Air Traffic Control Improvement Using Prioritized CSMA

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Abstract—Version 7 simulations of the industry-standard network simulation software "OPNET" are presented of two applications of the Aeronautical Telecommunications Network (ATN), Controller Pilot Data Link Communications (CPDLC) and Automatic Dependent Surveillance-Broadcast mode (ADS-B), over VHF Data Link mode 2 (VDL-2). Communication is modeled for air traffic between just three cities. All aircraft are assumed to have the same equipage. The simulation involves Air Traffic Control (ATC) ground stations and 105 aircraft taking off, flying realistic free-flight trajectories, and landing in a 24-hr period. All communication is modeled as unreliable. Collision-less, prioritized carrier sense multiple access (CSMA) is successfully tested. The statistics presented include latency, queue length, and packet loss. This research may show that a communications system simpler than the currently accepted standard envisioned may not only suffice, but also surpass performance of the standard at a lower cost of deployment.

1. INTRODUCTION

Due to a lack of surveillance and communications coverage, in many parts of the world, aircraft are forced to fly routes and maintain separations that are inefficient from both a fuel and scheduling perspective. The total loss to airlines due to these inefficiencies is measured in billions of dollars [1]. The problem is expected to rapidly mushroom given the expected user demand for scheduled air service. The Advanced Air Traffic Technologies (AATT) Program has been instituted to develop new technologies that enable free-flight, an operating system in which pilots have the freedom to select their path and speed in real-time [2].

To implement free-flight, two applications are viewed as very important for the new aeronautical communications infrastructure: ADS-B will provide future surveillance capability, and Controller Pilot Data Link Communications (CPDLC) will eliminate voice-only communications.

The Internet has been very successful in terms of providing self-healing global connectivity for heterogeneous communications nodes. Engineers look favorably upon successfully working systems that have stood the test of time as foundations upon which to build new systems, which will hopefully enjoy equal success. Now we seek to have the convenience and connectivity of the Internet in the aerospace environment. The idea is prevalent that with some minor modifications, we will have the Internet in the sky as well. However, currently engineers are very good at building terrestrial networks. The cost and complexity involved in implementing the aeronautical Internet is staggering, and would slow its deployment. This paper pursues the idea of implementing that convenience and connectivity without the cost or complexity of extending the Internet in an aerospace environment. In the simulations of this paper, realistic air-to-air, ground-to-air, and air-to-ground communications are achieved by assuming an effective, intact terrestrial network and by treating planes as traffic generators and sinks, in a manner analogous to the transparent usage of a traffic injector or "sniffer" in a network. Further, the idea of prioritized CSMA is introduced and successfully tested through simulation. Prioritized CSMA trades off the use of an additional radio frequency in order to implement efficient CSMA without collisions. The benefit gained of efficient, collision-less CSMA is that the inefficiencies introduced by wasted time division multiple access (TDMA) time slots may be avoided.

2. Simulation Focus

The primary focus of the simulations is to examine the behavior of air traffic control (ATC) communications and surveillance over VDL-2 in a realistic aviation scenario. Both weather and terrain were ignored, and the simulation assumes a perfectly spherical earth. Multipath communication is not implemented in this OPNET simulation so two nodes may communicate only when they are in line-of-sight. So extending the range of ground stations by bouncing signals off of the ionosphere is not permitted here. The air traffic between only three cities was simulated to bound the scope of this six-month research project. As an excellent starting point for predicting gravitational effects, physicists model the earth as a point mass. An analogous approach is taken here. Since the media access layer (MAC) layer is especially important in LANs, largely determining the limit of performance, heavy emphasis was placed upon the data link layer, VDL-2. Likewise, these simulations do not model the presentation, session, transport, or network layers, nor do they need to. Perhaps the most important use of these simulations is to test prioritized CSMA. The use of the simulations to test this new idea also enables us to study the upper bound for the performance of VDL-2 with the same given traffic.

3. Simulation Overview

As previously stated, the simulation involves 105 flights, 35 ATC transceivers or ground stations, and 3 airports. The take off, arrival, and flight times for one day were based on real flight plans obtained from the airports. Instead of actually modeling the fact that one plane may make several flights, a separate OPNET mobile airplane node is used for each flight. For reasons discussed later, CPDLC and ADS-B messages in these simulations have a 5,000 bit mean file size. CPDLC file sizes are chosen according to the normal distribution. CPDLC messages have a mean inter-arrival time of 6 min, according to the Poisson distribution. ADS-B messages have a constant inter-arrival time of 1 sec. All CPDLC transceivers operate at 136 MHz with a 10 KHz bandwidth. All ADS-B transceivers operate at 137 MHz with a 10 KHz bandwidth.

Message Length

Although 5,000 bit message lengths are somewhat excessive for CPDLC messages, they were chosen so that the effects of message collisions could be better studied given the unusually low amount of aeronautical communications traffic present in these necessarily bounded simulations. Given that ADS-B messages are meant to convey a coordinate triple of high precision numbers as a position and possibly up to 9 other coordinate triples for intent data, 5,000 bits may not be unrealistic for ADS-B message length.

Ground Stations

An interview with the FAA indicated that the maximum range of the Cleveland Hopkins air traffic control tower is ~20 miles. The ATC tower at Hopkins is ~100 m in height. It is assumed for the simulation that typical VDL ground stations are no taller than 100 m. For a tower 100 m in height, the horizon is ~22 miles away. Since they cannot be expected to see beyond the horizon, a spacing of 20 miles between ground stations is used in the simulation.

Let $d(X,Y)$ be the distance between X and Y. Then $d(\text{Detroit, Cincinnati}) \approx 256$ miles, $d(\text{Detroit, Cleveland}) \approx 168$ miles, $d(\text{Cincinnati, Cleveland}) \approx 243$ miles. In the simulation there are 13 ($\approx 256/20$ mile) ground stations between Detroit and Cincinnati, and also between Cincinnati and Cleveland. There are 9 ground stations between Detroit and Cleveland. The presence of an additional ground station or air traffic control tower at each airport gives a total of 38 ground stations. The ground stations are approximately equally spaced on the straight line joining each city.

The ground stations are capable of detecting the presence of a plane and only send CPDLC messages if there is a plane in range to receive them. The ground stations are coordinated and produce no uplink interference.

Details

The Cleveland airport is initially stocked with 34 planes, which will take off for either Cincinnati or Detroit during the course of the 24 hr simulation. Each ground station, including air traffic control towers, consists of a CPDLC transmission node, a receiver node and a later to be discussed connection transmitter (cnctrans) used to implement prioritized CSMA. Each airplane has identical communications architecture except for the addition of an ADS-B receiver and transmitter. So ADS-B surveillance is simulated only for aircraft to aircraft. Likewise, CPDLC exists only between aircraft and ground stations. The ADS-B transmission node architecture is shown in Fig. 1. The CPDLC node architecture is not shown, but is identical except that no count processor module is present in it.
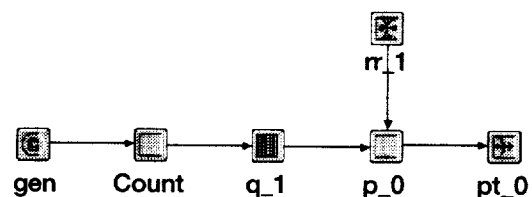

Figure 1.—ADS-B node architecture.

In Fig.1, "gen" is a clocked generator of packets. "Count" counts the total number of ADS-B packets generated in a short period. "q_1" is a queue to buffer the packets. "p_0" is a processor module which decides whether to leave the packets in the queue or to forward them on to the radio transmitter through pt_0. "rr_1" is a receiver of cnctrans packets, information from which p_0 uses for its decisions.

Based on research, trapezoidal flight trajectories were used. A cruise altitude of 25,500 ft was used with an ascent rate of 6.49 m/s.

The histogram, in Fig. 2, of the number of planes in flight, as a function of simulation time is based on the actual data from the airports and is not an output of simulation. Simulation results will be compared with this histogram.
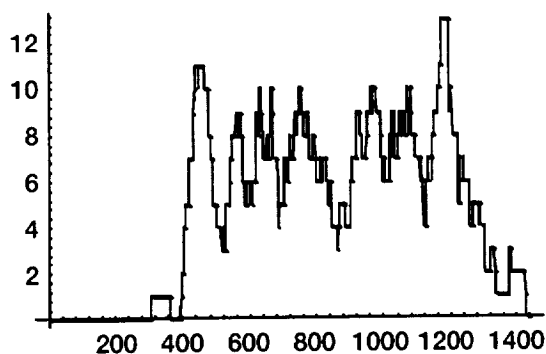

Figure 2.—Planes-in-flight histogram.

From the airport data, the average number of planes flying is 4.66806. So the expected number of CPDLC messages is 4.66806 (1440/6) $\approx$1,120, where 1440 is the number of minutes in a day. The peak traffic is at (60 s/min) (1200 min) = 72,000 s or 20:00 (8 p.m.).

4. CSMA DISCUSSION

A single communications frequency is used for radio frequency conservation. Just as in CB radio, one party communicates at a time. But as east coast truckers may talk to their east coast neighbors while west coast truckers may simultaneously talk to their west coast neighbors—on the same frequency as their east coast counterparts—without interference, so in the simulations here, different line-of-sight groups can communicate on the same frequencies simultaneously without interference.

CSMA is contention-based. All parties listen to the channel. When the channel is free, many parties contend for it until after a random back-off time. Eventually, one party gains control of the channel for uninterrupted usage. Because of the contention process, collisions can be inefficient.

5. PRIORITIZED CSMA

In prioritized CSMA, each communications party is assigned a priority for transmission, based on its need to transmit. In these simulations, the need to transmit is effectively measured by the length of a party's or node's transmitter queue, which is broadcast on a separate frequency to all neighboring nodes. In the event of a tie in transmitter queue lengths, the simulation kernel will arbitrarily choose one node to transmit; this occurrence is infrequent. When the channel is free, instead of a random back-off time elapsing before one node gains usage of the channel, in prioritized CSMA, the node with the next higher priority begins uninterrupted transmission immediately in an orderly fashion, without contention. By choosing to study prioritized CSMA, we simultaneously accomplish two purposes. We can test this new idea and also obtain the upper bound for performance of VDL-2 with the given traffic of the simulation. Because of its random back-off time, VDL-2 should not perform as well as prioritized CSMA.

Details

As previously mentioned, both planes and ground stations include a cnctrans transmitter. This transmitter broadcasts cnctrans packets at regular intervals. In the simulations, the packets are of length zero and contain the unique source identification code (srcid) of the transmitting node. They also contain a time stamp and the queue length of that node. When a node receives a cnctrans packet, it updates an array of queue lengths from its neighbors. If a cnctrans packet has not been received from a node in Δt, it is assumed unreachable. When a node seizes the channel, all nodes wait until it is finished. Each node waits until the farthest neighbor of the last transmitting node has received the transmission. When the transmission is finished, the next node begins orderly transmission. The cnctrans packets do not collide since they are small and each node is assigned a unique phase lag with which to broadcast them.

6. SIMULATION RESULTS AND ANALYSIS

Results

There were four simulation runs, which either used or did not use prioritized CSMA, and which either used transceivers and queues with data rates and service rates of 31.5 Kps or 1.544 Mbps:

I: no CSMA, 31.5 Kbps, [3]
II: no CSMA, 1.544 Mbps
III: prioritized CSMA, 1.544 Mbps
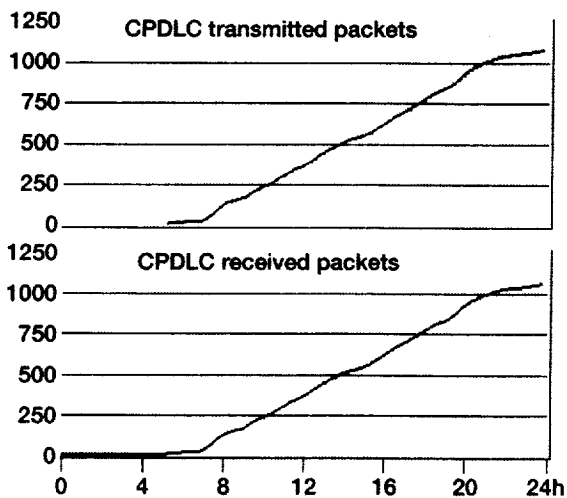IV: prioritized CSMA, 31.5 Kbps.

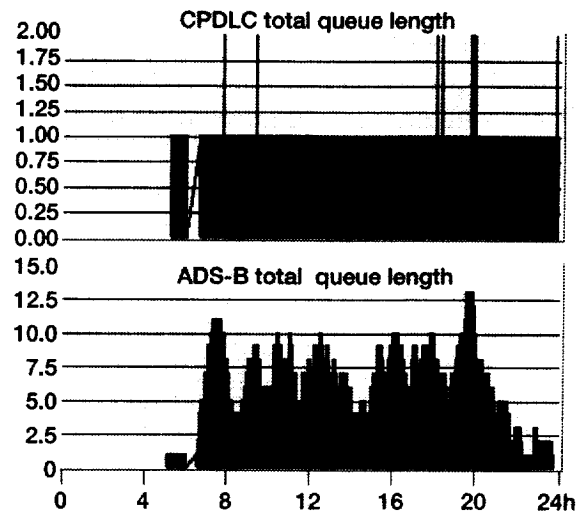Figure 3.—CPDLC transmitted and received packets.

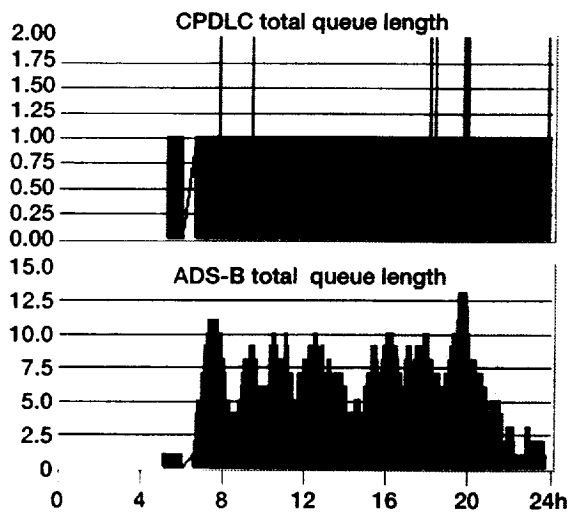

Figure 5.—Total queue length, Run II.
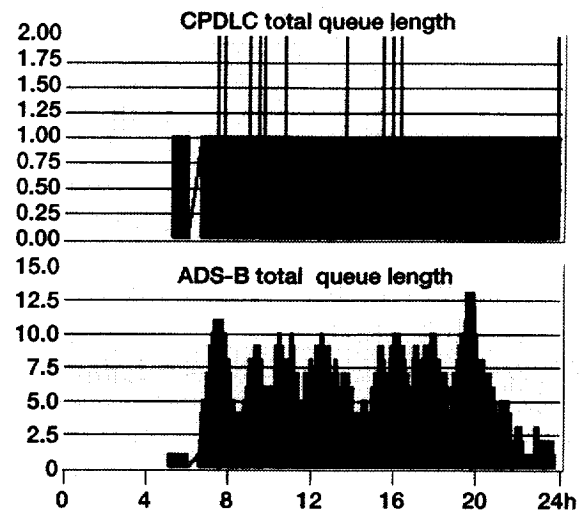

Figure 4.—Total queue length, Run I.

Figure 6.—Total queue length, Run III.

The number of CPDLC messages received per transmitted for each of the Runs I to IV is respectively (1,067/1,077), (1,048/1,066), (1059,1060), and (744,744). Plots of CPDLC transmitted and received packets for Run I are shown in Fig. 3. The other three plots are similar and have been suppressed since they convey no additional information. It seems impossible to determine the final number of packets transmitted and received from the plots. Therefore, the spreadsheet of their values was used to determine those final numbers.

Only the runs using prioritized CSMA successfully transmitted all CPDLC packets without collisions. These results show that this implementation of the idea of prioritized, collisionless CSMA works.

Figure 4 shows that an OPNET plot of ADS-B packets generated per time unit versus time is virtually identical in shape to Fig. 2. Since, in the simulations, a plane does not
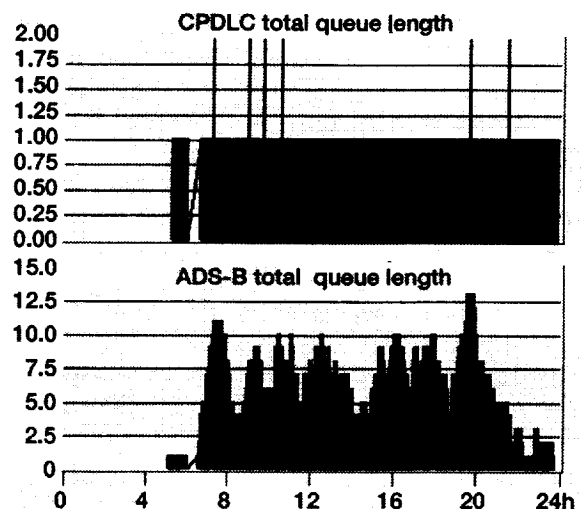

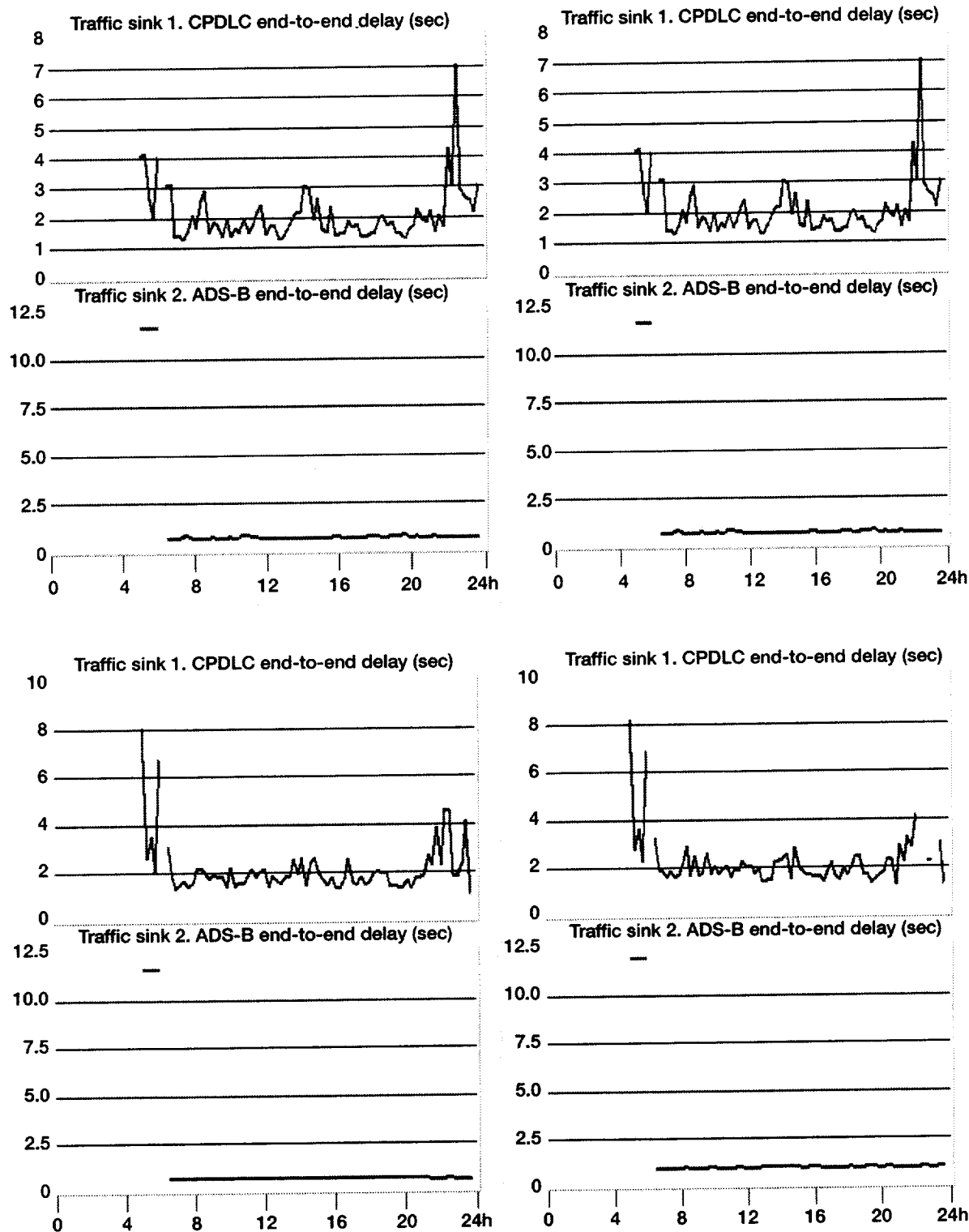Figure 7.—Total queue length, Run IV.

Figure 8.—CPDLC and ADS-B ETE delay versus time for Runs I-IV.

generate ADS-B packets until it takes off, the conformity of these plots shows that the ADS-B packet generators are functioning correctly and suggest that the copious take off and landing times were correctly input into the OPNET mobile nodes. In Figs. 4 to 7, plots of ADS-B queue lengths also exhibit this same conformity. The total queue length is the sum of the lengths of all CPDLC or ADS-B queues.

Figure 8 shows plots of CPDLC and ADS-B end-to-end delay versus simulation time for Runs I to IV. Figure 9 shows plots of the time average of CPDLC and ADS-B end-to-end delay versus simulation time for Runs I to IV.
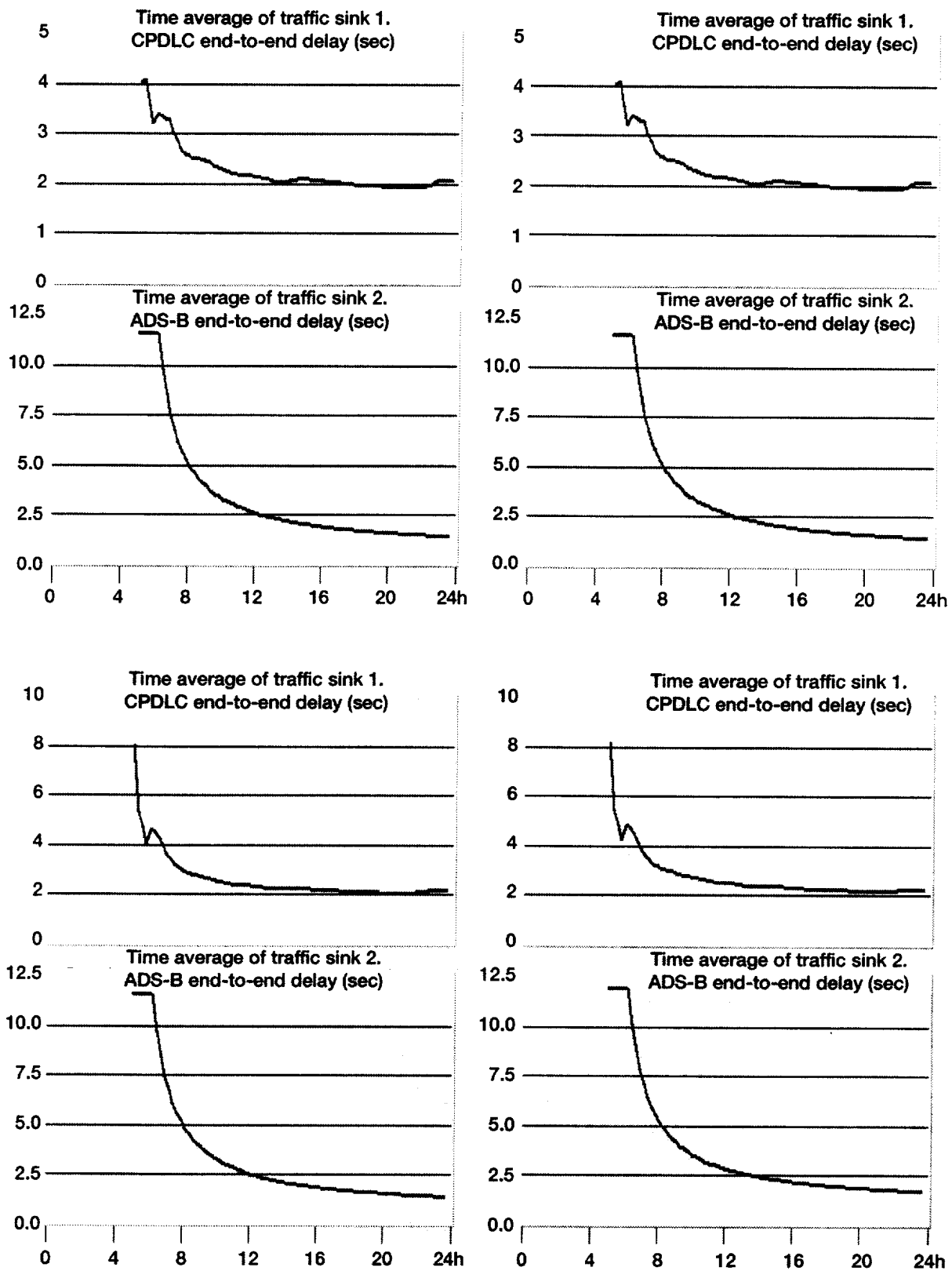
Figure 9.—Time average of CPDLC and ADS-B ETE delay versus time for Runs I-IV.

Analysis

The excessive startup delays are accounted for by a transient glitch in the simulation. Runs III and IV show that as the data rate of the transceivers and service rate of the queues increase, prioritized CSMA works better. Also, the large spikes towards the end of the CPDLC plots—for all runs—suggest a problem with using the normal distribution with a small mean packet size. In that case, the distribution would be very skewed above the mean, resulting in a large number of packets of greater sizes towards the end of the simulations.

7. CONCLUSIONS

One thing is obvious from a comparison of Runs I and II with III and IV: prioritized CSMA works. Prioritized CSMA would serve the same purpose for aeronautical communications traffic as the traffic light would for automobile traffic—to prevent collisions.

Although there was no bearing on this simulation, it appears as though the cnctrans packets may not contain enough information to determine priority. They should include a wait time so that a node is conferred a higher priority as it is delayed in transmission.

In the event that it is critical to receive messages without many retransmissions, prioritized CSMA may be very useful. Acknowledgements and retransmissions increase the amount of traffic, increasing the number of collisions and worsening communications throughput.

It appears as though this method could be used to obtain an upper limit for the performance of CSMA or as justification for further research into the use of prioritized CSMA. Plans are underway to improve this simulation and to use it as the basis for future research.

The simulation of communication was effected without the complexity involved in the aeronautical telecommunications network. Since planes merely need to access or "sniff" data on the ATN, and also to inject data onto the ATN, the author believes that a custom solution for aeronautical communications is more appropriate and effective than attempting to force the functionality of the Internet in an aviation scenario—potentially involving satellite communications with the concomitant delays involved. The problems involved with having mobile routing with periodic signaling or "hello" packets seem more difficult than to simply design ground stations of sufficient functionality and distribution.

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[1] Final Report of RTCA Task Force 3 on Free Flight Implementation, October 26, 1995.

[2] Tekla S. Perry, "In Search of the Future of Air Traffic Control," IEEE Spectrum, August 1997.

[3] Tekla S. Perry, "Tracking Weather's Flight Path," *IEEE Spectrum*, September, 2000.

BIOGRAPHY

Daryl C. Robinson received his BS in Mathematics from Case Western Reserve University (CWRU), MSEE from Cleveland State University, and is pursuing his Ph.D. in Computer Engineering from CWRU. Currently he is performing research for the AATT program. He has expertise in mathematical modeling and simulation and in his spare time enjoys reading and writing thoughtful literature.

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