MODELING OF AIR/GROUND AIR TRAFFIC CONTROL COMMUNICATIONS FOR FAST-TIME SIMULATION

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ABSTRACT

A fast-time simulation model of air traffic in the National Airspace System (NAS), developed by the Center for Advanced Aviation System Development (CAASD) of the MITRE Corporation, has been used over the past several years for capacity and delay analyses. Prior to the effort documented in this paper, this model did not explicitly account for the communications events that transpire, and the related communications messages that would ensue, as the simulated aircraft are moving through the NAS. The model did account for overall controller workload,, which incorporates communications workload, in an abstract sense. In order to properly engineer current and future air/ground (A/G) communications systems, it is necessary to explicitly quantify the communications traffic that those systems support. This paper describes the capability added to the simulation model during fiscal year 2005 (FY2005) to identify communications message triggering events, and to generate the appropriate voice or data communications messages. This work was facilitated through the MITRE Sponsored Research (MSR) Program of the MITRE Technology Program.

Keywords: Air/Ground Communications, ATN, Air Traffic Control, CPDLC, Fast-Time Simulation

1.0 INTRODUCTION

In order to effectively plan an A/G communications system for the NAS, it is important to have the capability to quantify the distribution of A/G communications transactions over different geographical locations over a typical day. This paper describes the work to provide an existing fast-time simulation tool of the NAS the capability to trigger and quantify A/G communications transactions.

2.0 BACKGROUND

The simulation model uses discrete event techniques to simulate the flow of aircraft in the NAS, and is used for capacity and delay analyses. Figure 1 shows a high-level diagram of the simulation model, with the new communications capability added during FY2005 highlighted with bold italics.

The inputs to the simulation model are data related to flights, such as aircraft characteristics, and the sectors, airports, and fixes that the aircraft encounter as they fly from origin to destination. The simulation model provides user options to customize flight details, sector and airport capacities, and other parameters affecting system performance.

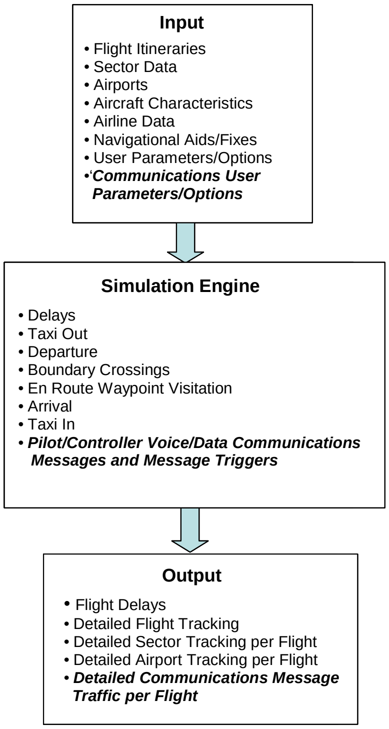

Figure 1. Model High-Level Description

Prior to the research documented here, the A/G communications events that transpire and the related communications messages that would ensue, as the simulated aircraft are moving through the NAS, were not explicitly accounted for by the model, but were accounted for by the model in an abstract sense in determining

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overall controller workload, of which communications is one contributing factor. The FAA is currently examining different technologies to support a future A/G communications system. One of the features under consideration for the future system is a data-link capability, to be used for air traffic services. Currently all A/G air traffic services are provided as voice in the non-oceanic NAS[1]. Providing selected air traffic services by means of data is expected to reduce congestion on the communications channel and also to reduce controller workload. In order to model the effects of data link, it is necessary to compare the amount of channel congestion and controller workload with and without data link. This requires the ability to explicitly quantify the amount of communications traffic of different types during different times of the day in different geographic areas. Figure 2 shows a high-level depiction of the use of the model for the purpose of quantifying A/G communications. The desired end-state model would be able to quantify A/G communications transactions for any Air Traffic Control (ATC) paradigm and for any communications system (reflecting their application, network, and subnetwork characteristics). This FY2005 MSR effort was an initial attempt along the way towards the end state, and has provided the model with the capability to identify communications message triggering events, and to generate basic voice and Controller-Pilot Data-Link Communications (CPDLC) data-link messages[2]. Although there are different data-link protocols that can be considered, during this past fiscal year, only the Aeronautical Telecommunications Network (ATN) Open System Interconnect (OSI) protocol [1] was added in detail to the model.

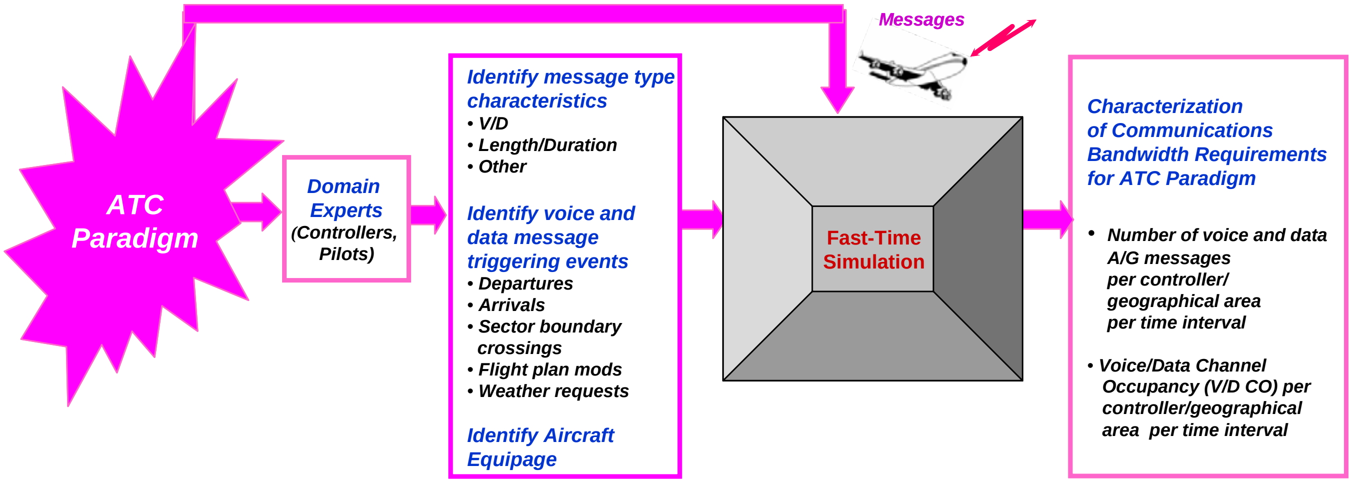

Figure 2. Proposed Use of Communications Capability

3.0 APPROACH

A/G communications between a controller and a pilot take place as a result of events that aircraft encounter from prior to departure from one airport to arrival at the gate of the destination airport. These events are called *communications message triggering events.*

This FY2005 MSR effort provided the simulation model with the capability to identify basic communications message triggering events and to generate the ensuing number of messages of the appropriate types and the communications load, for example, for a communications channel or a controller team. In order to determine communications loading, the size in bytes for data messages, and the channel occupancy for voice messages must be provided. Thus, two major efforts, in addition to other efforts described in this paper, were required just to provide the simulation model with a basic communications message generation capability: developing the capability to identify communications message triggering events, and developing a basic set of messages associated with each triggering event. De-identified transcriptions for voice recordings for Denver Center (ZDV), Fort Worth Center (ZFW), and Atlanta Center (ZTL) were available; they were used for determining voice message duration probability distributions, frequency of occurrence, and other statistics for different message types. An analysis was conducted as part of this MSR effort, and documented in reference [2]. A limited range of sectors

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[1] Data link for certain air traffic services is provided in oceanic airspace for properly equipped aircraft, and is called Future Air Navigation System -1/A (FANS-1/A), which has not been standardized through the International Civil Aviation Organization (ICAO).

[2] CPDLC is an automated application that supports the delivery of ATC operational services by means of data link, and is currently implemented under FANS-1/A.in oceanic airspace. Trials for implementing it in CONUS airspace over an ICAO-compliant system were conducted in Miami from 2002 – 2004.

in ZDV, ZFW, and ZTL are the only cases for which voice tape transcriptions were available at the time of the analysis, and thus the statistics documented in reference [2] are used in the simulation model for the other sectors and centers. Ongoing research in CAASD is concluding that variation in workload across sectors makes it hard to extrapolate from a limited sample set [3]. As the relationship between sector type and communication workload is better understood, and more transcription data is obtained, application of the conclusions of the voice tape analysis across NAS sectors will be updated.

Several sources of information of data message sizes are available for both the ATN OSI [1] and the ARINC 622 protocols [4], although only those for ATN OSI were developed and incorporated during this year’s effort. A mapping of message types from the various sources of information to communications triggering events was performed, and incorporated into the model.

4.0 COMMUNICATIONS MESSAGES

Table 1 shows a comprehensive list of the communications messages that are accounted for in the model. This list can be partitioned into five categories. The first category applies only to aircraft engaged in data communications, and contains messages related to the aircraft logon process. In the model this event takes place as soon as a pushback event for the aircraft occurs. The second category accounts for the messages that take place when the pilot must change frequencies (called a transfer of communications [TOC]) and effect an initial contact (IC) with the controller team using the next frequency. This combination of TOC and IC is referred to as a “handoff.” This occurs when an aircraft transitions from the control of the Airport Traffic Control Tower (ATCT) to the Terminal Radar Approach Control (TRACON) for departure, or vice versa upon arrival for landing, or when the aircraft crosses an airspace (terminal area, sector, or center) boundary. Regardless of where the handoff occurs, the voice communication that takes place is similar. For data communications, the type of boundary crossed does make a difference. As Table 1 shows, there are four different types of boundary crossings: TRACON-to-center, which occurs when an aircraft leaves the terminal area and enters the first en route sector; sector-to-sector within the same en route center’s airspace, as for example, when an aircraft crosses from one sector in ZDV (Denver) airspace to another sector also within ZDV airspace; center-to-center, as for example, when an aircraft crosses from ZDV airspace to ZLC (Salt Lake City) airspace; and, finally, center-to-TRACON, when an aircraft enters the terminal area and is directed to an airport runway for landing.

The third message category includes status and advisory messages that a controller provides to a pilot. The fourth message category includes those clearances initialed by the controller for tactical purposes, such as instructing the pilot to change altitude, heading, speed, etc. The fifth message category include pilot requests for changes in altitude and route. For the third through fifth message categories, there were no events or constructs in the model to identify when these messages should occur.

The following sections describe how triggers for these various messages are identified or generated in the model.

Table 1. Communications Messages Modeled

Message Category	Data	Voice
Logon	DLIC	N/A
Handoff : Transfer of communications (TOC) and Initial Contact (IC)	TRACON-to-Center	Boundary Crossing
	Sector-to-sector within Center	
	Center-to-Center	
	Center-to-TRACON	
	N/A	ATCT-to-TRACON
	N/A	TRACON-to-ATCT
Controller-Initiated Status /Advisory	Altimeter Setting Instruction	Altimeter Setting Instruction
	Beacon Code Setting Instruction	Beacon Code Setting Instruction
	Weather Advisory	Weather Advisory
	Traffic Advisory	Traffic Advisory
Controller-Initiated Clearance	Heading Change	Heading Change
	Altitude Change	Altitude Change
	Route Change	Route Change
	Speed Change	Speed Change
	Crossing Constraint	Crossing Constraint
Pilot-Initiated Clearance Request	Altitude Change	Altitude Change
	Route Change	Route Change

4.1 TRIGGERS BASED ON PROXIMITIES

The model considers two types of proximities: aircraft-to-airspace boundary and aircraft-to-aircraft proximities.

4.1.1 Aircraft-to-Airspace Proximity

In Figure 3, the large areas outlined with darker, thicker lines represent the center boundaries, and the lighter, thinner lines represent the boundaries of sectors within each center. Figure 3 shows examples for entering and exiting ZMP (Minneapolis) Center and where a sector boundary crossing occurs (small triangle) within ZMP airspace. Communications exchanges of messages for the various types of boundary crossings (center-to-center, sector-to-sector, center-to-TRACON, etc.) are different when using data link. When the aircraft is only equipped to communicate using voice, the communications message exchange is the same regardless of the type of boundary crossing, as mentioned previously.

Figure 4 shows an example in New York Center of a sector boundary crossing into or out the Allentown, PA, terminal area (ABE), for landing or taking off from the Allentown airport, respectively.

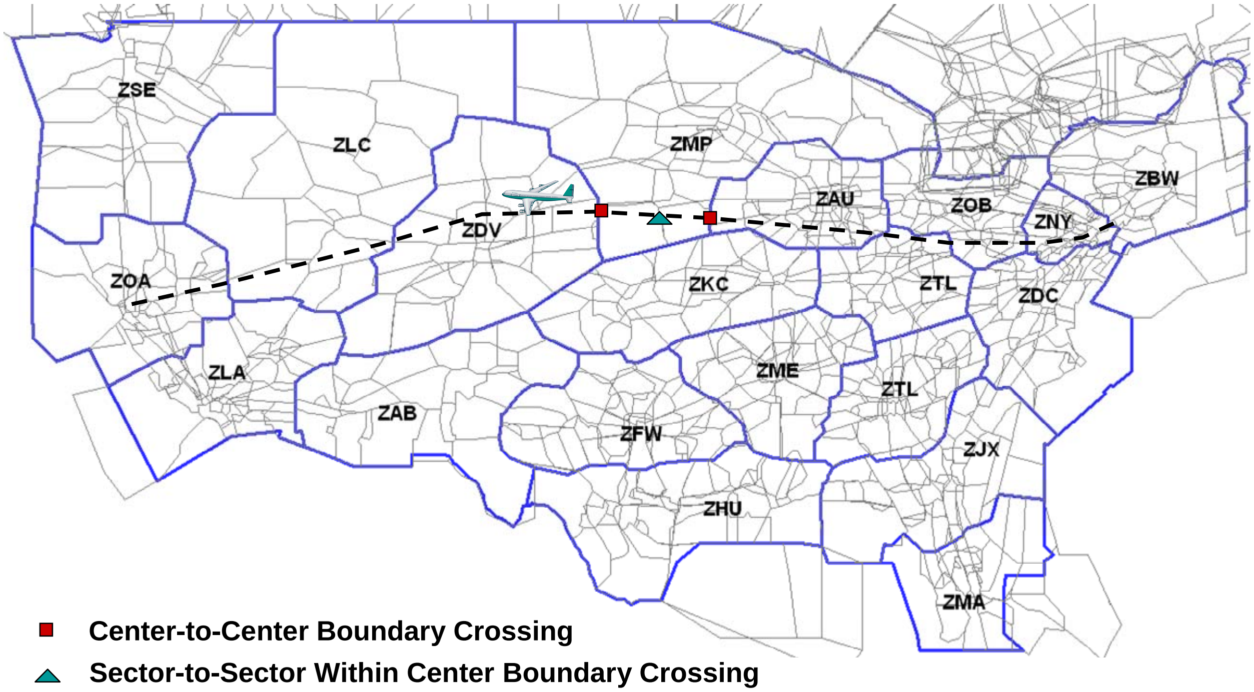

Figure 3. Example Trajectory of Flight from New York to San Francisco

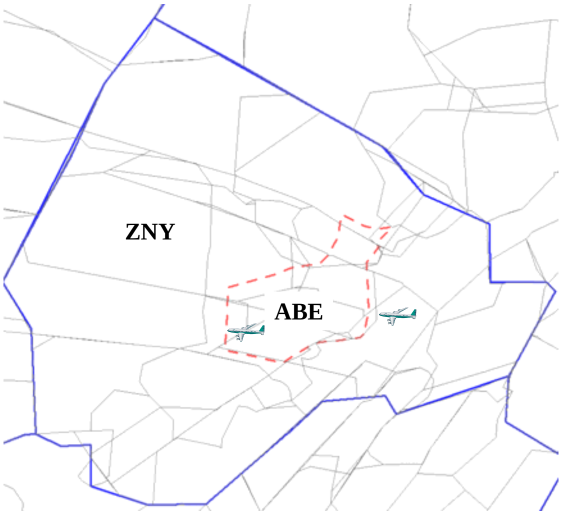

Figure 4. Terminal Area Boundary Crossing

For boundary crossings, the communications messages are triggered to occur when the modeled aircraft is within a parameter time (e. g., 2 minutes) from the sector boundary. A “headlight function” was developed to determine the time for transmitting the communications messages prior to or after encountering a modeled structure such as a boundary, or prior to or after a modeled event, such as the proximity of two aircraft.

4.1.2 Aircraft-to-Aircraft Proximity

Proximity events where aircraft would violate a separation buffer, thereby triggering a conflict resolution message from the controller to the pilot are shown in Figures 5 and 6. When an aircraft enters a sector, a check is made to determine whether there will be a 5 nmi lateral separation violation, and a 1000 ft. vertical separation violation between it and any other aircraft in the sector. If it is determined that there will be a separation encroachment, then a conflict resolution message is sent to the entering aircraft of the pair x minutes prior to when the conflict is predicted to occur, where x is supplied by the user as input. Figure 5 depicts the case where the user has specified x = 3 minutes. If the time to separation violation is less than 4 minutes, the conflict resolution

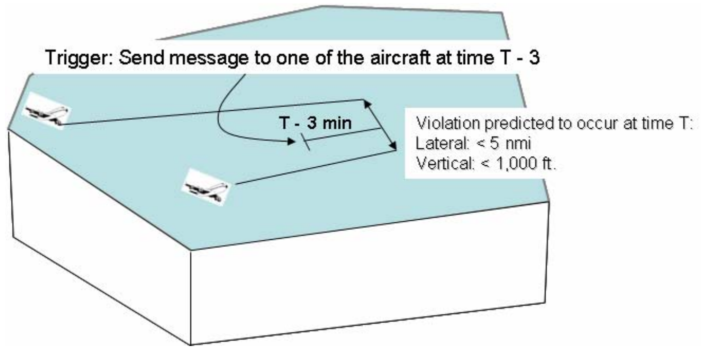

Figure 5. Identifying Conflict Resolution Messages

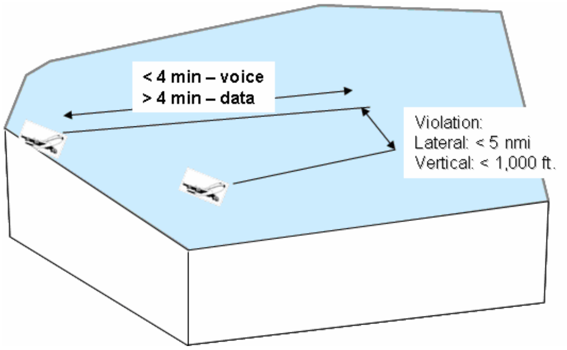

Figure 6. Identifying Conflict Resolution Messages as Voice or Data

message is sent as voice to equipped aircraft, and if the time to separation violation is greater than 4 minutes, then the message is sent as data to equipped aircraft, as shown in Figure 6. In the model, conflict resolution messages are sent either as a heading clearance or an altitude clearance where 80% are heading clearances and 20% are altitude clearances. The 80%/20% determination is based on operational experience[3].

4.2 TRIGGERS OBTAINED FROM HOST AMENDMENTS

Any changes to a flight plan that result from a communications between a controller and a pilot are supposed to be entered by the controller into the ATC host computer, one of which resides at every center. Flight plan data, and other data, such as aircraft radar track data, for each flight are sent every several seconds from the 21 centers and 31 large TRACONs to the Volpe National Transportation Center (VNTSC) in Cambridge. MA, for processing by the Enhanced Traffic Management System (ETMS). The processed information is sent back to the centers, TRACONs, and the Air Traffic Control System Command Center (ATCSCC), in Herndon, VA, for display, and to enable decision making regarding traffic flows, runway assignments, and other important matters. The ETMS data contains host amendment data, within which are any changes made to flight plans. This ETMS data has been made available to MITRE/CAASD for use in the various modeling efforts, such as the one described in this paper. The predominant types of controller/pilot communications found in the host amendments are altitude and route clearances. The capability to include these messages was added to the model.

4.3 TRIGGERS BASED ON VOICE TAPE TRANSCRIPTION DATA

Since it is known that not all clearances are recorded in the host amendment field of the ETMS data, statistics on the occurrences of the various messages were determined from the voice tape transcription data, and used in generating miscellaneous clearances. These supplement in the model the altitude and route clearance messages obtained from the host amendments.

Aircraft time in sector and number of miscellaneous clearances were averaged over nine sectors from three centers – ZFW, ZTL, ZDV, provided in the voice tape transcription data. The result showed that there were 3.3194 miscellaneous clearances per aircraft per sector, and the average time in sector for an aircraft was 8.83 minutes. This implies that there are, on average, 0.38 miscellaneous clearances per aircraft per minute per sector. Based on operational expertise, the number of miscellaneous clearances for any aircraft was capped at three per sector. Thus, the following equation was used to determine the number of miscellaneous messages for any aircraft per sector, where 0.5 is added to round up to the next highest integer:

Equation 1

Number of Misc. Clearances per Aircraft=
Max[3, int(0.38 X time in sector + 0.5)]

Table 2 shows the percentage of occurrence of the different types of miscellaneous clearances. These percentages are averages across the nine sectors provided in the voice tape transcription data of ZFW, ZTL, and ZDV. The average voice channel occupancy in seconds of the messages is also provided in the table, and includes the response times of the controller or pilot.

For an aircraft in a sector, there are times during the simulation when additional miscellaneous clearances are required to supplement the altitude and route clearances from the host amendments because the number of those

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[3] Operational expertise provided by Edward Brestle of the MITRE Corporation

Table 2. Miscellaneous Clearance Messages

Message Type	**Percentage of Occurrence**	**Average Length Including Response Time (seconds)***
Altitude Request	3.62	9.25
Route Request	8.33	9.57
Heading Clearance	6.62	8.47
Altitude Clearance	37.26	7.96
Fix Clearance (Route Change)	21.38	6.6
Speed Clearance	8.43	7.93
Crossing Constraint	3.67	9.23
Altimeter Setting Instruction	4.02	4.50
Beacon Code Setting Instruction	1.58	6.49
Weather Advisories	2.09	7.80
Traffic Advisories	3.00	7.45

*Includes controller or pilot response time

clearances is not equal to the number derived from Equation 1 above. The manner in which an additional miscellaneous clearance is selected is depicted in Figures 7 and 8. A uniformly distributed random number between zero and one is generated by the model. The interval in which it falls determines which additional type of miscellaneous clearance is sent. Selections of miscellaneous clearances are made using the bins until the number of miscellaneous clearances (those in amendments + additional) is equal to the number derived from Equation 1.

5.0 MESSAGE SIZES AND LATENCY

The model will designate aircraft as either equipped with data link or not equipped based upon user input of percentages of aircraft equipped and random variable drawing. For the FY 2005 effort, the ATN OSI protocol [1] has been modeled; though other technologies (e.g., Future Air Navigation System [FANS]-1/A [4]) can be adapted as needed. Message sizes in bytes for most of the different types of ATN/OSI messages were obtained from reference [5]. The sizes for some of the messages were not documented, and in these cases, engineering judgment was used to determine message size. Message size estimates include protocol-specific factors such as message header and cyclic redundancy check data.

Example 1: The random number 0.35 has been generated by MLM. It falls within the interval 0.1857 to 0.5583, therefore an altitude clearance message is generated

Example 2: The random number 0.9 has been generated by MLM. It falls within the interval 0.8966 to 0.9124, therefore a beacon code setting message is generated

Figure 7. Selection of Supplemental Clearances Through Use of Bin

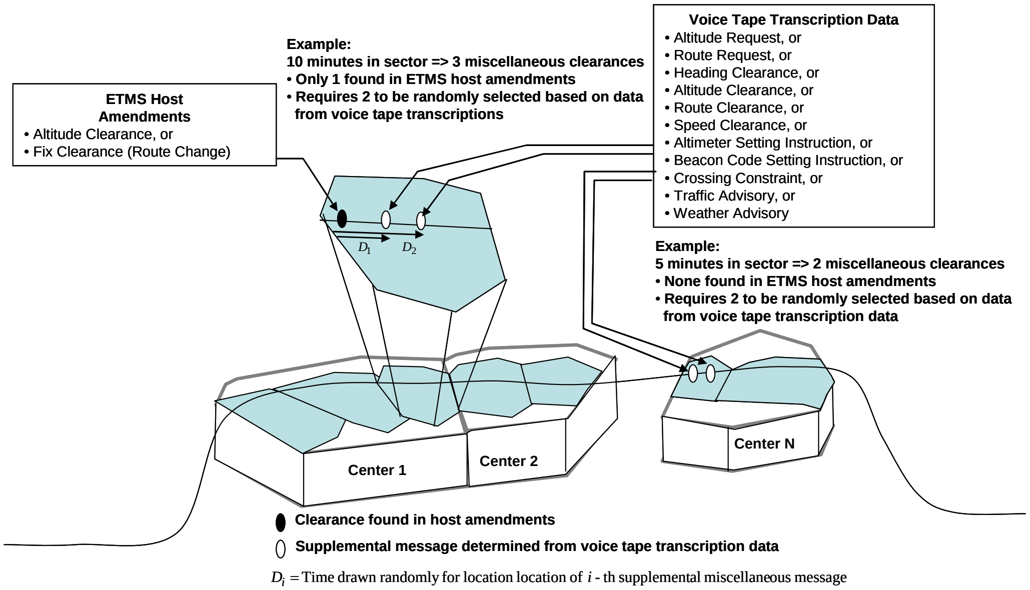

Figure 8. Triggering Events for Miscellaneous Messages

Unequipped aircraft will transmit all messages as voice. Equipped aircraft will transmit most messages as data, but depending on conditions, could transmit voice messages as well. As mentioned previously, voice message channel occupancy, and other statistics have been obtained from voice tape transcriptions [2].

In addition to message lengths, the latency of the communication infrastructure (time to transmit the message from the ground to the air and from the air to the ground) must be accounted for. This time must include: the time to transmit the message through the various ground systems such as the display systems, automation systems, and the communications subnetworks; and the time for a human to respond for those messages that have a human in the loop. The latency values used are distributions reflecting the uncertainty of the latency contributions of various elements of the end-to-end chain of contributors. Figure 9[4] shows the various components of the path through which the message must traverse. For cases in which a human response is required, Figure 9 shows the human response time. The CPDLC Specification, Version 2.0, Section 3.4.4.1.3 [6] provides specifications for end-to-end delays. Only the overall means for the total transit delay of 7.3 seconds (s) and the human response time of 25 s were used in the model. For the current version of the model, a uniform distribution is used for both transit time and human response time. The standard deviations are not readily available for the transit time and for the human response time so that distributions such as the normal or lognormal distribution could be used. Thus, for the transit time a uniform distribution is applied to the interval [5.3 s, 9.3 s], i.e., 2 s around the mean of 7.3 s; and for the human response time, it is applied to the interval [15 s, 35 s], i.e., 10 s around the mean of 25 s. Although a uniform distribution is currently used, it is not difficult to change this in the model to some other distribution such as the normal or lognormal distribution when the standard deviations are known.

6.0 FUTURE ENHANCEMENTS

At the outset of this project, there were a number of features that were considered for adding a communications capability to the model. It was not possible to incorporate all of these features during this initial attempt at adding a communications capability to the model; however, the important features to consider are provided in the next several sections so that they can be considered for incorporation in some future evolution of the model. The following sections discuss providing the model with additional communications modeling features to obtain a better understanding of the technical and operational implications of candidate architectures and capabilities to determine the impact of future communications on bandwidth and workload [7].

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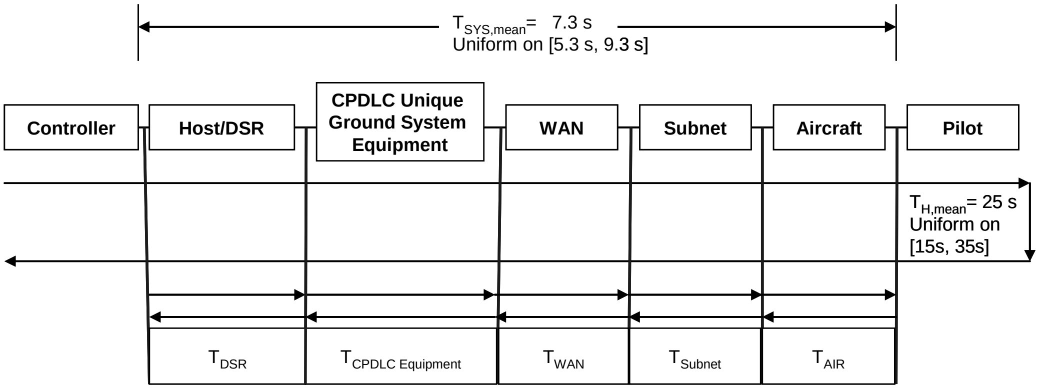
[4] Figure developed by Stephen Giles, The MITRE Corporation.



DSR **Display System Replacement**
WAN **Wide Area Network**

Figure 9. Message Uplink/Downlink Path

6.1 SECTOR CATEGORIES

Statistics estimated from the voice tape transcriptions from nine sectors at three centers were averaged together and used to determine frequencies of occurrences and voice channel utilization durations that were extrapolated to every en route sector across the NAS. The initial plan was to use a different set of statistics for each sector or group of sectors that would better characterize them. When voice tape transcription data or other indicators of communication workload become available for a larger sample of sectors, then it may be possible to identify unique characteristics for each sector or type of sector; and then to develop a more appropriate set of statistics for each sector or type of sector to be used in a simulation. Reference [3] provides one way of characterizing sectors based on a newly developed concept of the "DNA" of a sector. The usage of "DNA" is meant to convey the notion that sectors with similar "behavior" can be identified through "DNA" samples, which could be representations of the different types of messages that are transmitted and received in the sectors over different time periods. This concept should be explored as a means of determining percentages of different types of messages that would be sent in a sector based on its "DNA."

In addition, the available voice tapes were sampled during certain times of the day. Therefore, the statistics obtained are valid with reasonable confidence for those times of the day in which they were collected. In the future, either data should be collected for each sector or group of sectors for different parts of the day, or some methodology should be developed to estimate statistics for other parts of the day from the available statistics.

6.2 PROBABILITY DISTRIBUTIONS

The uniform distribution was assumed for response times, and times for data-link messages to transit the various systems. The original intent for the transit times was to use a lognormal distribution; however, the model requires that a standard deviation be supplied as input. The standard deviation was not known at the time of the analysis. However, once the standard deviation is known, it is an easy task to change from the uniform distribution to a lognormal distribution in the model.

A normal distribution was assumed for voice message sizes. However, the voice message sizes may not actually be normally distributed. Again, once a distribution function is determined that would better represent voice message sizes, it would be an easy task to incorporate it into the model

6.3 A/G COMMUNICATIONS

Currently all messages are successfully transmitted. In reality, there are many cases where messages must be retransmitted due to problems encountered along the transmission path. Some technique based on the probability of retransmission (once known) would be easy to incorporate into the model.

Voice messages are sometimes not clearly understood by either the pilot or controller. Therefore, some voice messages require repeating, which would increase the bandwidth required. This has not yet been modeled. Again, with known rates at which this occurs, it would be an easy task to incorporate into the model.

For a certain percentage of messages, the controller or pilot cannot respond immediately and will send a standby message. In the current implementation of the model "standby" has been left out of all but one of the messages, and whenever that message is sent, "standby" is always transmitted. For a future enhancement of the model, "standby" should be included a certain percentage of the time in the appropriate messages.

Reference [1] contains information regarding timers, which are functions that indicate when an expected response has not been received within a certain predetermined amount of time. A timer expiry results in additional messages being sent such as error and notification messages, resulting in more bandwidth being used; also, the original message, or one changed to reflect the changed operational circumstances, has to be sent to the pilot or controller. Using probabilities to model timer expiry can be incorporated into a future evolution of the model.

6.4 G/G COMMUNICATIONS

There are G/G voice and, in the future, data communications that result from or give rise to A/G communications. Enhancing the model to include G/G communications would provide a means of quantifying G/G communications in order to determine the connectivity and estimate the bandwidth required on the links of the G/G network.

ACKNOWLEDGMENTS

We would like to thank our colleagues at MITRE/CASED. Foremost we would like to thank Stephen Giles for sharing his expertise in data link with us, for directing us to the documentation needed, for pointing us in the right direction as this project was just beginning, for laying out a framework for us to follow, and for helping us along the way to completion.

We would also like to thank:

- Niamh Lowry for her guidance and for providing us with the operational expertise necessary to adding the communications capability correctly to the model.
- Edward Brestle for allowing us to take advantage of his controller expertise that was invaluable to incorporating the communications capability into the model.
- George W. Flathers for providing us the pilot’s perspective in using air/ground communications systems.
- Brian Hung who did a thorough analysis of the voice tape transcription data, and whose results were used in this modeling effort.
- Brian Simmons, the Principal Investigator of the modeling effort, for his support and patience and for providing us the opportunity to work on this research project.

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