

A TDMA BROADCAST SATELLITE / GROUND ARCHITECTURE FOR THE AERONAUTICAL TELECOMMUNICATIONS NETWORK

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Abstract: An initial evaluation of a TDMA satellite broadcast architecture with an integrated ground network is proposed in this study as one option for the Aeronautical Telecommunications Network (ATN). The architecture proposed consists of a ground based network that is dedicated to the reception and transmissions of Automatic Dependent Surveillance Broadcast (ADS-B) messages from Mode-S or UAT type systems, along with tracks from primary and secondary surveillance radars. Additionally, the ground network could contain VHF Digital Link Mode 2, 3 or 4 transceivers for the reception and transmissions of Controller-Pilot Data Link Communications (CPDLC) messages and for voice. The second part of the ATN network consists of a broadcast satellite based system that is mainly dedicated for the transmission of surveillance data as well as En-route Flight Information Service Broadcast (FIS-B) to all aircraft. The system proposed integrates those two network to provide a nation wide comprehensive service utilizing near term or existing technologies and hence keeping the economic factor in prospective. The next few sections include a background introduction, the ground subnetwork, the satellite subnetwork, modeling and simulations, and conclusion and recommendations.

1. Introduction

The Aeronautical Telecommunication Network (ATN) is comprised of many entities which are under development or at a

research stage [1]. Several communication links, technologies, and architectures were considered which differ in complexity, cost, and the time frame for its implementation. Here we are proposing an architecture based on the following objectives:

- Cost: A system that takes into account the initial cost of implementation. Considering the fact that such architectures are not mass produced, the initial cost will likely determine the expected final costs.
- New but tested technologies: In this we mean a system that relies on technologies that are new but already tested as oppose to being in the initial research stage. Also minimum use of what is defined as older technologies is assumed.
- Enough Room for Technology growth: while the cost and the technologies in existence or near term existence determines the main architecture, it is important to leave room for other not yet mature technologies to be implemented within the architecture at hand without significant changes. Nonetheless where there may significant changes required, they are noted.

The ATN proposed architecture is illustrated in Figure 1. It is divided into three parts.

- 1-The ground sub-Network which consists of (but is not limited) two major sub components:

- a- Surveillance System: ADS-B (mode S and UAT) ground transceivers. Primary and secondary surveillance radars (mode S and Air Traffic Control Radar Beacon System (ATCRBS)).
 - b- CPDLC and voice communications network: This consists of VDL 2, 3, or 4 communication transmitters and receivers (depending on which link will be chosen). All VDL links will be in the VHF band and hence will not effect the surveillance systems design.
- 2- The satellite sub-Network which consists of two major parts:
 - a- Satellite ground stations used to transmit TIS-B and FIS-B messages collected from all the ADS-B and radar ground transceivers.
 - b- The satellite itself used to relay the satellite ground stations TIS-B and FIS-B messages to all the aircraft.
 - 3- Ground links used to connect all the surveillance, VDL, and ground satellite stations to each other or to main stations.
 - 4- The airplane transceivers, which consists of VDL, ADS-B, and Satellite equipment.

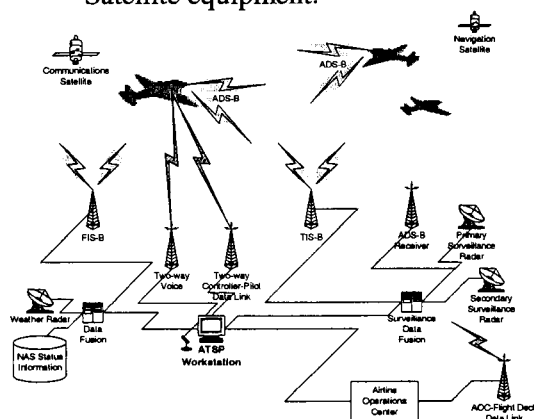


Figure 1: ATN major components

The next two sections outlines some of the details of the ATN parts discussed above with the ground links and the airplane nodes mentioned within. While the key element of this design comprises the integration of satellites with ground based networks, it is also the architecture which is seen to meet best all the objectives outlined in the beginning, cost, new technology, and room for improvement.

In summary, the architecture works as follows; aircraft equipped with ADS-B (UAT or Mode S) transceivers transmit their ADS-B message to ground stations that are located approximately 150 miles apart (enough distance to receive from any altitude). At the same time, aircraft which are not equipped with ADS-B transceivers will be detected by the primary or secondary surveillance radars. The ADS-B ground receivers, and the radar stations will all be connected via ground links (such as T1 or fiber, or possibly microwave, or a combination) to the satellite ground station. Satellite ground stations are presumed to be located in strategic locations such as at the ground control centers of each of the major airspace sectors. Data collected will be filtered to remove any redundant messages received by more than one system (i.e. one aircraft message seen by more than one ADS-B receiver as well as with radar) and a TIS-B message will be constructed per each to transmit to the satellite. The satellite ground stations will access the satellite via a TDMA accessing scheme hence at each satellite ground station the filtered data will be queued and a burst will be transmitted within the corresponding time slots. The satellite will receive those messages and simply broadcast it down to the aircraft which will listen to the slots of interest based on the region of interest. At the same time while this is happening, CPDLC data and voice will be transmitted and received via ground VDL links with no satellite usage. Also, FIS-B messages will be created and sent along with TIS-B messages from each of the ground stations to be broadcast to all the aircraft. The systems

can have redundancies in the form of redundant satellite transponders, redundant ground stations or reliance on radar vs. ADS-B, redundant ground links via other means if necessary. The details of those redundancies were not investigated for this study

2. The Ground Network

The ground network, shown in Figure 2, consists of a network of ground-based radar sites, as well as stations listening to ADS-B transmissions from nearby aircraft.

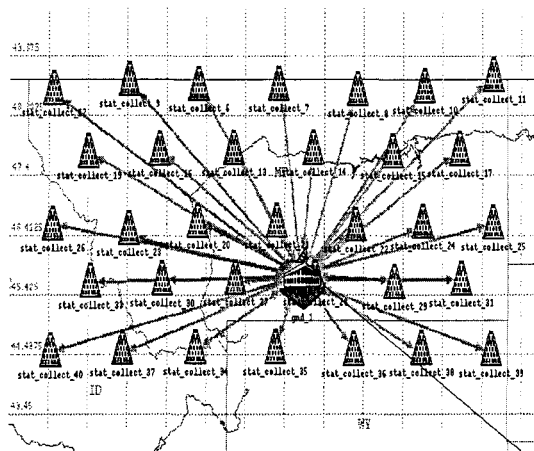


Figure 2: Surveillance Ground Subnetwork

The ground-based radars are of three types: primary surveillance radars, located at major airports, higher power en-route radars, and secondary surveillance radars co-located with the first two types, which interrogate transponders on board aircraft in the vicinity. The secondary surveillance radars are of two types: Air Traffic Control Radar Beacon System (ATCRBS) and Mode Select (Mode S.) The ATCRBS radars, in turn, are divided into two further types: older radars interrogating aircraft at a higher rate using a sliding window, and newer monopulse radars which interrogate aircraft

at a slower rate. Secondary surveillance radars are described further in [2].

Supplementing the radar systems are ADS-B ground stations which listen to ADS-B transmissions from aircraft sent via the Mode S and Universal Access Transceiver (UAT) data links. Commercial aircraft, and other high-performance jet aircraft optionally broadcast their position, velocity, and intent information using Mode S, while most general aviation aircraft optionally use UAT. The minimum aviation system performance standards for ADS-B are described in [3], and descriptions of the Mode S and UAT data links as used in ADS-B can be found in [4] and [5].

The ground-based ADS-B listening stations, and the primary, enroute, and secondary surveillance radar sites feed their information to TIS-B ground stations, which process the incoming data to remove redundant information. The TIS-B ground stations then uplink filtered data to aircraft via a satellite network to provide a complete situational awareness picture to aircraft equipped to receive TIS-B information.

Redundant data needs to be removed for the following reasons:

- 1) ADS-B transmissions from the same aircraft may be heard by more than one listening station in the ground-based network. However, that information should be relayed via satellite only once.
- 2) Even when an aircraft broadcasts ADS data, it is probably being tracked by ground-based radars as well (except in remote areas.) The satellite ground stations should only uplink whichever data is collected that is of a higher quality.

Each listening station in the ground network generates ADS-B packets at a specified rate for the purposes of the simulation, as opposed to actually listening

to many aircraft. This is done in order to speed up the simulation. The ADS-B traffic is generated at the intervals specified for individual aircraft in RTCA DO-260A, the 1090 MHz Extended Squitter MOPS, divided by a mean number of aircraft per ground station, defined at simulation time.

The packets transmitted are 112 bit Mode S packets, again chosen for convenience. ADS-B and TIS-B information relayed to the satellite ground stations in a real system are likely to be Mode S Extended Squitters. Although different packet formats may be used within the SATCOM network, in the current experiment the Mode S format was retained because in a SATCOM system, each ground station will still need to relay the 56 bit ADS-B payload, as well as the 24 bit ICAO address. Using a 112 bit packet allows for four bytes of header information, at least some of which will definitely be present in any SATCOM link.

The primary reasons for the existence of the TIS-B satellite network can be described as follows:

- 1) Not all aircraft are equipped with ADS-B, and even aircraft that are equipped may be using either Mode S, or UAT, but not both. Aircraft sending ADS-B information, will receive ADS information broadcast over the same data link (Mode S or UAT) that the aircraft use to transmit their own ADS-B data. An external source (the satellite network) is needed to provide data about aircraft using the other data link, or about aircraft which are not transmitting ADS-B information at all. The last group of aircraft are only seen by ground-based radar.
- 2) The range of ADS-B is limited by the transmitter power of the sending aircraft, and by the interference environment present between sending and

receiving aircraft. The interference environment for Mode S ADS-B consists of replies to Mode S and ATRBS ground radars which are sent on the same frequency (1090 MHz). The interference environment for the UAT data link consists of military JTIDS transmissions and interference from TACAN/DME navigational aids.

The ground network is structured in a hierarchical fashion. ADS-B listening stations and primary, enroute, and secondary surveillance radar sites, feed their information to regional processing centers via either T1 or optical links. The regional centers in turn, forward the collected information to one or more satellite uplink ground stations. Multiple satellite uplinks may be used to combat the effects of local weather disturbances on the uplink transmissions. The downlink to aircraft will not be as affected by weather since most aircraft using the service will be flying above the cloud layer.

3. The Satellite Network

Figure 3 shows an OPNET [6] network layout which also serves to illustrate the architecture of the satellite sub-Network. The figure is shown for the continental United States (CONUS) but can be easily generalized to other areas of the globe. The satellite ground stations are assumed collocated (not required but preferably for economical reasons) with the regional control centers hence there are 20 within the CONUS. In addition to the 20 stations we show a central processing center that is connected to all stations which can be use for multi purposes including redundancy management in case of weather, malfunction or upgrade reasons, global data

manipulations, and other. The Geostationary satellite is located at (W101 degrees) to serve those stations. Again the satellite location is chosen to serve the CONUS and surrounding area but can be used for most of the North and South American continents with more satellites needed to fill the globe if necessary.

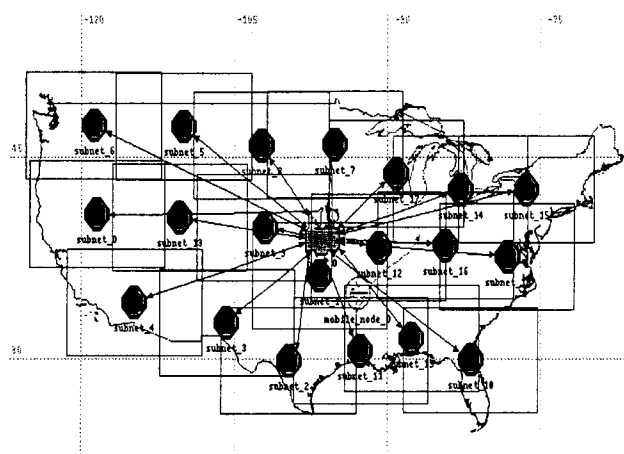


Figure 3: CONUS Satellite sub-Network (note that each node above corresponds to a sector with a satellite earth station and ADS-B ground stations as shown by Figure 2. The satellite node is not shown).

As described in the last section and in the introduction, each of the ground stations will be transmitting a burst of messages at a TDMA rate of 0.01 second time slots with a 0.005 guard band. Hence for 20 stations we are able to receive a TIS-B or a FIS-B faster than the minimum required rate of 1 per second. Note the time slots can be increased five fold and still meet that requirement. Again if more ground stations are added to fill other regions then correspondingly smaller time slots will have to be used. Other types of accessing schemes can be considered, none the less TDMA is widely used and hence from a implementation point it is an acceptable choice. Also, since for this architecture, we are not requiring uplinks from the airplanes to ground (or no Return channels), as well as the broadcast feature, the need for more capacity via other accessing schemes is not the main issue. In

Uplink Frequency (GHz)	29.750
Downlink Frequency (GHz)	19.95
GSO Satellite Transponder Parameters	
Uplink xponder saturation flux density (dBW/m ²)	-96
Xponder saturation EIRP (dBW)	54
Uplink receive G/T (dB/K)	13.9
Uplink receive noise temp (K)	575.44
Uplink receive gain (dBi)	41.50000047
Satellite Altitude (km)	35786
ATC Hub Station Parameters	
Antenna diameter (m)	2.4
Xmit gain (dBi)	55.26205892
Xmit power (dBW)	17 (50.12 watts)
Xmit EIRP (dBW)	72.26205892
Recv gain (dBi)	51.79117752
System Noise Temp (dB-K)	26.67 (464.52 K)
Recv G/T (dB/K)	25.12117752
Elevation angle to satellite (deg)	40
Aircraft Terminal Parameters	
Recv gain (dBi)	37
System Noise Temp (dB-K)	25 (316.23 K)
Recv G/T (dB/K)	12
Elevation angle to satellite (deg)	40
Signal Modulation/Coding Parameters	
Hub source data rate (Rb) (bps)	10000000
Channel symbol rate Rs (sps)(1/2 coding & QPSK)	10000000
Required Eb/No (dB) (10-6 @ 1/2, K=7 FER, QPSK)	4.5
Bandwidth-limited Capacity of Xponder	
Xponder BW (Hz)	27000000
User Xmit BW (Hz)	20000000
Brdcst Grnd-Aircraft Lnk Bdgt Final results	
UPLINK factors	
Hub Elevation Angle(deg)	40
Coverage Angle (deg)	13.30864957
Central Angle (deg)	43.34567522
Slant Range to Sat (km)	37780.30419
Free-Space Path Loss (dB)	-213.4628304
Atmospheric Loss (dB)	-0.461666838
Rain Loss (dB) 99.90 % availability	-14.56591541
Polarization Loss (dB)	-1
Received U/L C/No (dB-Hz)	85.2728554
DOWNLINK factors	
Slant Range to Sat (km)	37780.30419
Free-Space Path Loss (dB)	-209.991949
Atmospheric Loss (dB)	-0.447838163
Polarization Loss (dB)	-1
A/C Noise Temp	316.23 K
Recv Downlink C/No (dB-Hz)	79.41685937
NET LINK PERFORMANCE	
Net C/No (dB-Hz)	78.41433558
Available Eb/No (dB)	7.414335582
Required Eb/No (dB) 10-6;QPSK; r=1/2 conv code	4.5
Link Margin at Hub (dB)	2.914335582

Table 1: Satellite System Parameters per Transponder (Final results of link margin shown obtained from more detailed models

[7])

[7] more results are shown for trade off between TDMA and CDMA accessing. In summary the choice of TDMA for this architecture is appropriate because we have fixed ground links that can be synchronized with less effort, as well as the fact that we can use the full power settings. The links proposed are not rigid at this stage but are recommended to be in the Ka band mainly to reduce the antenna sizes to be mounted on the aircraft [8]. Other advantages of Ka band such as higher bandwidth availability are not applicable or critical since mobile and broadcast FCC requirements limits the available bandwidth to 500 Mhz regardless. The C band, Ku band, and Ka band all have the same allocations, hence the main thrust will be antenna size and available spectrum at time of implementation. None the less, if the antenna sizes and cost of mounting issues are not taken into account, then in reality the lower bands (i.e. C band) will be better with respect to rain, and weather attenuation. Table 1 below shows some of the parameters assumed for the satellite system per an assumed 27 Mhz transponder.

4. Modeling and Simulations

The previous two sections summarized the ground and satellite networks respectively and Figures 2 and 3 were obtained from the architecture built using the simulation package OPNET [6]. The aircrafts were simulated by transmitting ADS-B message sets directly from the ADS-B ground stations (shown in Figure 2) at the mean rate of 10 ADS-B sets (corresponding to 10 aircraft per ground station per ARTCC) with a standard deviation of $(0.4 * \text{mean rate})$ using a uniform distribution. The reason for not including the aircraft as separate mobile nodes was mainly to speed up simulation time and not due to inability to do so as per the description in Section 2. The one mobile node in Figure 3 was included for testing purposes to check reception quality at higher aircraft speeds.

The data traffic modeled in this simulation was only ADS-B messages purely for matter of convenience. The data traffic could conceivably include TIS-B messages generated from radar, as well as FIS-B information as well, provided that additional resources are allocated (i.e. higher bandwidth transponders, or additional transponders on the satellite and ground ends).

Figure 4 is a plot of two of the ground stations. The top plot shows the TDMA burst transmission rate for one ground station from Figure 3 (and Figure 2). Similarly, the bottom plot shows the TDMA transmission rate for another ground station. The other stations are not shown, but the profiles will look similar taking different time slots per station. The time between each burst of TDMA transmissions is seen as equal to the total number of stations minus 1 (or $20-1=19$) multiplied by each station time slot (in this case 0.01 sec).

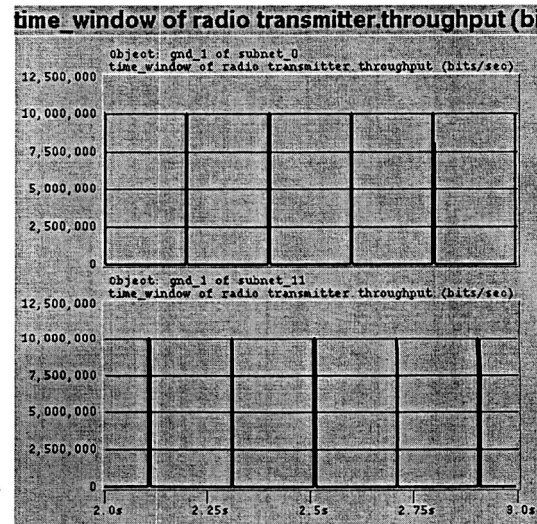


Figure 4: Plots a and b, TDMA transmissions from satellite ground stations (only two station shown of the 20)

Also, it is worth noting that during one TDMA time slot, the burst rate is at maximum setting until all the packets in the ground station queue are transmitted. If the queue is emptied before the end of one time slot then the transmitter will stay idle unless

it receives any packets within that time in which case it will transmit those directly (at least based on the present design).

The satellite on the other hand is receiving from all of the ground stations and hence its data rate profile has no gaps (assuming all stations are active) and that is shown by the top plot of Figure 5. Since the satellite is a bent pipe, it simply re-transmits all the data it receives at the downlink frequency where it will be intercepted by the receiving mobile (or fixed) nodes. The second plot of Figure 5 shows the received S/N at the satellite node. It is worth noting that this value is large compared to that shown in Table 1 of the link budget analyses due mainly to not including rain attenuation (14.56 db) (i.e. clear sky condition) along with polarization and atmospheric attenuation effects (1 db and 0.5 db respectively) in the channel model of the simulation used. Note that if we subtract those values from the S/N value seen in plot, we arrive at the values shown in Table 1 for the Uplink taking into account the 20 Mhz of bandwidth assumed to convert to S/No in db-hz. In numerical terms $(30-14.4-1-0.5)+10\text{LOG}(20\text{e}6)=87.1$ which is very close to the values found in Table 1 for the S/No of 85.3. The reason for the 1.8 db difference comes from a variation in the antenna gains (amounting to almost 0.7 db) and small path distance differences due to the locations of the stations and the satellite. Hence, we had kept that in mind as we arrived at the very small BER using the standard BER tables for QPSK in OPNET (not shown). Even if we included those additional terms we would still have negligible BER that matches with the link budget results of Table 1.

The data rate from each TDMA satellite ground station is set at 10e6 bits/sec per transponder on board the satellite using 1/2 FEC and QPSK. Note in Table 1, it is assumed that the Bandwidth occupied by a channel with data rate Rb is $2 \cdot R_b$ (which is a worse case formula) and hence the bandwidth occupied for 10e6 bits/sec is 20 Mhz. This bandwidth fits well within one

typical satellite transponder with enough additional room for higher data rates that are needed for transmission of other than TIS-B messages such as FIS-B, control and paging channels, and others. Needless to say if higher data rate are needed then the use of higher bandwidth satellite transponders is an option, or the use of more than one is another more costly option. Other performance parameters were observed from the simulation that are not shown here included queue sizes and number of packets received, power levels, and several more.

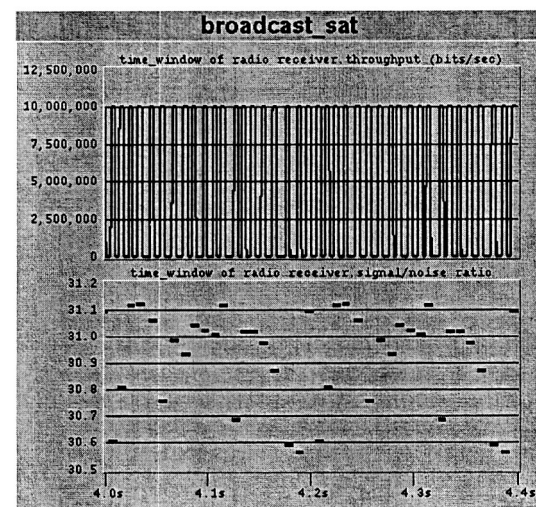


Figure 5: Plots a and b, TDMA receptions at satellite (first Plot shows bits/sec throughput, second plot show S/N in db)

On the downlink side, the signal was observed from a moving mobile node (airplane in flight), and at the fixed earth stations. With clear sky conditions the reception between the aircraft and the earth fixed nodes differs due to the different gains of antennas, and the path distance (hence path loss) all stated in Table 1. The plots of Figure 6 shows the received signal data rate at the mobile node (or aircraft) as per the top plot. This is the same profile as that received by the satellite because of the bent pipe operation of the satellite already described. Also the second plot shows the S/N received at the aircraft node. Again just as in the Uplink verification, we see here that the values are very similar to Table 1

taking out the polarization effects of 1 db and the atmospheric attenuation of 0.5 db. Note the rain attenuation is not included due to the aircraft being at higher altitudes in the En Route phase. With that the numerical calculation shows $(7.8-1-0.5)+10\log(20e6)=79.3$ which is practically the same as the number shown in Table 1. Again the BER are very negligible at the S/N from the QPSK BER vs. S/N standard curves.

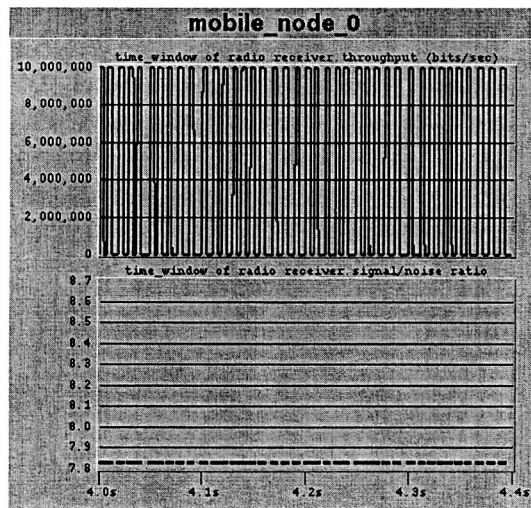


Figure 6: Reception at aircraft (first Plot shows bits/sec throughput, second plot shows S/N in db)

Finally, the plot of Figure 7 shows a typical queue size in packets at a satellite ground station. As predicted, the queue builds up until its time for the beginning of the stations time slot at which case it drops down rapidly based on the given TDMA burst rate. Although the packets arriving from all the ADS-B transmission are random in quantity due to the uniform distribution imposed, they average in the mean to values that are predictable. If more packets were to be sent (via increasing the mean of the ADS-B sets transmission, or the number of aircrafts) to values larger than 10, the queue would have kept building up due to inability of the TDMA processor to catch up. The way to compensate for higher rates or larger number of aircrafts is by utilizing higher bandwidth transponders, or by using

multiple transponders for the satellite and the ground ends. In the next section, more comments are made with respect to the options available to increase overall system capacity in terms of data rates or aircrafts.

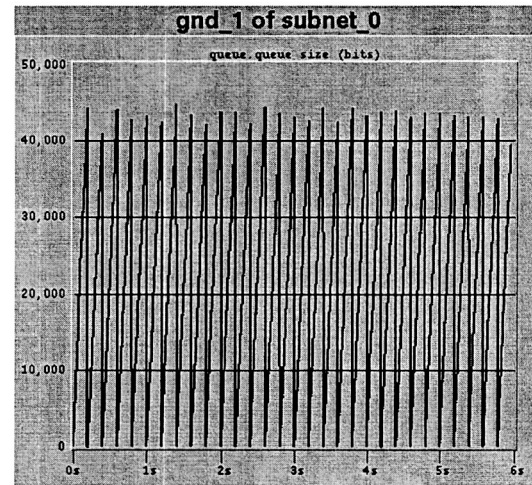


Figure 7 Queue build up and empty operation at a typical ground TDMA transmitter.

5. Conclusions and Recommendations

A simulation was built and a proposed architecture was presented for the use of AMSS for the ATN. Specifically, the use of satellite links for the transmission and broadcasting of TIS-B and FIS-B messages was proposed as an alternative to ground based proposals. The architecture considers use of ground ADS-B mode S, and UAT transceivers as well as VDL, and secondary and primary surveillance radars, all for transmission of ADS-B, CPDLC, and present radar operations. In addition, a single (and if necessary more) satellite transponder is used in a bent pipe method along with satellite ground stations, one for each of the sectors. The satellite earth stations would collect ADS-B and radar information from all the aircraft within its sector, filter the data to remove redundancies and to create TIS-B messages. The TIS-B messages are then queued along

with other data such as FIS-B and transmitted at the TDMA time slots designated for each earth station. The satellite receiver takes all the messages from all satellite ground stations and simply down links the data which will then be received by receivers on board the aircraft. The present architecture does not require a satellite transmission capability on board the aircraft (only reception) and hence simplifies the satellite as well as the aircraft transceiver design. The aircraft receiver will be able to get the data from any location in the CONUS (or satellite coverage area) and it is envisioned that on board displays can feed that information into a CONUS, or local maps which will show the aircraft in a given area. This capability will be useful for free flight planning, for initial flight plans, and for predicting future traffic patterns at any location based on the intent messages of the ADS-B. Also, last but not least the FIS-B information will be more readily available for not only the local areas but for any area within the satellite earth stations and satellite broadcast coverage area. The availability of information that is not simply localized to the aircraft position will be useful not only to the pilots for flight planning, but also for the airlines, and the FAA center.

In summary the advantages of using the satellite links and the architecture proposed here are among many:

- broadcast capability to wide areas and areas that are outside the range of ground stations signals such as over oceanic regions.
- The reception only (or broadcast option) requirement for the aircraft simplifies and reduces the cost of the aircraft equipment as well as the satellite system itself. The broadcast capability of satellites is ideal for such an application.
- Having TIS-B, and FIS-B data readily available about any area (or within CONUS for a non-global design) is beneficial for the airlines, FAA, and pilots in making flight plans, free flight, and scheduling.
- The satellite links are reliable for En Route.
- Each transponder on the satellite, with a data rate of 10 Mbps, is capable of supporting twenty ARTCC uplink sites, each being fed from 33 TIS-B ground stations, each relaying ADS-B information from a mean of 10 aircraft +/- 40%. With two transponders on the satellite each at a different frequency, it would be possible to support 660 aircraft per ARTCC, with TDMA slots of 0.02 seconds, with one transponder handling eastern traffic, and the other handling western traffic.
- Using two transponders each with a 27 (or higher bandwidths such as 36 Mhz), it is possible to realize the proposed design. Hence for a short term application it is a cost effective method that can utilize satellites that are already in operation by simply leasing one (or if needed more) transponders. Additionally redundancy can be achieved by using other satellite transponders for back up.
- While other accessing schemes could have been considered, TDMA is an acceptable option that is not difficult to achieve especially since the ground stations are fixed nodes (as oppose to mobile) hence the synchronization is not as difficult. TDMA is used in many existing satellite architectures and hence the capability, and equipment is readily available. At this point it is also worth noting that a dynamic TDMA slot assignment can also be considered as an option to increase throughput by accommodating the differences in the density of the airspace over different sectors.

- The use of the ground part of this architecture conforms with the accepted standards that are proposing VDL, Mode S and radar for the various communications and navigations services for the ATN.
- Although in the present architecture the satellite earth stations were located at each sector control center, it is possible to reduce the number of them assuming the sectors' data can be shared. Nonetheless, the use of one satellite station per air sector is beneficial from many aspects:
 - a- It can provide redundancy in case of weather, service outage, or any other reasons that may require one of the station to stop operating.
 - b- For a future outlook where there may be a possibility of utilizing spot beams, for uplink capability in which case gateways will be necessary and hence the availability of such stations within each spot beam is useful.

Possible disadvantages of the architecture proposed are:

- For other than En Route, the satellite links can fail with a small percentage when receiving during rain. That is for altitudes below the clouds (or below 5 Km) it is possible that the signals will fade causing a loss of reception. This disadvantage can be overcome at airport locations for the aircraft that are landing or taking off by providing back up ground based broadcasts via an alternate link. The information in that link could be localized to reduce data rates until the satellite signal becomes available. Note the rain fade will also effect the transmissions of the satellite earth stations, and in that case it is necessary to re-route the data using the central ground station to transmit from else where. Hence in that case

it is more feasible and not as difficult (in addition to being a necessity) to transmit the information.

- While the satellite broadcast can cover remote areas, oceanic or other, the lack of ground stations in those remote areas makes the availability of the messages to be transmitted to ground (which include ADS-B, UAT, CPDLC) an issue. Unless HF frequency is assumed, or a more costly satellite uplink design is available, that disadvantage is there regardless of the use of satellite links for broadcasting.

6. Acknowledgements

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