HYBRID APNT ARCHITECTURE USING DME/DME AND MULTILATERATION

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Abstract

DME/DME and Passive Wide Area Multilateration (P-WAM) are two proposed FAA's Alternative Position, Navigation, and Timing (APNT) architectures that provide navigation and surveillance capability to National Air Space during a GNSS outage. Although Distance Measuring Equipment (DME) and Multilateration (MLAT) system operate in a very different way, they use the same frequency band and can share the same antenna, which allows for one system integrating DME and MLAT electronics. Similarly, Automatic Dependent Surveillance-Broadcast (ADS-B) can be integrated with DME and MLAT. This DME/MLAT/ADS-B integrated system in one cabinet can be used to simultaneously provide DME and MLAT service for navigation and ADS-B for surveillance. With this dual navigation service capability of the integrated system, it is possible to develop a hybrid APNT architecture enabling both of DME/DME and P-WAM) service as a back-up of GNSS. The important advantage of the hybrid architecture is that the impacts on the avionics of General Aviation users and commercial jet airliners would be minimal by requiring only software and additional input/output connections. This paper describes the methodology and results for the feasibility study of the hybrid architecture and investigates the required ground station layout of the hybrid architecture that meets the anticipated APNT navigation and surveillance performance requirements by evaluating selected areas of the continental U.S. The required ground network will be determined through an optimization process called Coverage Analysis Method [1, 2] and be compared with the respective required ground networks for DME/DME and P-WAM based architectures to evaluate the additional number of ground stations needed in the hybrid architecture. In addition, the capacity of the DME/MLAT/ADS-B integrated systems in the hybrid architecture will be evaluated.

Introduction

The U.S. NextGen Air Transportation System primarily uses the Global Navigation Satellite System (GNSS)to meet future air traffic demands. However, the GNSS service is susceptible to interruption by manmade and atmospheric effects. If a GNSS outage occurs for a significant time, air traffic management will be severely disrupted. For this reason, FAA has recently initiated an Alternative Position, Navigation, and Timing (APNT) program that would provide seamless RNAV/RNP capability during the GNSS outage. From FAA's preliminary study on possible APNT systems, three architectures have been considered [3, 4]. They are DME, passive Wide Area Multilateration (P-WAM), and Pseudolite based architectures. These architectures would use a ground station network of 1100 currently deployed DMEs and 800 Automatic Dependent Surveillance-Broadcast (ADS-B) Ground-based Transceiver (GBT) facilities. Additional sites may need to be added to provide seamless APNT coverage over the CONUS and increased accuracy in major terminal areas. There has been active research on the three proposed architectures. The research involved a possible signal structure [5], capacity analysis [6], and the optimal ground station network layout using the existing or planned DME and ADS-B GBT facility [1, 2].

Previous APNT research did not consider an integrated DME/MLAT/ADS-B system. The close frequency band of the three systems allows a convenient integration of each independent system. In fact, MLAT and ADS-B have already been integrated since both use 1090 Extended Squitter and Universal Access Transceiver (UAT) 978 MHz signals. The DME/MLAT/ADS-B integrated system would provide a dual navigation capability of DME and MLAT as well as ADS-B surveillance. This feature greatly minimizes aircraft avionics changes because existing multichannel DME (scanning DME) and ADS-B avionics can potentially be used. The feasibility study also investigates the required ground station layout and capacity of the DME/MLAT/ADS-B integrated system. This paper provides an overview of DME/DME and P-WAM and their range accuracy followed by a discussion of the hybrid architecture development approach including APNT requirements and a site location algorithm. Then, the resultant ground station layout of the hybrid architecture will be presented and compared with the ground station layout of the independent DME/DME or P-WAM based architectures. Lastly, the capacity of the integrated system will be evaluated and conclusions will be provided.

DME/DME and Passive WAM Overview

The DME operating frequencies are in the range of 962 – 1215 MHz. These frequencies are divided into 252 channels with 1 MHz separation. Aircraft equipped with multichannel and/or scanning DME avionics can compute horizontal position by using range measurements from 2 or more ground stations, which is known as DME/DME position. The DME/DME positioning is one of the enablers of Area Navigation (RNAV) that allows user-preferred and direct courses within DME/DME service areas. Most large airline and business jets are equipped with and use DME/DME avionics. The FAA is expanding the DME/DME positioning service at Flight Level 180 by filling coverage gaps in the current DME infrastructures in the Conterminous U.S. (CONUS) [3]. The DME range accuracy required in the current specifications should be better than 0.2 nm for 95% of time including any performance degradation contributed by airborne interrogators, propagation effects, and ground transponders [8]. From the survey of FAA APNT team, the current state-of-the-art DME has a significantly better range accuracy than the current standards and is expected to have the total range error about 70 meters (95 %) [9].

Multilateration (MLAT) is one of the Advanced Surface Movement Guidance and Control Systems (A-SMGCS) for airport surveillance. MLAT positioning technique commonly uses Mode A/C/S signals as ranging sources with multiple receivers installed in known geographic coordinates around the airport. The receivers are typically time synchronized using a timing squitter unit or a GPS receiver such that the time difference of arrival (TDOA) measurements can be solved for a target position. To compute horizontal position, MLAT requires range measurements from more than 3 stations. MLAT is distinguished as active or passive. The active system incorporates interrogation transmitters to induce the Mode A/C/S transponder signals from aircraft and take advantage of the associated round-trip ranging function. More recently, this technique has been employed for large areas such as en route or approach [7], which is called as Wide Area Multilateration (WAM). The passive system design only listens to the Mode A/C/S signals transmitted from aircraft, and relies on interrogations from other sources (e.g. TCAS, Radar) to trigger avionics. Because Automatic Dependent Surveillance-Broadcast (1090 ES or UAT) would be widely used and replace the legacy Mode A/C/S transponder functionality for air traffic surveillance, ADS-B signals (1090 ES and UAT) would also be used as a ranging source by employing passive MLAT (P-WAM) systems [5, 6].

The range error of MLAT mainly consists of time of arrival (TOA) determination and ground station time synchronization errors. For a P-WAM, range measurement error is almost entirely attributable to the ground station time synchronization and is 24 meters (95%) when a GPS/Rubidium clock combination is used [10]. Since the time synchronization method for APNT P-WAM architecture has not been determined, the range accuracy of 24 meters is used in this analysis.

The P-WAM system calculates aircraft position that can be used in lieu of radar for air traffic control. Identification-specific position information is also transmitted to aircraft via the Traffic Information Service Broadcast (TIS-B) to be utilized by the corresponding aircraft for navigation when GPS service is interrupted. Although the impact of TIS-B system on navigation accuracy has yet to be validated, it is believed to be sufficient to support terminal and en route navigation to navigate to an Instrument Landing System, or away from the interference area altogether, and potentially non-precision approach capability in select terminal areas.

APNT Hybrid Architecture of DME/DME and P-WAM

A DME/MLAT/ADS-B integrated system would consist of separate DME/MLAT/ADS-B modules and one master control unit. The antenna would have multiple sectors whose maximum gain is centered on its designated azimuth sector. The integrated system may be able to share one transmitter or require a separate transmitter for DME and ADS-B to meet the required capacity. The separate transmitter could allow for flexibility in designing the integrated system.

Hybrid APNT Architecture Development Approach

To enable the dual navigation capability of DME/DME and P-WAM, the hybrid architecture must have the ground network layout that provides required position accuracy. An optimal ground network of the hybrid architecture is determined through the process shown in Figure 1. In this process, the constraints of the architecture development are accuracy/integrity requirements, existing DME/GBT station network topology, defined airspace, terrain geography, and range accuracies of DME and P-WAM. Given those constraints, an optimal ground station network is determined through the coverage analysis method based on binary integer linear programming incorporating various heuristics such as distance between stations, aircraft altitude, and preference of existing stations. This algorithm searches for an optimal ground network having the minimum total number of stations while possessing the maximum number of existing DME/GBT stations.

Figure 2 shows an example of the good station placement that the algorithm is designed to look for. In Figure 2, the entire area is the airspace projected onto the ground. Region 1 is the low altitude airspace near an airport and Region 2 is the high altitude airspace. The red 'X' is an existing station and the yellow circle is the determined station location. A good station placement typically has stations outside of the low altitude/high accuracy airspace near an airport and selects as many existing stations as possible while minimizing the total number of stations. The stations around the low altitude airspace provide good geometry, thus low HDOP (high position accuracy), to the aircraft within the low altitude airspace. However, the bad placement example has the multiple stations inside the low altitude. This ground station network geometry is not desirable since it would likely result in high HDOP (low position accuracy) around the edge of the low altitude airspace. Thus, additional stations would be required. On the other hand, high altitude airspace typically does not impact a ground station network layout because aircraft at that altitude can have a line of sight to a number of ground stations with a good geometry from the determined ground station network for the low altitude airspace.

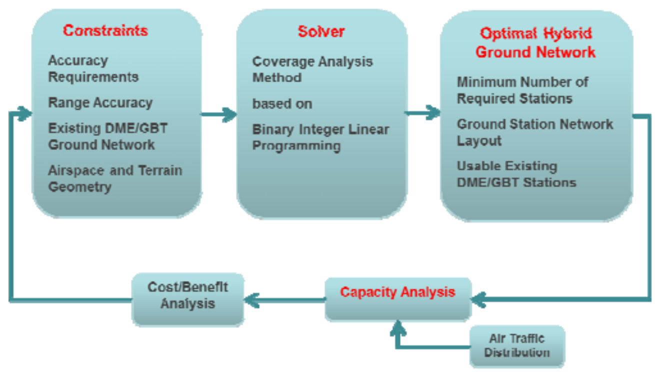

Figure 1. APNT Hybrid Architecture Network Development Process

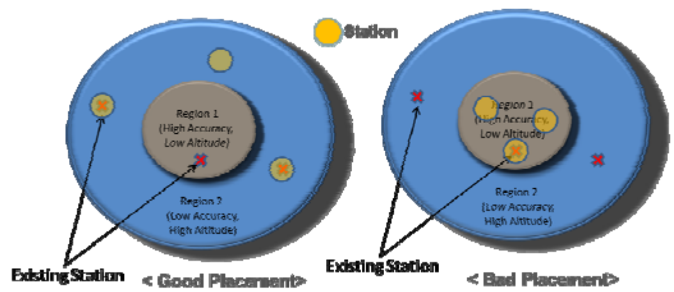

Figure 2. Examples of Station Placement from Heuristics-based Binary Integer Linear Programming

The capacity demands of an integrated DME/MLAT/ADS-B system with required air traffic density will determine the antenna configuration such as the number of sectors and transmitters. The last procedure is a cost/benefit analysis that is not addressed in this paper. More details on the coverage analysis method and the heuristics-based binary integer linear programming can be found in [1, 2].

APNT Requirement

The FAA's APNT performance requirements are listed in Table 1 for the operation of en route, terminal, and lateral navigation (LNAV). The airspace performance zones of each case are depicted in Figure 3 [3]. Note that the required surveillance horizontal position accuracy is up to 92.6 meters and is higher than navigation accuracy in all of the airspace. Because the surveillance accuracy has more stringent requirements than navigation, the analysis in this paper will be against the surveillance accuracy requirement. If we use the assumed range accuracy of the state-of-the-art DME and P-WAM, the corresponding Horizontal Dilution of Position (HDOP) is 1.32 for DME/DME and 3.90 for P-WAM, respectively.

Table 1. APNT Horizontal Position Accuracy Requirements

	Navigation		Surveillance		
	Accuracy (95%)	*Containment (10^{-7})*	*Separa -tion*	*NAC_p (95%)*	*NIC (10^{-7})*
En Route	4 nm	8 nm	5 nm	92.6 m	0.2 nm
	2 nm	4 nm			
Terminal	1 nm	2 nm	3 nm	92.6 m	0.2 nm
LNAV	0.3 nm	0.6 nm			

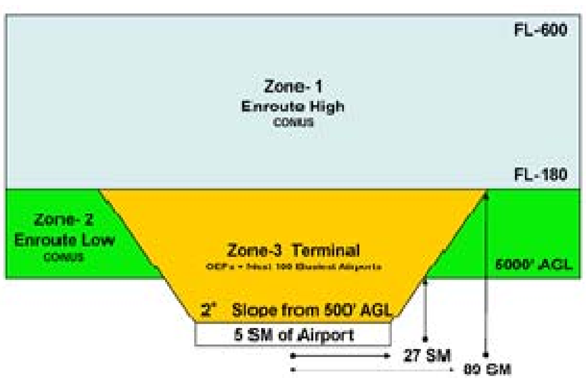

Figure 3. FAA Airspace Performance Zones (Courtesy of FAA)

Southern Florida Example

In this section, a hybrid architecture ground network is investigated for the southern Florida region using the proposed procedure in Figure 1. It is assumed that the aircraft is equipped with a scanning DME having 5 channels available for DME/DME positioning. When more than 5 DME transponders are available to the aircraft, the scanning DME can choose a set of channels that will minimize the HDOP value, which may require a change to the way that some flight management systems operate.

Figure 4 depicts 23 DME transponders and 23 GBT stations identified in southern Florida. The figure also indicates the location of 8 international airports. It should be noted that the DME/GBT stations shown in Figure 4 may not represent all of the existing stations. Aircraft altitudes in this region follow the airspace performance zone-3 in Figure 3.

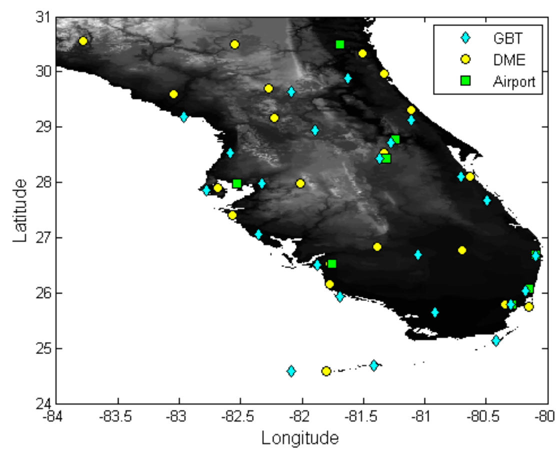

Figure 4. DME and GBT Facility in Southern Florida

The red areas in Figures 5 and 6 show coverage gaps where DME/DME and P-WAM have insufficient HDOP when using all of the existing DME/GBT ground stations. Therefore, additional sites either for DME/DME or P-WAM need to be placed to meet the accuracy requirement.

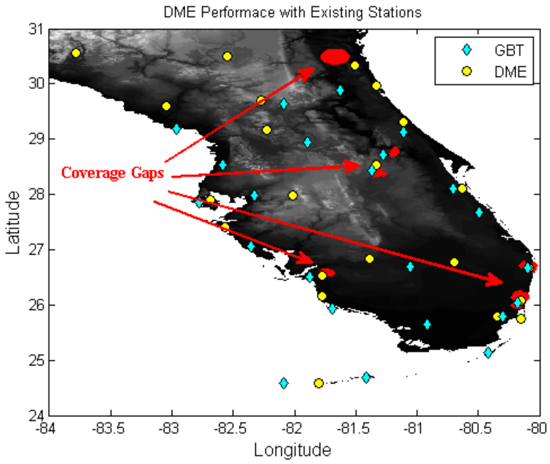

Figure 5. DME/DME Surveillance Coverage Gaps with All of the Existing DME/GBT Stations

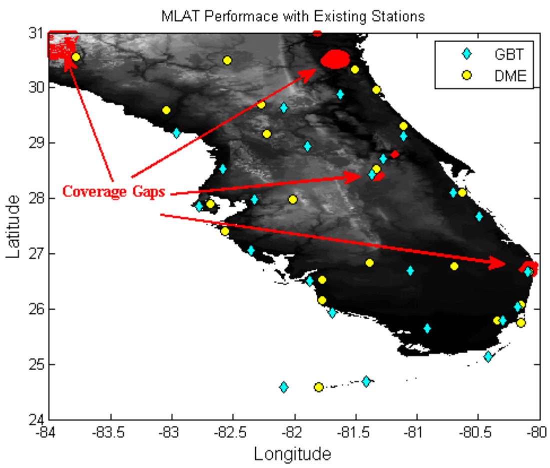

Figure 6. P-WAM Surveillance Coverage Gaps with All of the Existing DME/GBT Stations

Optimal Hybrid DME/P-WAM Ground Network

Figure 7 shows the optimal hybrid DME/P-WAM ground network from the coverage analysis method. The optimized hybrid network requires the integrated system on 7 new sites, 13 DME sites, and 7 GBT sites. Note that coverage gaps still exist in the northern part of the map. These coverage gaps are not of concern at this moment because they will be removed when other stations above the map are taken into account.

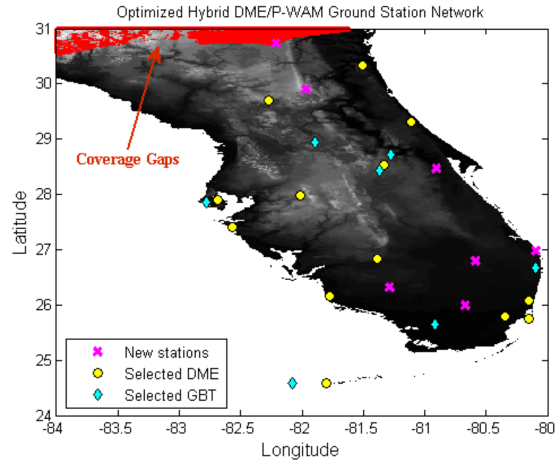

Figure 7. Optimized Hybrid DME/P-WAM Ground Station Network

Figure 8 and 9 show the optimized independent DME/DME and P-WAM ground station networks, respectively. Note that DME and P-WAM stations have separate DME and MLAT receiver units in these two architectures. The optimized DME/DME network requires DMEs on the 6 new sites, 12 DME sites, and 7 GBT sites. The optimized P-WAM network requires MLAT receivers on 5 new sites, 14 DME sites, and 10 GBT sites.

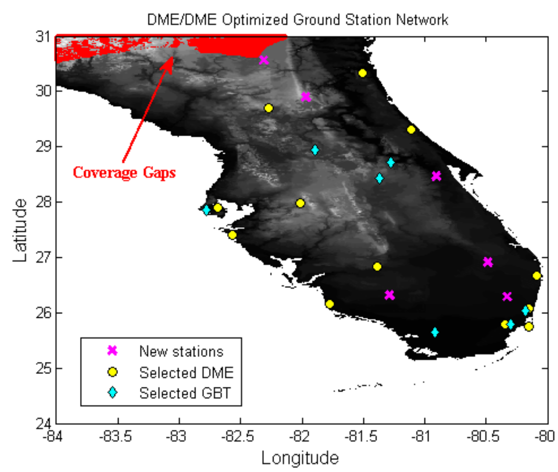

Figure 8. Optimized DME/DME Ground Station Network

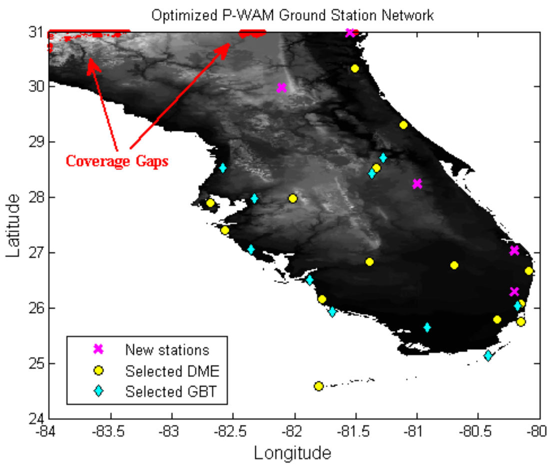

Figure 9. Optimized P-WAM Ground Station Network

The three resultant optimized APNT ground station networks are summarized in Table 2. In the table, the hybrid network needs at most 2 additional new sites than the other architectures, which is the penalty of providing both of DME and P-WAM service using the integrated system. Note that the number of new sites would be the driving cost factor to develop the architecture.

Table 2. Summary of the Three Resultant Optimized Ground Station Network

	New Sites	DME Sites	GBT Sites	Total Number of sites
Hybrid	7	13	7	27
DME only	6	12	7	25
P-WAM only	5	14	10	29

Discussion of Optimality of Resultant Ground Station Network

It is often difficult to verify if a solution from an optimization process is optimal because the global or even local optimality cannot be easily found in general. The same is true for this facility location problem. The optimal solution that the coverage analysis algorithm searches for is the ground station network having the minimum total number of stations while possessing many of the existing stations as possible, thus requiring a minimum number of new sites. Then, the optimality of a solution can be inspected by considering the following two factors: the total number of stations and the number of new sites.

First, the minimum total number of stations can be approximated by finding the minimum number of stations near an airport. The reason for this is that the required set of stations for the low-altitude airspace near an airport mostly determines the entire network layout. On the other hand, the high-altitude airspace usually has no impact because aircraft can typically have a line-of-sight to many stations at those altitudes that good ground station geometry is a given in most regions of the country. The minimum required stations for surveillance per airport would typically be 3 or 4 to meet required low HDOP values. Since there are 8 airports in the considered region, the total number of stations should be between 24 and 32, which is true in Table 2.

The minimum number of new sites can be approximated by evaluating the coverage gaps from utilizing every possible existing station as shown in Figure 5 and Figure 6. Even with all of the existing stations, there still exist some localized coverage gaps near the airports. Those coverage gaps mostly exist in low-altitude airspace except in the northern part of the airspace in the map. Considering the low altitudes airspace suffering from coverage gaps and the large distance among the coverage gaps, it would be ideal if one or two new sites are added to meet the required HDOP for each localized gap. This is also true in Figure 7, 8, and 9. As discussed in this section, the two factors of the optimality criteria are well satisfied in the three optimized ground station networks. However, there could be various ways of checking the optimality of the solution and further research would be needed for a tighter optimality inspection.

Capacity Analysis of the Integrated System

The integrated system must process the requests of DME interrogations, Mode A/C/S, Mode S Extended Squitter (ES), and UAT from aircraft within the service coverage of the station. Because the antenna is sectored and each sector has its own receiver, the integrated system would have sufficient target detection capability. If the DME and ADS-B have separate transmitters sharing one antenna, the DME and ADS-B capacity of the integrated system would be similar to independent DME and ADS-B ground stations. However, when the integrated system shares one transmitter, the capacity of the integrated system would be primarily limited by the transmitter unavailability. Since the integrated system having separate transmitters is expected to have a sufficient capacity, this paper analyzes the integrated system with one transmitter.

The capacity analysis approach of the integrated system with one transmitter is to evaluate the DME reply efficiency by assuming that the integrated system has a priority of transmitting ADS-B messages when DME and ADS-B need to use the transmitter at the same time. The DME reply efficiency (RE) is the percentage of replies provided by the DME transponder relative to valid interrogations from aircraft. The minimum RE of the current specification is 70% [8]. If the RE is less than 70% with one transmitter under the expected air traffic distribution, another transmitter or antenna would be desirable. To evaluate the RE of the DME, a Monte Carlo simulation was used to generate the interactions between an integrated system and the randomized air traffic distribution which is based on the 2020 Los Angeles (LA) Basin air traffic model [11]. Figure 10 shows an example of LA Basin air traffic model up to 60 nautical miles from the center. Aircraft on ground is not considered in this analysis.

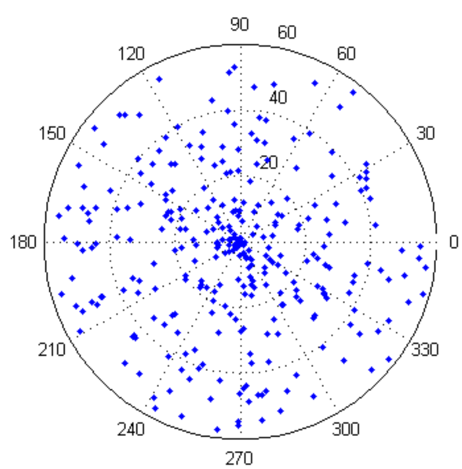

Figure 10. Example of Air Traffic Distribution from LA Basin Model

For the simulated interactions, the percentage of commercial jet and GA aircraft needs to be defined. Transportation Security Administration reported that some 77% of all flights in U.S. were by GA users [12]. Although it may not be accurate to assume that 77% of aircraft within the service coverage of the integrated system are GA aircraft, it could be used as a guideline. With that, three distributions of jet airlines and GA users are hypothesized in the simulation: Case 1 is 70% of GA and 30% of jet airliners, Case 2 is 60% GA and 40% jet airliners, Case 3 is 50% GA and 50 % jet airliners. These aircraft distributions send requests to a DME/MLAT/ADS-B integrated system, then the RE of the DME will be calculated as the metric of the capacity of the integrated system with one transmitter.

It is assumed that GA aircraft use UAT (ADS-B In and ADS-B Out) for WAM-based navigation and surveillance during GNSS outage. And, jet airliners use DME/DME for navigation and 1090 ES for surveillance. During the simulation, GA aircraft randomly (uniformly distributed) selects its transmission slot in the ADS-B Segment shown in Figure 11 and transmits ADS-B message via UAT medium once per second [13]. The UAT ADS-B message can be either short (276 bit) or long (420 bit) and each bit is 0.96 μs long. The message length is also randomly (uniformly distributed) chosen in the simulation. In turn, the jet airliner is assumed to transmit 1090 ES messages (120 μs long) several times per second and send DME interrogations in between the 1090 ES transmissions. Figure 12 shows a snapshot of DME interrogation and 1090 message sequences. The broadcast 1090 ES messages and their rates used in the simulation are summarized in Table 3 [14]. Once these requests arrive at the DME/MLAT/ADS-B integrated system on ground, the integrated ground system prepares the transmission of Flight Information Services-Broadcast in the Ground Segment and TIS-B and ADS-B replay in the ADS-B Segment. The remaining time will only be used to send DME replies. In addition, there are several factors that inhibit the DME transponders from processing the interrogations. Those factors are a dead time interval, self-interrogation for monitoring, garbling, and maximum reply transmission as summarized in Table 4 [8]. These factors are also taken into account in the simulation.

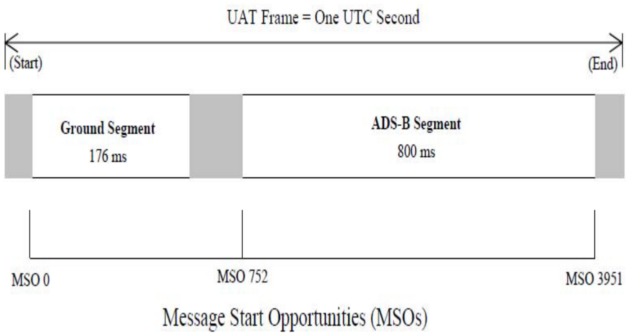

Figure 11. Ground and ADS-B Segments of UAT Frame

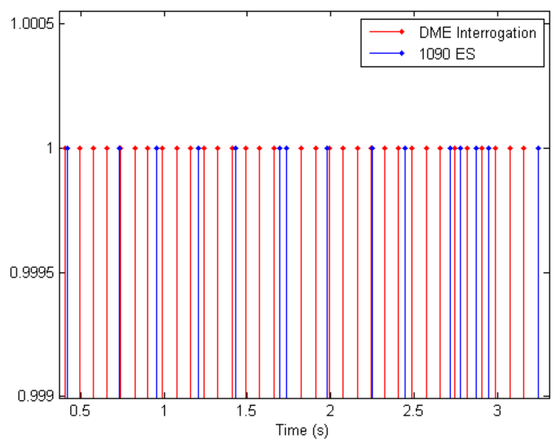

Figure 12. A Sequence of DME Interrogation and 1090 ES Messages

Table 3. 1090 ES ADS-B Messages and Broadcast Rates

1090 ES ADS-B Message	Broadcast Rate
Airborne Position	0.4 ~ 0.6 sec
Aircraft Identification and Category	4.8~5.2 sec
Airborne Velocity	0.4 ~ 0.6 sec
Aircraft Status	4.8 ~ 5.2 sec
Target State and Status	1.2 ~ 1.3 sec
Aircraft Operation Status	2.4 ~ 2.6 sec

Figure 13 shows the resultant DME reply efficiency of the Case 1, 2, and 3 with respect to 200 and 300 aircraft from 5 minutes duration of the simulation. In Figure 13, as the percentage of GA aircraft increases, the RE increases and the calculated REs were above 74% for all of the cases.

Table 4. DME Parameters Setting for the Simulation

Parameters	Range
Interrogation Rates/ Interval	Average number of channels in use is 4, Rate = 48/4=12, Interval = $\frac{1}{\text{Rate}}$ ± random jittering 4800 per second
Dead Gate Interval	60 μs
Monitor Self-Interrogation	50 ppps
Maximum Reply Transmission	4800 ppps
Downlink Garbling	A = Maximum pulse amplitude, First Pulse: Pulse overlap within 12 μs from the time at 0.1 A (leading edge), Second Pulse: Pulse overlap within 7 μs from the time at 0.1 A (leading edge)

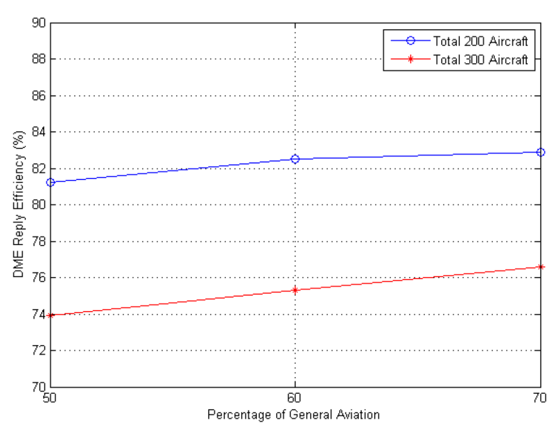

Figure 13. Expected DME Reply Efficiency wrt. Percentage of GA Users and Total Number of Aircraft within the Service Coverage

Conclusions

This paper presented the required ground station network layout and capacity analysis of the proposed hybrid APNT architecture providing DME/DME and Multilateration service with the DME/MLAT/ADS-B integrated system. The required ground station networks of the independent DME/DME and P-WAM based architectures were also presented. Considering that the number of additional sites is the driving cost factor in developing the APNT ground station architecture, the results suggest that the additional cost to enable the hybrid architecture would be insignificant. The reason for this is that the hybrid architecture requires only 1 more new site than the DME/DME based architecture and 2 more new sites than the P-WAM based architecture. The capacity of the integrated system having one transmitter was analyzed since this configuration may have the worst case capacity. The DME reply efficiency of this configuration was still better than 74 % with a total number of 300 aircraft (150 GA and 150 jet airliners). Encouraged by the results, the hybrid APNT architecture could be a cost-effective alternative to the airborne users and ground service provider.

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