells are delays that exceed the DLORT requirements, summarized in Table 6.

Table 5. Delays With Expected Traffic Levels

		CPDLC Delays					
		Mean			95th Percentile		
Sensor	Airspace	Uplink Delay (sec)	Downlink Delay (sec)	One Way Delay (sec)	Uplink Delay (sec)	Downlink Delay (sec)	One Way Delay (sec)
terminal	terminal	3.3	2.6	2.9	6.9	4.9	5.6
terminal	en route	3.0	2.5	2.8	5.5	4.9	5.1
en route	en route	8.6	3.3	5.9	21	8.5	17

		ATIS Delays					
		Mean			95th Percentile		
Sensor	Airspace	Uplink Delay (sec)	Downlink Delay (sec)	One Way Delay (sec)	Uplink Delay (sec)	Downlink Delay (sec)	One Way Delay (sec)
terminal	terminal	12	3.6	6.5	24	8.5	15

Table 6. Excerpt of DLORT Delay Requirements

Airspace Domain	CPDLC Delay (sec)		ATIS Delay (sec)	
	Mean	95th %ile	Mean	95th %ile
Terminal	5	6	15	55
En Route	10	13	N/A[6]	N/A

All CPDLC delay requirements are met with the exception of the 95th percentile uplink delay. Downlink delays are surprisingly short with an en route sensor because most CPDLC downlink messages are responses. The pilot response time lies between 6.8 and 10.9 seconds (Table 1), which means the response arrives at the Mode S transponder just before the sensor antenna returns to the aircraft 12 seconds after delivery of the uplink message. This statistic is obviously very sensitive to the actual distribution of pilot response times.

The ATIS uplink delays are relatively long because the ATIS messages sent to the aircraft were 270 octets, which require a minimum of two scans plus one scan for the transport acknowledgment to the request received from the aircraft

[6] Delay requirements for ATIS in en route airspace were presented in [1]. This paper does not address these requirements.

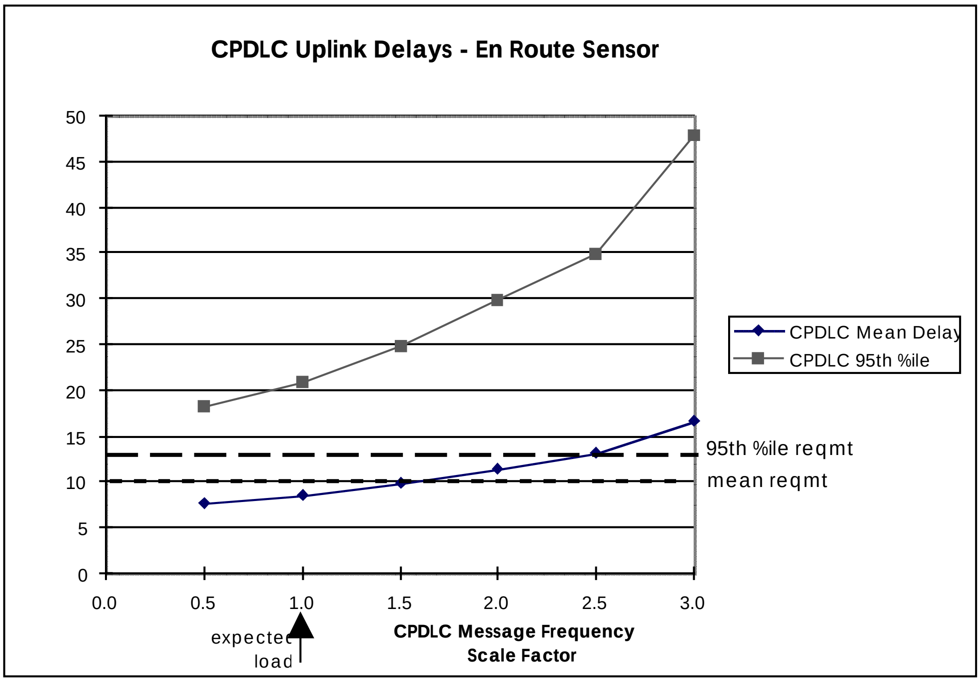
3.2 Sensitivity of Delay to Application Traffic Load

Because the amount of future air/ground data traffic is very uncertain, the simulation was run with varying levels of data traffic to assess the sensitivity of delays. The charts in Figures 1 - 3 show how the mean and 95th percentile delays for ATIS and CPDLC vary with different CPDLC message frequencies. In the real world, message frequencies might be increased not only by more frequent CPDLC transactions but also by the use of Mode S specific services or by the introduction of new ATN data link applications.

The figures show the delay requirements as horizontal dashed lines. For Figure 1, which shows delay with an en route sensor, an arrow points to the expected level of application traffic for an aircraft in en route airspace. In Figures 2 and 3, which show delay with a terminal sensor, an "E" indicates the traffic load for an aircraft in en route airspace, and a "T" indicates the traffic load for an aircraft in terminal airspace.

Figure 1 shows that the mean CPDLC uplink delay will exceed the 10 second requirement if the CPDLC message frequency increases by about 50 percent. The 95th percentile delay increases rapidly as message frequency increases. CPDLC delay increases more rapidly in the uplink direction than the downlink direction because CPDLC downlink messages are small enough to be sent as SLMs. Uplink messages are larger and must be sent as ELMs; therefore, the uplink messages must contend with transport acknowledgments, which are also sent as ELMs. If ELMs were multiplexed, uplink delays would increase less rapidly. Figure 2 shows similar results with a terminal sensor.

Figures 3 shows increases in ATIS delays even though the ATIS message frequency was constant. The increase results from additional queueing behind more frequent, higher priority CPDLC messages.



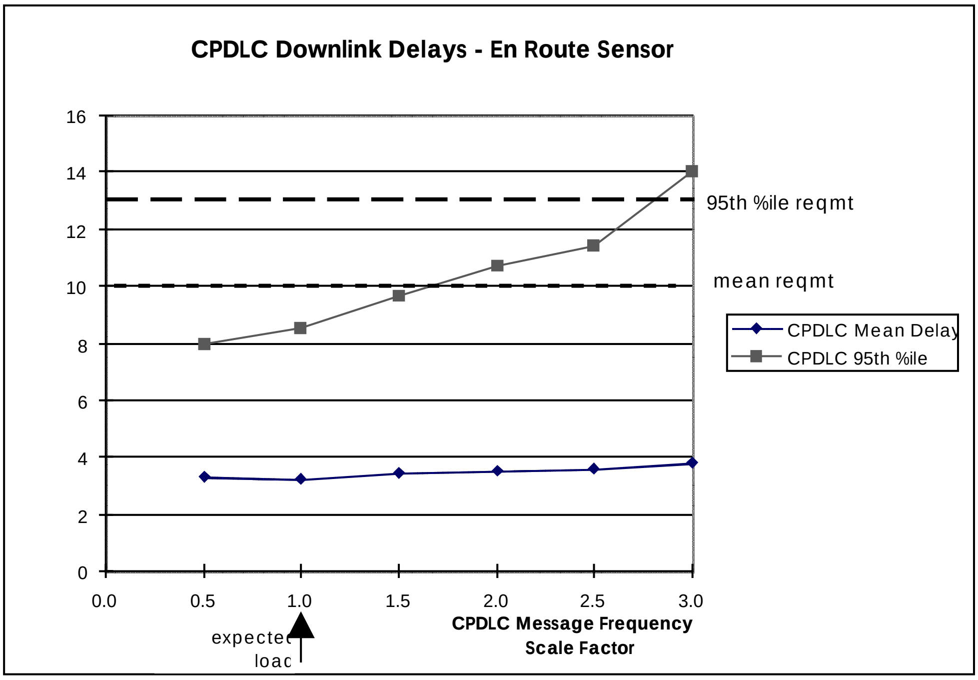
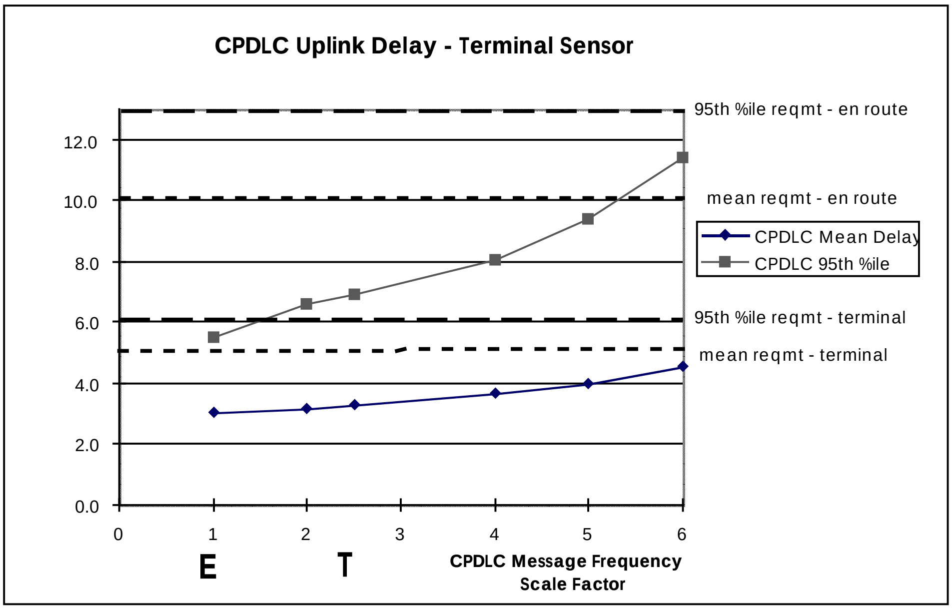
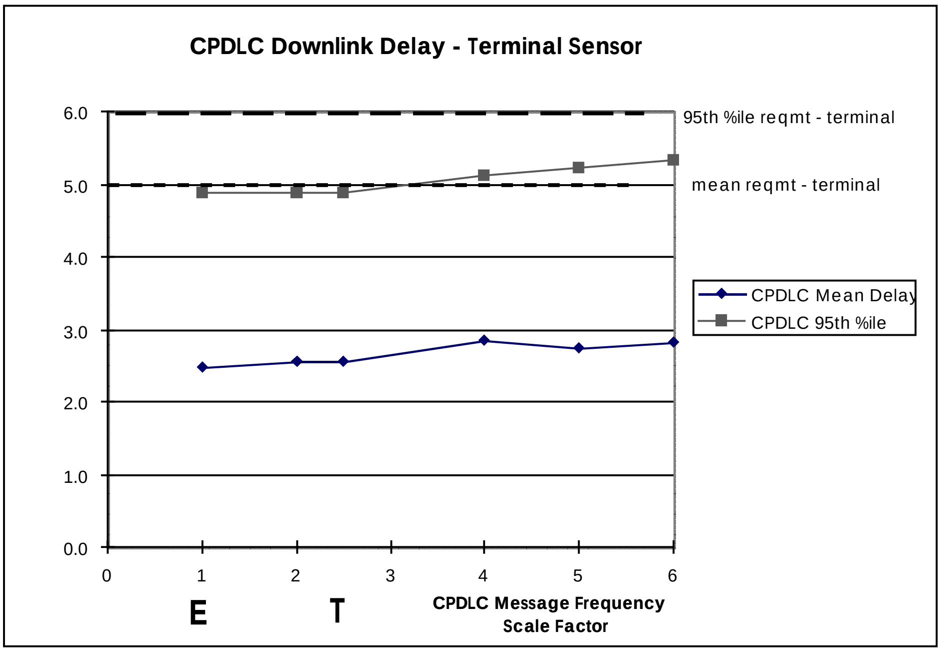


Figure 1. Sensitivity of CPDLC Delay to Mode S Utilization - En Route Sensor



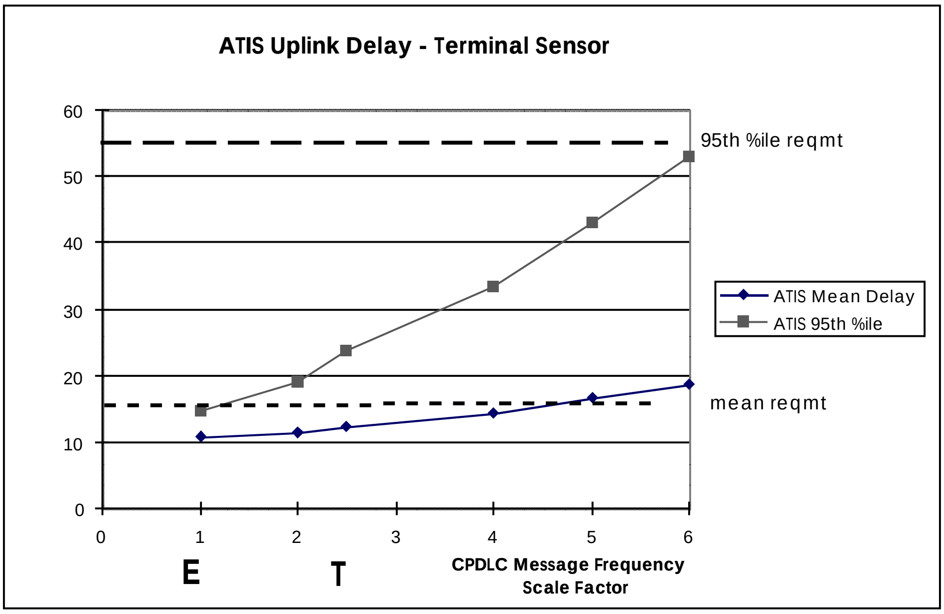


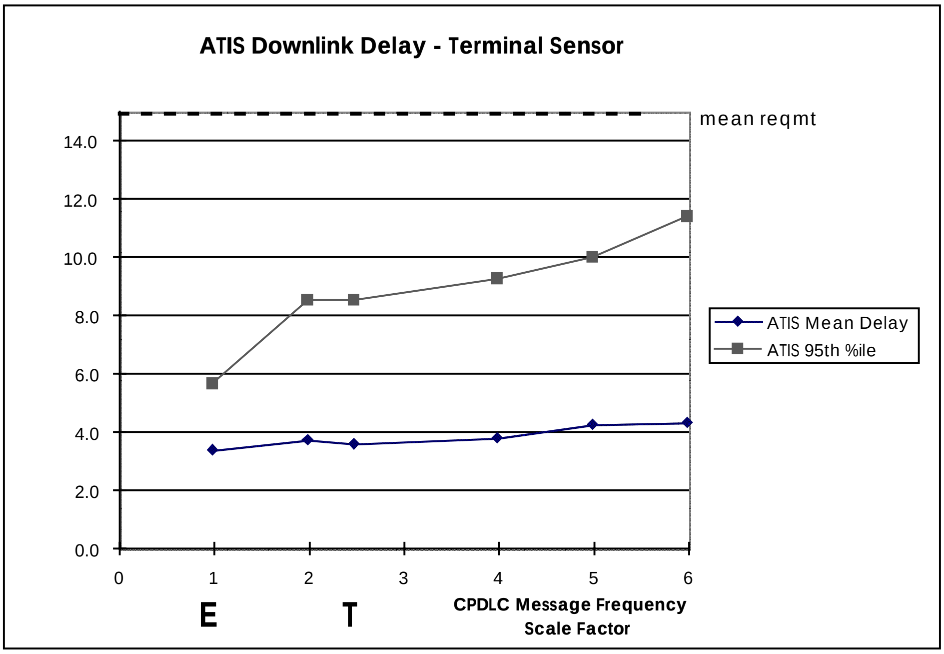
Key:

E: Expected load in en route airspace

T: Expected load in terminal airspace

Figure 2. Sensitivity of CPDLC Delay to Message Frequency - Terminal Sensor





Key:

E: Expected load in en route airspace

T: Expected load in terminal airspace

Figure 3. Sensitivity of ATIS Delay to Message Frequency - Terminal Sensor

4.0 CONCLUSIONS

Most end-to-end delay requirements stated in [1] and [2] can be met with Mode S for the expected message rates. A exception is 95th percentile uplink delay for CPDLC in both terminal and en route airspace.

5.0 REFERENCES

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