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A SIMULATION STUDY OF THE COMMUNICATIONS PERFORMANCE OF THE FEDERAL AVIATION ADMINISTRATION MODE SELECT BEACON SYSTEM FOR AIR TRAFFIC CONTROL

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ABSTRACT

This paper describes a simulation study of the communications performance of the Mode Select Beacon System. The system is an integrated aircraft surveillance and communications system which is being implemented by the Federal Aviation Administration for use in air traffic control in the 1990s. The study was initiated in order to study the interaction of network layer entities within the Mode S system and to quantify the effect of higher layer communication protocols on the performance of the system. In addition, the study investigates the impact of operational scenarios and data transfer techniques on the performance characteristics of the system. Simulation results are used to estimate system behaviour under various air traffic conditions and confirm the suitability of the communications system to the projected air traffic environment.

1. INTRODUCTION

The Federal Aviation Administration (FAA) is upgrading its Air Traffic Control (ATC) system for the next decade and beyond. One of the elements in this plan is the replacement of the existing ATC radar system with the Mode S beacon system. Mode S is a combined surveillance and communications system, the communications part providing a digital data communications called "Data Link". Data Link is to augment the existing voice channels in providing ATC and weather information to aircraft. The resulting system is expected to improve communications performance as well as reduce controller workload.

This simulation study addresses performance concerns and examines the interaction of network layer entities within the Mode S system. This work responds to the need to quantify the effect of higher layer communication protocols on the performance of the system. In addition, some concerns have been raised as to whether the Mode S digital communications channel has a sufficient capacity to operate under the projected traffic load, and as to how the operating environment will affect channel performance. Several paper studies addressing the link capacity issues have been conducted; however, lack of an extensive study of the above concerns leads to the necessity of this work.

This paper describes the model, the simulation assumptions, and the results and conclusions from the study. The focus of the paper is on the effect on performance of a realistic operating scenario. Simulation results indicate that link performance is more than sufficient for the expected traffic environment in the 1990s.

2. SIMULATION PERFORMANCE STUDY

The remainder of this paper is divided into three main sections. Section 2 describes the model, its components, parameters, and measures of performance. Section 3 describes the simulation results and conclusions, and Section 4 discusses the model applications.

2.1 Simulation Model

A diagram of the simulation model is shown in Figure 1. Model components consist of a Ground Data Link Processor (GDLP), a Mode S Sensor, multiple aircraft Transponders and Aircraft Data Link Processors (ADLP), and communication links.

Input to the simulation are packet streams destined for aircraft. Data packets arriving at a GDLP from a source of packets (Higher Level Entity or HLE) are mapped into Mode S subnetwork packets. Control packets are forwarded directly to the frame processor function within the GDLP, while data packets are queued then forwarded to the frame processor based on sliding window handshaking. In the frame processor, packets are segmented into frames and forwarded to the sensor where they are queued awaiting transmission. Since a single sensor communicates with multiple aircraft, the sensor maintains multiple FIFO queues, two for each aircraft. Two queues are necessary with two types of frames, Comm-A and Comm-C, which are transmitted via different protocols. The frames are transmitted to the transponder associated with the target aircraft, and then passed to the ADLP. The frames are reassembled into Mode S packets within the ADLP. The reverse of this operation occurs in the downlink direction.

Two basic types of packet formats are used: data packets and control packets. A data packet contains a virtual circuit number, send and receive sequence numbers, and an M bit (used to indicate multiple packet concatenation) as well as user data. A control packet includes a packet type identifier, a virtual circuit number, and any other information pertinent to its control function. Control packets are necessary for evaluation of the effect of communication protocols on performance of the Mode S link. A sliding window protocol is modeled to evaluate flow control mechanisms implemented in order that a source of packets does not overwhelm a receiving process.

The model includes communication channel management functions. If a logical channel is not established prior to the transfer of a data packet, the opening of a logical channel causes a delay in the transmission of a data packet. This is particularly noticeable in Mode S since the channel establishment sequence cannot take place in one scan of the antenna. The minimum delay to set up a logical channel is two scans (rotations). No activity over a channel for 'Tx' minutes causes the channel to be cleared. The advantage of closing a channel in this manner is a reduction in the amount of buffer space that the GDLP must maintain.

The simulation is implemented using Optimized Network Engineering Tools (OPNET) (OPNET was developed by MIL 3, Inc., 3400 International Drive, N.W., Washington, D.C. 20008)

and run on a SUN 3/160 workstation under the UNIX operating system. OPNET simulations are based on a modeling hierarchy consisting of network, node, and process models. The network level defines the scope of the simulation with nodes and links forming the network. Nodes are defined by OPNET-provided modules such as traffic generators, queues, transmitters, receivers, and antennae. Process models are represented as Finite State Machines (FSMs). An FSM makes use of user-supplied C language code, and a library of OPNET support functions which allow access to packets and network variables.

2.2 Simulation Parameters

Simulation parameters consist of packet arrival rates and packet size distributions. These parameters have been carefully chosen to reflect expected operating conditions, and are described below.

Packet arrival rates are increased from a low to a high rate in order to push the system until it reaches capacity. Interarrival times for packets follow the exponential distribution. The exponential distribution is frequently used for modelling arrivals since it reflects reality well and is also computationally tractable. (Packet service times are deterministic.)

Three different sizes of packets are generated for use as input to the GDLP; short (144 bits), medium (328 bits) and long (1024 bits). These packet lengths are representative of ATC applications currently being developed by the FAA and include user data as well as protocol overhead as estimated in current specifications. A Mode S frame has a fixed data field of 56 bits, and a percentage of these are unused bits when packets are segmented into Mode S frames (14%, 18%, and 2% unused bits for short, medium and long messages, respectively). A packet stream can be made up of a combination of the three packet types uniformly distributed. Four different packet combinations are used in this study as shown in Table 1.

Distributions 1 and 2 were chosen to examine the effect on performance of a single class of packets; distribution 1 uses the Comm-A protocol exclusively, while distribution 2 only uses the Comm-C protocol. Distributions 3 and 4 were selected to be representative of proposed ATC and weather applications; they use both Comm-A and Comm-C protocols.

Table 1. Packet Distributions Used as Simulation Input for Uplink

Packet Distribution Type	% of packet types Short	Medium	Long
1	100	0	0
2	0	100	0
3	34	33	33
4	50	40	10

A scenario was developed to describe operating conditions in the near and medium term. This scenario has 20 aircraft in an ATC sector for a duration of 20 minutes under the control of one Air Traffic Controller. During this time period, a complete set of messages as shown above is uplinked to each aircraft by the Controller (with the exception of the weather message which is uplinked via the weather processor). This scenario results in each aircraft receiving a message about every 5 minutes and, with 20 aircraft in the sector, a message being uplinked every 16 seconds. It is equivalent to an offered load to the Mode S subnetwork on the order of 1 bit per second per aircraft.

2.3 Performance Characteristics

The performance of the system is characterized by delay and throughput, as described below.

Delay is measured as the time interval from arrival of a packet at the GDLP (or ADLP) until receipt of all frames of the

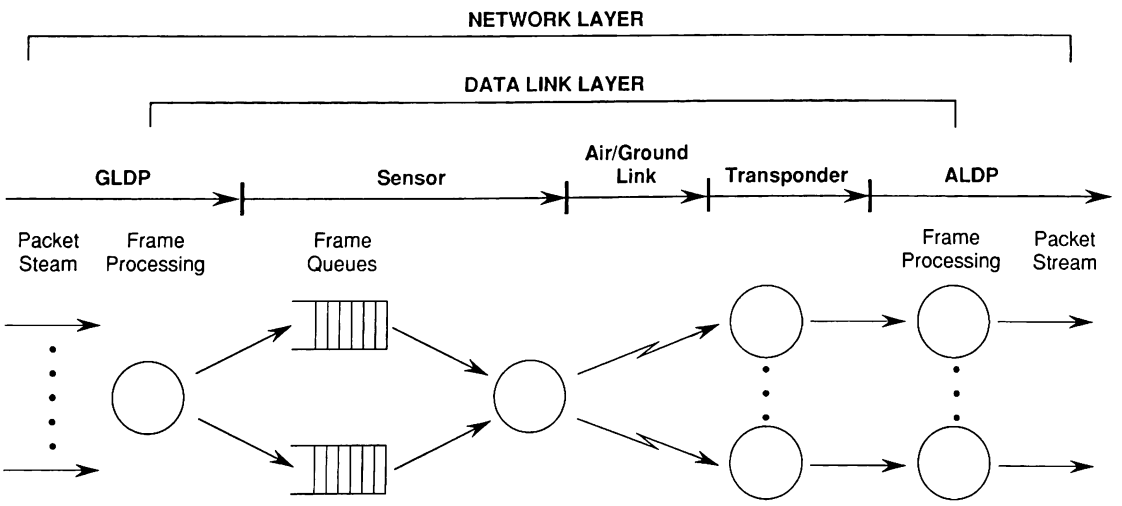

Figure 1. Simulation Model

packet by the corresponding ADLP (or GDLP). It includes processing times in the GDLP, sensor, transponder, and ADLP; propagation delay; and the delay incurred while waiting for the sensor to illuminate the target aircraft.

The evaluation of system throughput is based on the total number of frames, which include both user data and protocol overhead, exchanged between the peer entities of the layer. The throughput characteristic for any aircraft in a beam dwell is specified by an average value.

3. SIMULATION RESULTS AND CONCLUSIONS

Simulation results are given in Figures 2 - 6. Performance variables such as throughput and delay are represented by the mean of their sampled values. Throughput is measured in bits per second and delay times are measured in seconds. Throughput and delay are measured on a per aircraft basis. For simulation accuracy, each simulation is run until the sample size of a measured variable is large enough that its coefficient of variation is smaller than 10%.

Figure 2 plots delay versus throughput for four distributions of uplink messages, for a loading of one to three aircraft in a sensor beam dwell. The delay parameter represents average delay for all messages during a simulation run. The simulation shows that the required near-term throughput is easily achievable and can be exceeded by a factor of 20 to 50 with acceptable delays.

3.1 Variability of Packet Delays

Although average packet delay is an important measure of performance, users of the system are interested in knowing the maximum transit time for data through the system. Thus, there is considerable interest in the variablity packets delays. The table below summarizes the simulation findings. As expected, the higher the utilization of the system, i.e. as throughput increases, the greater the variability in delays for individual packets.

Figures 3 - 5 plot the distributions of the delays for individual packets during 3 simulation runs, with packet distribution type 3 as input and sensor loading of one to three aircraft. These results illustrate the increasing variability of delays as offered load is increased. The delay distributions all have a similar shape, with a large number of observations around the mean, and as the mean delay increases, a greater number of observations in the tail. When the system is not stressed, few observations occur far from the mean. However, as the system becomes saturated, observations far from the mean become more frequent. Table 2 summarizes delay statistics for one to three aircraft with packet distribution type 3 as input.

3.2 Effect on Performance of Network Level Protocols

Since the effect on performance of network level protocols is of concern, the simulation model was used to evaluate the sliding window sizes that have been recommended, as well as the effect of network channel management.

A simulation parameter designed to measure the amount of delay that was introduced into the system due to insufficient buffer space was introduced into the model. This statistic was always zero in these runs, indicating that the sliding window protocol had no effect on performance. Thus, sliding window size as recommended in the system specifications was found to be adequate, and was not found to adversely affect performance.

An investigation was made into the effect on performance of opening and closing channels. On the basis of this analysis, closing a channel according to a fixed timer is not recommended.

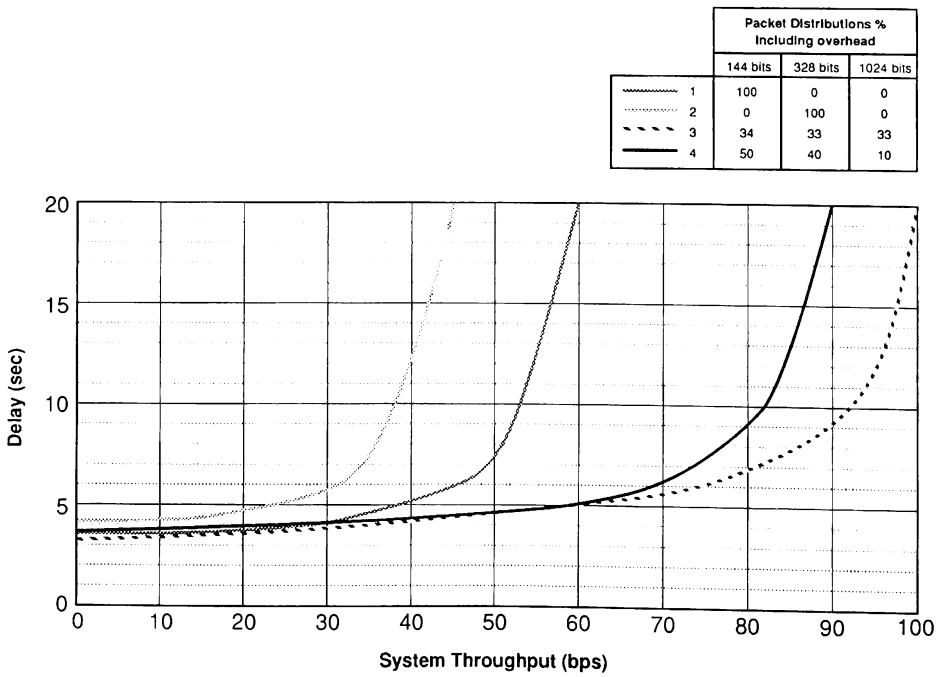

Figure 2. Delay-Throughput Characteristics as a Function of Packet Distributions (Average Throughput) – One and Three Aircraft in a 2.4° Beam Dwell –

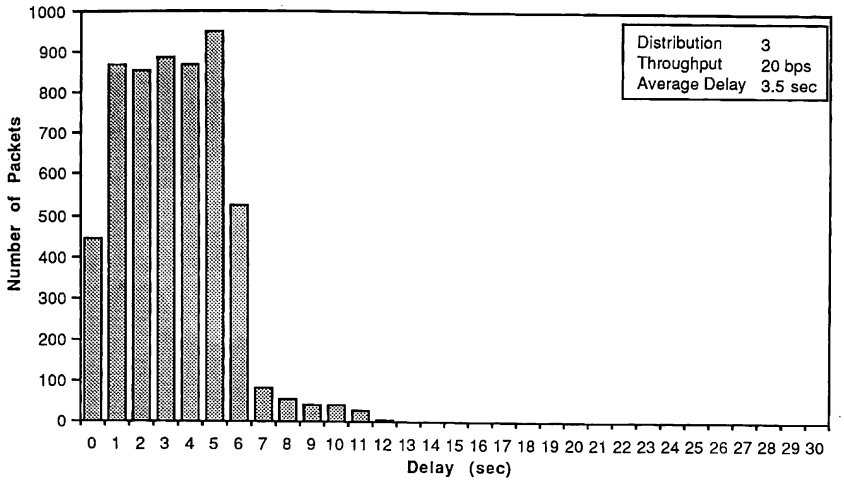

Figure 3. Packet Delays
– Distribution 3, One Aircraft, Throughput 20 bps –

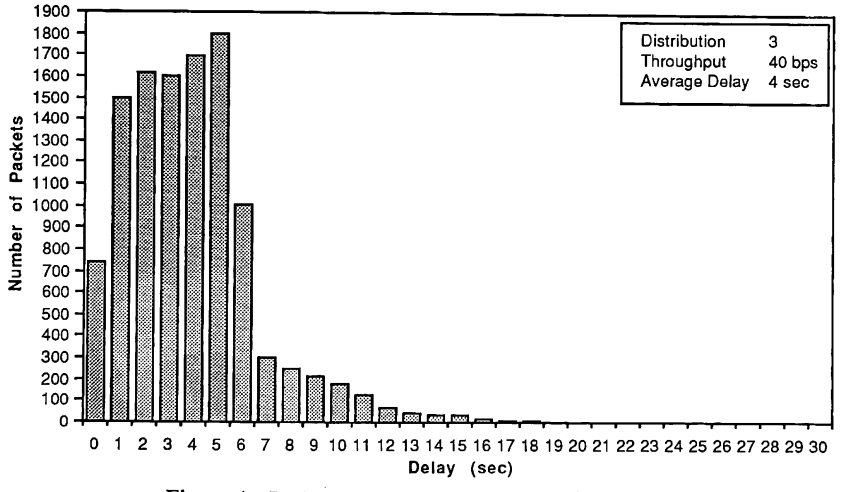

Figure 4. Packet Delays
– Distribution 3, One Aircraft, Throughput 40 bps –

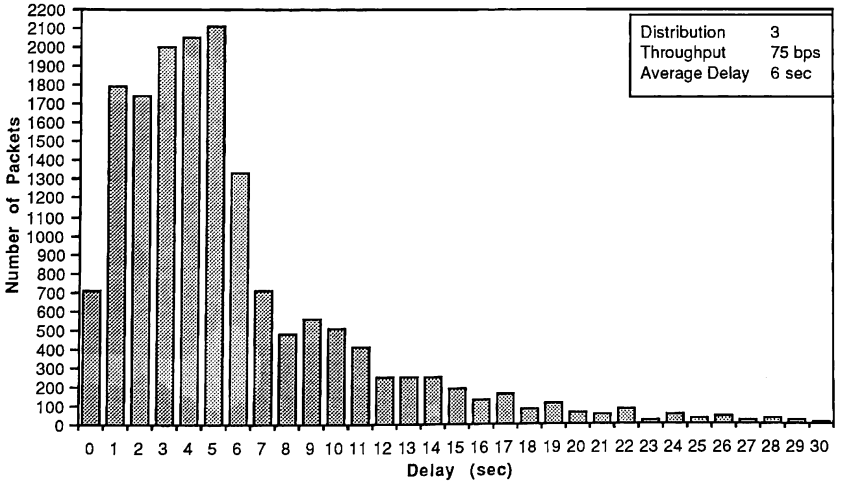

Figure 5. Packet Delays
– Distribution 3, One Aircraft, Throughput 75 bps –

Table 2. Average Delays vs. Percentage of Packets Delivered

Average Delay (secs)	% packets delivered in <= 3 secs	% packets delivered in one scan	% packets delivered in two scans
3.0	57	98	100
3.5	54	95	99
4.0	48	88	98
4.5	45	84	96
5.0	43	79	94
5.5	41	75	91
6.0	39	7	89
6.5	37	70	88

In the near term, expected usage will be low, causing channels to be closed frequently due to inactivity. Long delays may be introduced since messages will have to wait more often for channels to be opened. In the long term, when the GDLP might benefit from the reduced buffer space afforded when using channel timers, the data loading is probably sufficiently high that a channel is never closed (since some activity occurs over the channel).

3.3 Utilization of the Link

The bursty nature of communications traffic and less than optimal message lengths have a significant effect on system performace and make predictions based directly on the Mode S specification unrealistic. The following analysis illustrates the effects of each of these factors on performance in terms of utilization.

Three major factors or assumptions that affect utilization are: (a) packet interarrival times are exponential, (b) not all frames are filled with data, and (c) an ideal mix of 16 Comm-Cs and 8 Com-As for uplink to an aircraft is not usually available.

To illustrate the effect of (a), the simulation was run with input that generated one full 16-segment ELM and 8 full Comm-As at a constant rate of arrival, thus reproducing the maximum amount of data that there would be time to uplink to an aircraft in a beam dwell. This input produced throughput of 287 bps ((16 * 80 bits + 8 * 56 bits) / 6 seconds), which can be thought of as 100% link utilization. The simulation was then run with the same input, this time generated with exponential interarrival times. The resulting throughput was 181 bps, a 63% utilization of the link.

To illustrate (b) and (c), packet distribution type 3 (containing short, medium, and long messages), generated at a constant rate was used as input. The result was a throughput of 106 bps, which represents a 37% link utilization.

Finally, to illustrate the combined effect of (a), (b) and (c), the simulation was run with packet distribution type 3 and exponential packet interarrival times as input. The throughput dropped to 70 bps, representing a 24% link utilization.

It is clear from the above analysis that under realistic operating conditions the link cannot be fully utilized. Arrival rates are not constant and frames will not always contain the maximum possible number of data bits due to the variable length of packets. In addition, an optimal mix of Comm-A and Comm-C frames is not always available.

3.4 Optimization of the Link

An investigation was made of ways in which throughput might be improved. The planned Mode S system maps each individual packet to be sent via the Comm-C protocol into a set of up to 16 Comm-Cs. However, the Comm-C protocol could be

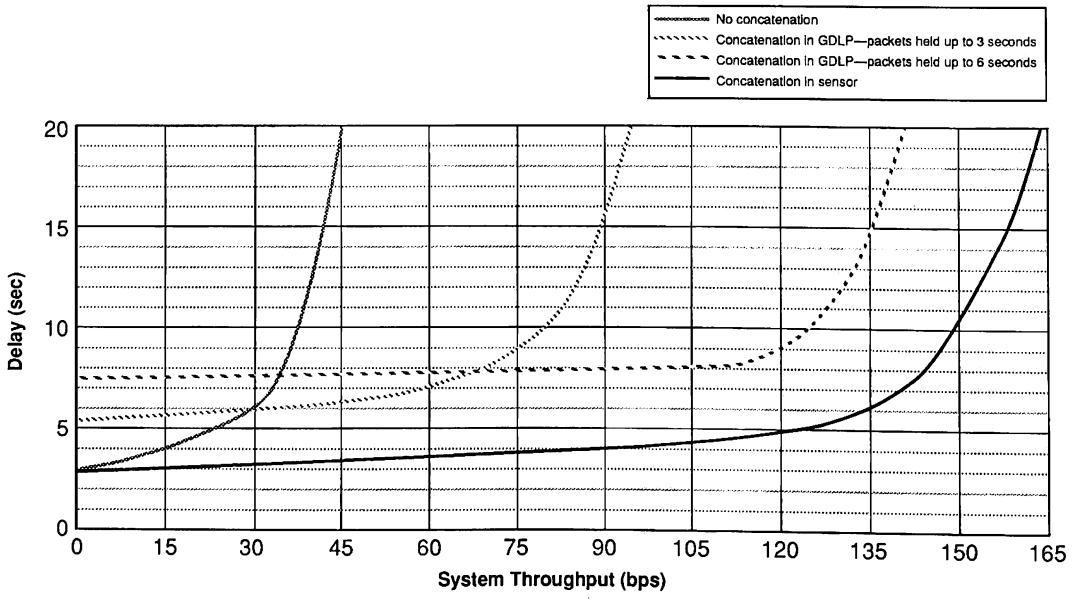

Figure 6. Delay-Throughput Characteristics Using Packet Concatenation (Average Throughput) - One Aircraft in a 2.4° Beam Dwell, Packet Distribution 2 -

used more efficiently if multiple packets (of suitable size) were able to be transferred at one time (for example, a packet segmented into 4 Comm--Cs could be transferred in the same uplink as a packet segmented into 12 Comm-Cs). Two options would allow this concatenation of packets in order to transfer more Comm-Cs in one uplink.

The first option, concatenation within the GDLP, is simple to implement. It assumes a small amount of additional logic in the GDLP and ADLP. Packets are held in the GDLP for a maximum time in seconds or while their combined length is less than 1280 bits (16 Comm-Cs). They are then forwarded to the sensor in the normal manner. The disadvantage of this method of concatenation is the additional delay of up to that maximum time that may be incurred.

The second method for concatenation can be implemented within either the GDLP or the sensor. It does not incur any additional delay but assumes that aircraft tracking information is available. Using track information, the GDLP or sensor can concatenate Comm-Cs for uplink to an aircraft until just before interrogation of that aircraft is scheduled. This method has the advantage of introducing no extra delays but at the expense of more complexity.

Concatenation requires an additional byte of network level protocol overhead to represent packet length. This enables the ADLP to reconstitute packets from a number of Comm-Cs that may correspond to more than one packet.

Figure 6 plots delay versus throughput for each of the concatenation schemes compared with no concatenation. The graphs show results for one aircraft in a beam dwell using packet distribution 2, all Comm-Cs.

As expected, packet concatenation provides better throughput. This improvement is most noticeable for packet distribution type 2 which consists of relatively short packets that must be sent using the Comm-C protocol.

The figures illustrate both the advantages and disadvantages of these optimization methods. It can be seen that, while throughput is increased by concatenation in the GDLP, delays are always greater than one scan. Concatenation in the sensor does not introduce additional delays and improves throughput significantly.

3.5 Conclusions

In summary, the simulation yields the following results:

- First, the capacity of the Mode S data link will support the projected operating scenarios. Traffic loading in the near term is predicted by the FAA to be on the order of one message every 5 minutes per aircraft. This is calculated from the initial applications that are planned to replace current routine voice messages such as Transfer of Communication and Altitude Assignment and which occur on a predictable basis. The throughput achieved in the simulation is more than adequate for this load.

- Second, the flow control window sizes as recommended in the ADLP MOPS are adequate and do not adversely affect throughput or delay.

- Third, channel closing based on timer values is not recommended.

- Fourth, utilization of the link is greatly affected by bursty traffic and "non-optimal" packet lengths.

- Fifth, variability of individual packet delays increases greatly when the offered system load produces average delays of greater than one scan.

- Lastly, packet concatenation achieves a higher throughput by more fully utilizing the Comm-C protocol.

4. MODEL APPLICATIONS

The simulation findings will help the FAA to determine at what level of throughput they can operate in order to achieve the desired delay. Delay is an important consideration in the ATC environment since some messages are time critical and must reach their destination quickly. For certain applications, especially ATC, a delay of more than a few seconds is not desirable. However, for some non-critical applications such as weather, a longer delay can be tolerated.

Considerable work has been done to predict the amount and nature of air traffic in the next decade. Results from this study indicate that the system as designed is sufficient for projected needs in the near term. However, new applications for Data Link will be developed. Some applications may be automated and thus be used more frequently. It is therefore recommended that estimates be made of projected Data Link loading when a new application is proposed. Delays can be predicted based on estimated loading, and future procurements of Mode S Data Link equipment can be modified accordingly.

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