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GPS-Squitter Channel Access Analysis

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16. Abstract

GPS-Squitter is a system concept that merges the capabilities of Automatic Dependent Surveillance (ADS) and the Mode S beacon radar. The result is an integrated concept for seamless surveillance and data link that permits equipped aircraft to participate in ADS and/or beacon ground environments, offering many possibilities for transition from a beacon to an ADS-based environment.

A number of choices exist in the selection of the squitter channel access protocol, including the access technique (i.e., random or organized), as well as such issues as the rate of squitter transmissions and whether they are fixed or variable.

This report provides an analysis of the performance of the channel access protocol selected for GPS-Squitter compared with other alternative approaches. The results of this analysis indicate that the performance of the selected protocol is superior to the defined alternatives.

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1. INTRODUCTION

1.1 GPS-SQUITTER

The International Civil Aviation Organization (ICAO) has defined a concept for communications, navigation, and surveillance for the next century known as the Future Air Navigation System (FANS). A cornerstone of the FANS is the increasing reliance on the use of satellite-based navigation systems such as the Global Positioning System (GPS). A second thrust of the FANS is surveillance based on the down linking of aircraft-derived satellite position information, a technique known as Automatic Dependent Surveillance (ADS).

The general application of ADS under the FANS concept will require that all aircraft in a region of airspace be equipped with satellite navigation and some form of data link. Since such general equipage will take many years, early implementation is expected to take place in regions where other surveillance techniques are not practical, e.g., over ocean and in remote areas. Planning is currently under way for ADS to support Air Traffic Control (ATC) management of oceanic routes. Significant economic benefits are anticipated due to the reduction in separation (and the resultant capacity increase at favorable altitudes) made possible by ADS. This form of ADS connects an aircraft via a point-to-point link with the controlling oceanic ATC facility.

The application of ADS in terminal and overland areas requires a more general form of ADS in which the aircraft broadcasts its position in an omni-directional fashion. This form of ADS is known as ADS broadcast (ADS-B). The use of broadcast makes it possible for one ADS transmission to simultaneously serve the surveillance needs of multiple ground ATC and airborne collision avoidance activities.

GPS-Squitter [Ref. 1] is a system concept that merges the capabilities of ADS Broadcast and the Mode S beacon radar [Ref. 2] via the randomly timed transmission of a Mode S 112-bit reply known as an extended squitter. The result is an integrated concept for seamless surveillance that permits equipped aircraft to participate in ADS-B or beacon ground environments. GPS-Squitter is a natural way to transition National Airspace System (NAS) surveillance from a ground-based beacon radar system to a GPS-ADS-based environment. It also offers several other possibilities for significant benefits to the NAS.

1.2 SURVEILLANCE APPLICATIONS

The GPS-Squitter transmission can be received by omni-directional or sector-beam ground units in order to support air traffic control activities of airborne aircraft. Surveillance of aircraft on the airport surface can also be provided based on the extended squitter transmission. Special surveillance applications such as the monitoring of closely spaced parallel runways can also be supported.

A 56-bit squitter, containing just the aircraft Mode S address, is currently the basis for TCAS acquisition of Mode S equipped aircraft. The address is then used to discretely interrogate the Mode S aircraft for TCAS surveillance purposes. If TCAS aircraft are equipped for GPS-Squitter (i.e., there is an on-board GPS unit), a modification to the TCAS equipment to receive the long squitter containing the ADS data will permit TCAS to perform most of its surveillance by passively listening to squitters. The information available from GPS can also serve as the basis for a form of TCAS that generates horizontal maneuvers as resolution advisories, in contrast to the current vertical-only maneuvers.

The squitter can also serve as the basis for Cockpit Display of Traffic Information (CDTI). In this role, the squitters would be received by nearby aircraft, as would be done for TCAS. For CDTI, the receiving aircraft has the ability to display nearby aircraft to the pilot, but no resolution advisories are generated. This mode of operation is similar to the traffic advisory portion of TCAS as provided in TCAS 1. The squitter will make it possible to provide this service to general aviation at low cost.

1.3 DATA LINK CAPABILITY

Since GPS-Squitter is based on the use of a Mode S transponder, the capability exists to provide two-way data link to equipped aircraft. The ground component of this data link can be provided by the 143 Mode S narrow-beam interrogators now being fielded, or it can be provided by omni-directional or sector-beam ground stations, including those used for surface surveillance.

1.4 GPS-SQUITTER CHANNEL ACCESS TECHNIQUE

The GPS-Squitter design uses the same pseudo random channel access approach, but at a 2-Hz rate for higher reception reliability. For airborne aircraft, the rate is fixed at 2 Hz. Surface aircraft use a 2-Hz rate when moving, but switch to a rate of once per 5 s when the aircraft is stationary in order to reduce channel occupancy at high density terminals.

In addition to the squitters containing ADS position information, GPS-Squitter transponders transmit an additional squitter containing the aircraft's ICAO identity. This identity squitter is broadcast pseudo randomly at a rate of once per 5 s for airborne aircraft and moving surface aircraft, and once per 10 s for stationary surface aircraft.

1.5 REPORT PURPOSE

Other approaches to GPS-Squitter channel access are possible, e.g., other data rates and the use of time division multiple access (TDMA) rather than pseudo random transmissions. The purpose of this report is to analyze the performance of the channel access technique selected for the GPS-Squitter and to compare this performance with alternative data rates and channel access approaches.

1.6 REPORT OVERVIEW

GPS-Squitter shares the channel with activities related to surface beacon radar and TCAS. An analysis of GPS-Squitter capacity must account for this activity. Section 2 defines several cases that span the range of interference that would be encountered in GPS-Squitter operation. An analysis of the effect of pseudo random squitter rate in each of these interference environments follows. Section 4 considers a variable squitter rate for surface and airborne aircraft. The channel access characteristics resulting from that analysis are used to estimate the capacity of the GPS-Squitter concept using a pseudo random channel access technique. The results of this capacity analysis are then compared with the capacity that would be obtained using a TDMA rather than a pseudo random approach. The report ends with a summary of the principal conclusions.

2. INTERFERENCE MODEL

The interference model used to evaluate GPS-Squitter performance is defined in terms of a rate of Air Traffic Control Radar Beacon System (ATCRBS) and Mode S replies per second per aircraft. Values chosen for the interference model are presented in Table 1, a breakdown of the Mode S reply source is presented in Table 2.

Case 1 is intended to represent a worst case ATCRBS and Mode S environment. The 120 ATCRBS replies per transponder per second represent a higher rate than has been observed over large areas in the United States, although higher rates have been reported in Europe. The Mode S rate of 14 replies per second per aircraft represents a very high level of Mode S and TCAS activity.

Case 2 represents an ATCRBS rate more typical of current high density environments in the United States.

Case 3 represents a future environment where ATCRBS activity has been replaced by Mode S.

Case 4 represents the environment where TCAS has converted to passive surveillance using GPS-Squitter and thus does not include the five short Mode S replies per second indicated in Table 2.

TABLE 1

Interference Cases

REPLIES PER SECOND PER AIRCRAFT			
CASE	ATCRBS	MODE S SHORT	MODE S LONG
1*	120	8	6
2	60	8	6
3**	0	8	6
4***	0	3	6

* CURRENT HIGH DENSITY
** ALL MODE S WITH HIGH DATA LINK ACTIVITY
*** CASE 3 WITH PASSIVE TCAS

TABLE 2

Mode S Reply Source

SHORT REPLIES	
• GROUND SURVEILLANCE AND DATA LINK	1
• CURRENT SQUITTER	1
• ALL-CALL	1
• TCAS	5
LONG REPLIES	
• GPS-SQUITTER	2.2
• GROUND DATA LINK	3.8

3. FIXED PSEUDO RANDOM AIRBORNE SQUITTER RATE

The airborne traffic capacity for a ground-based GPS-Squitter receiving station is presented in Figure 1 as a function of the number of squitters transmitted per second by each aircraft. For ease in calculation, the results of Figure 1 assume that the number of squitter reception opportunities available in N seconds is N times the number of squitters per second, which leads to the assumption of 10 opportunities in 5 s for the 2-Hz case. The capacity analysis of Ref. 3 (and the following sections of this report) make the more conservative assumption that only 9 squitter reception opportunities are certain to be available, due to the pseudo random jittering of the squitter broadcast times.

The results shown in Figure 1 are for a station with an omni-directional antenna and indicate a capacity that can be supported for each interference case while providing an update once per 5 s with a probability of greater than or equal to 99.5%. The traffic capacity shown represents the traffic within 150 nmi of the station.

The figure indicates a substantial increase in capacity through a change from one to two squitters per second. Further increases in squitter rate offer only a modest increase in capacity for Cases 1 and 2, indicating that the improvement in performance offered by an increased number of squitters per 5 s is offset by the reduced probability of receiving each squitter due to the increased channel activity. This effect of the increased channel activity is shown in Case 4 where the squitters become the dominant activity at the higher squitter rates. For Case 4, the capacity reaches a peak and then decreases due to the effect of squitter occupancy on the probability of squitter reception.

These effects are shown more clearly in Figure 2, which presents the fractional capacity change resulting from one additional squitter per second. The change in squitter rate from one to two per second results in an increase in capacity of from 0.7 to over 0.9 for Cases 1 through 4, respectively. An increase to three squitters per second provides an additional improvement of less than 0.3. The selected operating point of two squitters per second is seen to represent a reasonable rate for airborne surveillance.

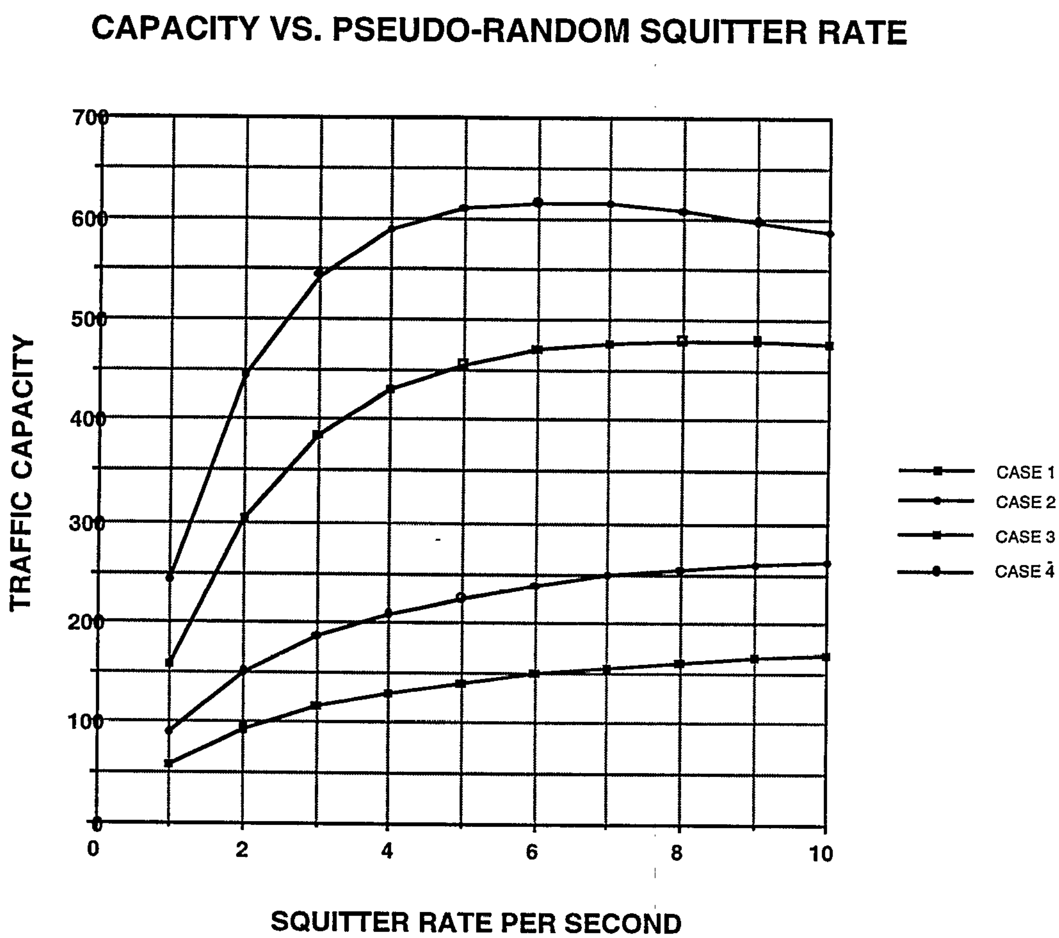

Figure 1. Airborne capacity vs. pseudo random squitter rate.

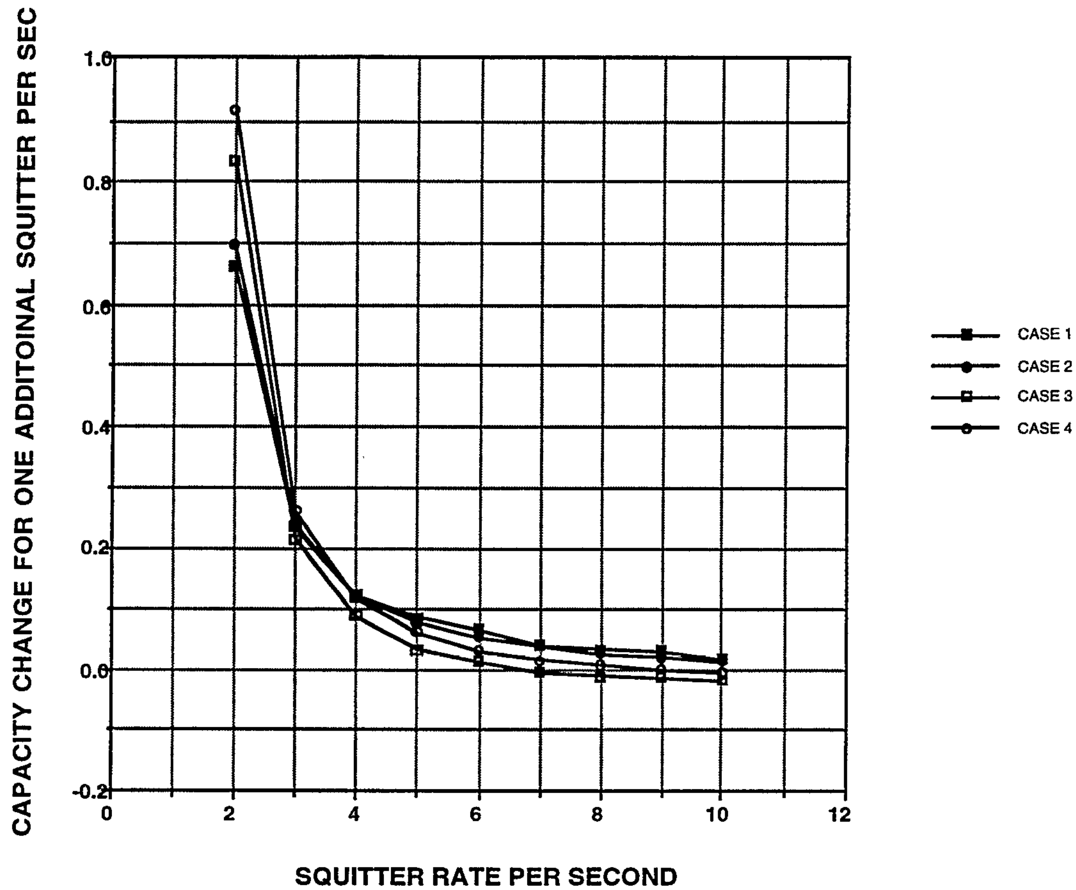

Figure 2. Effect of one additional squitter per second.

4. VARIABLE PSEUDO RANDOM SQUITTER RATE

4.1 PURPOSE

The purpose of a variable squitter rate is to reduce channel occupancy by using a reduced squitter rate when the aircraft is stationary on the surface or not accelerating when airborne. A variable squitter rate can be expected to provide greater benefits when squitter is the dominant channel activity. This is the case on the surface, but not the case when the aircraft is airborne.

4.2 VARIABLE AIRBORNE SQUITTER RATE

In order to evaluate the performance of a variable squitter rate for airborne aircraft, the following candidate technique is assumed:

a) Squitter at a 2-Hz rate when the aircraft is accelerating,

b) Squitter once per 5 s when the aircraft is not accelerating,

c) Transition to the higher rate immediately when acceleration is detected on board the aircraft.

The capacity performance for a variable rate squitter technique for airborne aircraft was calculated for the four interference cases. The results are presented in Figure 3 where the capacity of an omni receiving station is plotted as a function of average squitter rate for the aircraft under surveillance. An average squitter rate of zero to two per second was used in the capacity estimate. An average of two per second corresponds to the fixed rate technique.

As expected, the results of Figure 3 show virtually no change in capacity as a function of average squitter rate for Cases 1 and 2, since the squitter represents a very small part of the channel activity for these cases. Some increase in capacity is observed for the other two interference cases, but these capacity gains are modest and do not justify the complexity of using the variable rate technique. Similar results are presented in Figure 4 for the six-sector antenna case. A six-sector antenna reduces the input to each receiver by a factor of 2.5 as compared with an omni-directional antenna, as described in Ref. 3.

4.3 VARIABLE SURFACE SQUITTER RATE

The approach under development for a variable surface squitter rate is as follows:

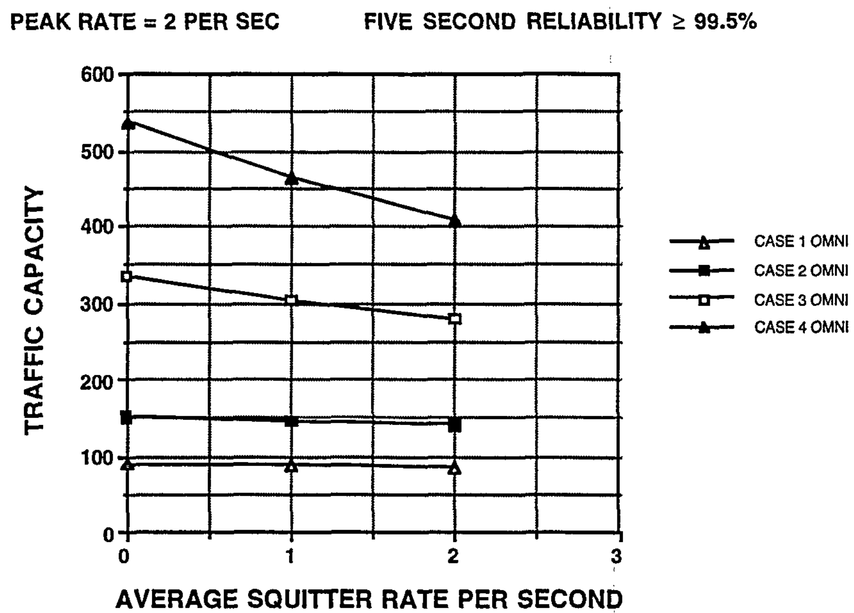

Figure 3. Omni airborne capacity vs. average squitter rate.

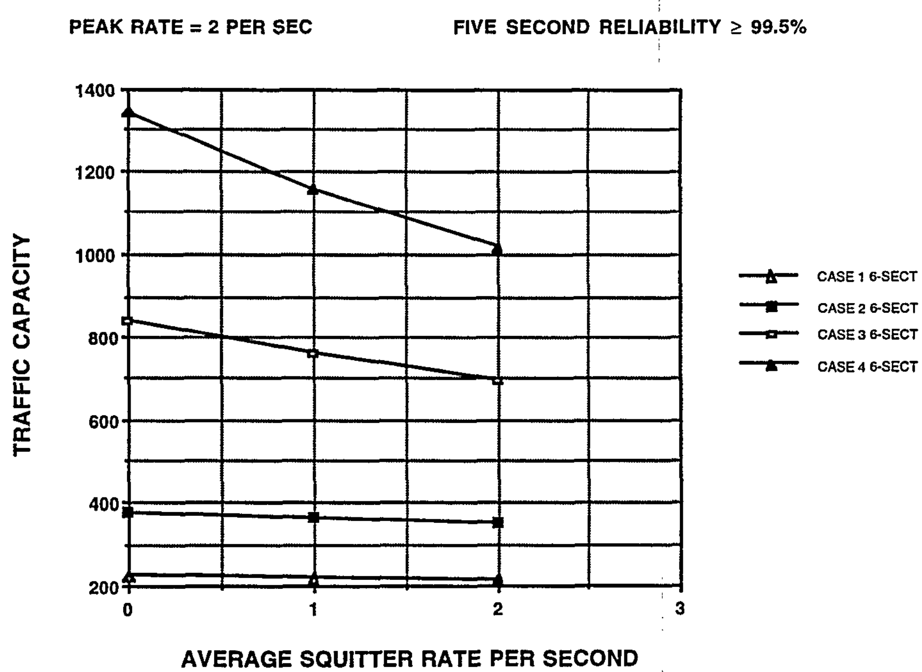

Figure 4. Six-sector airborne capacity vs. average squitter rate.

a) When the aircraft is moving, emit:
   - Position squitter at a 2-Hz rate
   - Identity squitter once per 5 s

b) When the aircraft is stationary, emit:
   - Position squitter once per 5 s
   - Identity squitter once per 10 s

c) Transition to the higher squitter rate immediately when motion is detected on board the aircraft.

d) Provide controls for the ground to prevent a transition to the low rate when the aircraft is in a critical position, e.g., stopped at the entrance to an active runway.

A recent survey conducted by Lincoln Laboratory of the top 10 airports in the United States indicates an instantaneous peak movement area count of 100 or less, as shown in Table 3. The occurrence of more than 100 aircraft in the movement area corresponds to overload conditions caused by weather or other problems. In these cases, large numbers of aircraft would be queued and the percentage of stationary aircraft would increase as the surface count increased. Based upon this reasoning, it is assumed that the peak squitter rate at a high density terminal will be no more than 220 squitters per second. This is the rate that would be received from 100 moving aircraft, using the preceding algorithm.

TABLE 3

Movement Area Peak Aircraft Count

RANK	CITY	AIRPORT	INSTANEOUS PEAK
1	CHICAGO	ORD	100
2	DALLAS/FT WORTH	DFW	100
3	LOS ANGELES	LAX	60
4	ATLANTA	ATL	60
5	DENVER	DEN	24
6	MIAMI	MIA	75
7	BOSTON	BOS	30
8	PHOENIX	PHX	40
9	CHARLOTTE	CLT	36
10	ST. LOUIS	STL	36

A comparison of the probability of successful reception vs. the number of surface aircraft is shown in Figure 5. The results of this figure include the assumptions that (1) each surface receiver detects the replies from 20 airborne aircraft, each replying at the rate defined for Case 2 in Table 1, and (2) replies received without interference from other replies will be received at a 95% probability due to multipath effects. The rationale for these assumptions is explained in Ref. 3.

Note that the use of the variable squitter rate will accommodate a greater number of aircraft while maintaining a high probability of successful reception.

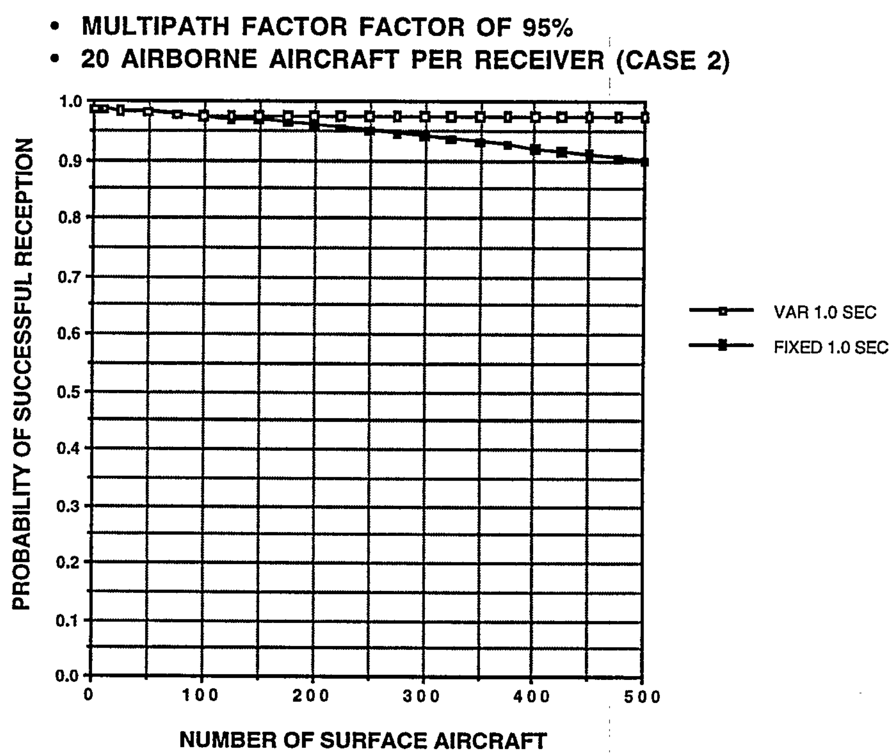

Figure 5. Surface detection probability over 1.0 second.

5. BASELINE PSEUDO RANDOM SQUITTER CAPACITY

The preceding analysis has confirmed the choice of a fixed rate of two squitters per second while airborne and a variable squitter rate while on the surface. The airborne capacity achievable for omni and sector antenna stations is presented in Table 4 for each of the four interference cases. The capacity achievable for surface operation is presented in Table 5.

TABLE 4

Airborne Capacity vs. Number of Antenna Sectors, 2-Hz Squitter

5 SEC UPDATE RELIABILITY ≥ 95%

CASE	REPLIES/AC/SEC		MAX AIRCRAFT			
	ATCRBS	MODE S	OMNI	6-SECTOR	9-SECTOR	12-SECTOR
1	120	14	85	215	325	425
2	60	14	140	350	525	700
3	0	14	280	695	1050	1400
4	0	9	410	1015	1525	2030

TABLE 5

Surface Operating Capacity, One-Second Update

SQUITTER RATE	CAPACITY	RELIABILITY
FIXED	250	95%
	500	90%
VARIABLE	500	97%

6. TDMA VS. PSEUDO RANDOM CAPACITY FOR GPS-SQUITTER

6.1 TDMA CHARACTERISTICS

6.1.1 Definition

TDMA is a technique for minimizing signal collisions on a channel shared among multiple users. In practice, each user is assigned a time slot for transmission in a repeating pattern of time slots called a frame.

6.1.2 Range Guard Considerations

The user cannot occupy all of the time available in a time slot, since time must be reserved for signal propagation to the most distant user. This is necessary to prevent interference with the transmission in the next time slot. The time reserved for propagation is called the guard time. In effect, the guard time ensures that the transmissions from all users within the guard range occur in the form of expanding rings, as shown in Figure 6, where the transmission from aircraft B cannot take place until after the passage of the transmission from aircraft A. The expanding ring propagation pattern ensures that the rings never cross and therefore there can be no garble to users within the guard range.

The guard range must be chosen correctly, since operation outside this protected range will lead to garbling by a distant user as shown in Figure 7. Since slot assignments are normally fixed, once garbling occurs, it will occur repeatedly frame after frame.

6.1.3 Application

TDMA is an excellent technique for improving channel utilization when the following criteria are true:

a) All (or at least most) of the channel users are transmitting only in assigned TDMA time slots,

b) The range guard is small compared with the message length, and

c) In a broadcast application, all users have the same update rate requirement.

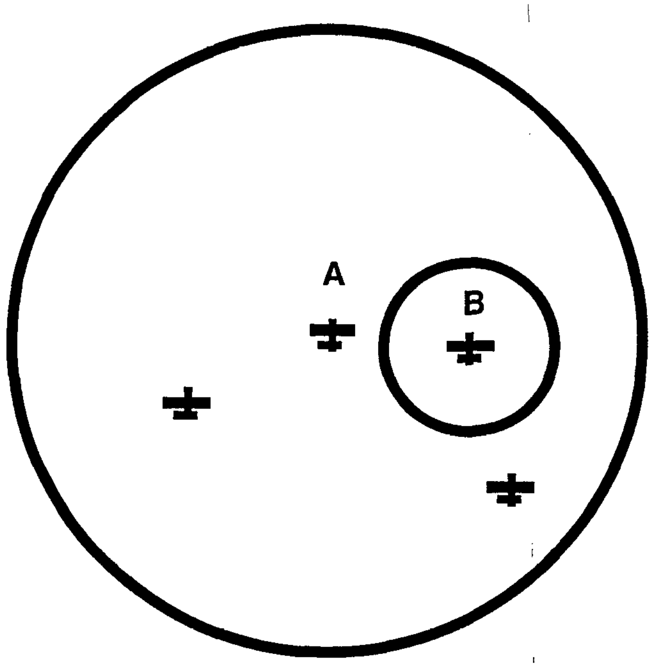

Figure 6. TDMA garble protection within the guard band.

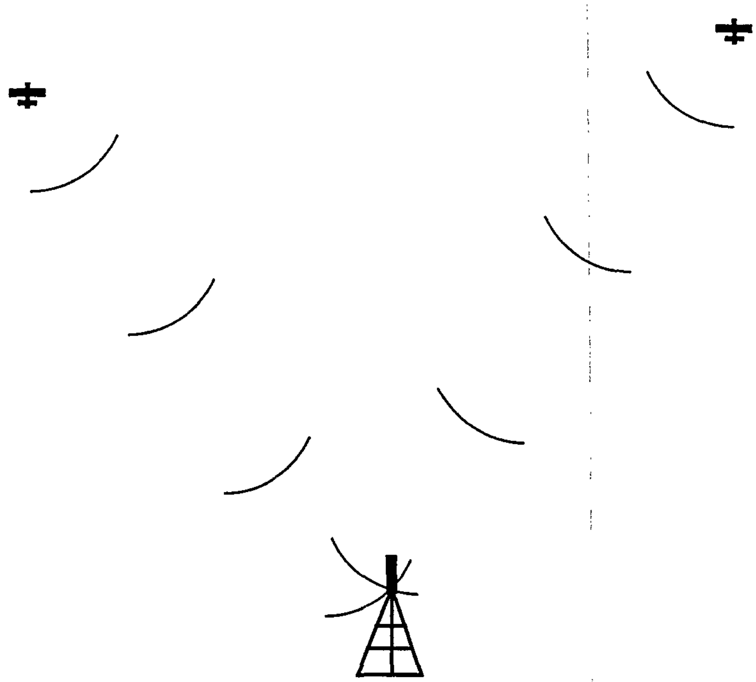

Figure 7. TDMA garble outside the guard band

6.2 DESIGN CONSIDERATIONS FOR TDMA APPLICATION TO GPS-SQUITTER

6.2.1 Channel Activity

GPS-Squitter operates on a shared channel with users that could not feasibly be required to follow the TDMA protocol. As seen from the interference model (Table 1), squitter is not the dominant activity on the channel. The majority of the channel activity is related to ground beacon radar and TCAS operation.

6.2.2 Range Guard

The Mode S squitter is 120 μs long. The guard time for a protected range of 150 nmi would be about 925 μs, yielding a maximum channel utilization of less than 12%. A system with a 200 -mi range guard would have a maximum utilization of less than 9%.

6.2.3 Sector Antennas

Sector antennas are used in GPS-Squitter ground stations to break up the traffic population and thus reduce the squitter rate to the receiver connected to each sector, which has the effect of increasing the maximum operating capacity, as shown in Table 4.

TDMA operation cannot achieve higher operating capacity through the use of sector antennas in overlapping coverage. This effect is illustrated in Figure 8. Ground stations A and B both use sector antennas with overlapping coverage as indicated in the figure. Ground station A is receiving ADS transmissions from the two aircraft in different beams and therefore could achieve a higher capacity by assigning theses two aircraft to the same time slot. Such an assignment would cause the replies from these aircraft to be garbled at ground station B, since both of these aircraft are in the same antenna beam for that station. The same garble situation would apply if ground station B used an omni-directional antenna.

6.2.4 User with Different Update Rate and Range Requirements

The update rate for a TDMA time line must satisfy the requirements of the user with the highest update requirement. The range guard must be set to be appropriate for the longest range user, meaning that a TDMA system intended for use for TCAS and en route surveillance must provide a 1-s update rate out to 200 nmi. The result is a higher than necessary data rate for en route surveillance.

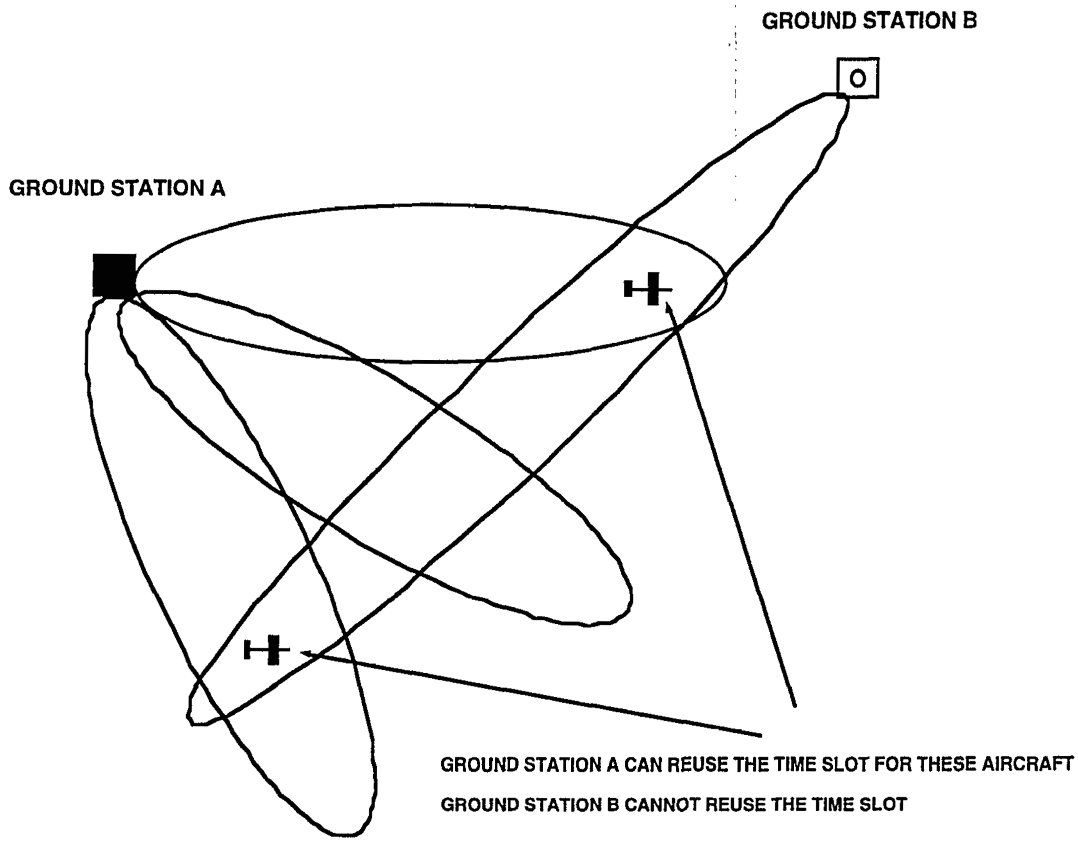

Figure 8. TDMA slot reuse.

Compared with a TDMA approach, the pseudo random approach has the ability to satisfy aviation surveillance users with different update requirements. The TCAS surveillance requirement is for a 1-s update rate out to about 14 nmi. A 5-s update is required for terminal ATC operation for aircraft out to 60 nmi. En route sensors currently provide a 12-s update rate to a range of 200 nmi.

A TCAS receiving GPS-Squitter broadcasts would operate at a sensitivity level adequate for 14 mi. This level means that the TCAS squitter receiver would process squitters from a small fraction of the aircraft visible to a terminal or en route squitter receiver, permitting the TCAS to operate at a squitter probability level suitable for a 1-s update. The en route and terminal receivers operate with a much higher signal traffic density due to their greater operating range. While leading to a lower probability of reception of a single squitter, the multiple squitter opportunities produce a high probability of an update during the 5- or 12-s update period. Both requirements are handled simultaneously by the same pseudo random squitter.

6.3 GPS-SQUITTER CANDIDATE TDMA CHARACTERISTICS

In order to compare a TDMA approach versus a pseudo random approach for GPS-Squitter, it is necessary to define the characteristics of a candidate TDMA time line. The characteristics of such a time line are as follows:

- 120-μsec transmission
- 250-nmi guard range
- 1545-μsec guard time
- 1665-μsec frame time
- 600 slots per 1-s frame

6.4 TDMA CAPACITY

An analysis of a GPS-Squitter system using a TDMA technique is presented in Figure 9. This figure presents the capacity provided by a TDMA technique applied to GPS-Squitter. The solid curves represent the maximum traffic capacity that will provide a 5-s update rate with a probability of 99.5%, as determined by the channel activity caused by the reply by other aircraft. Note that these curves show slightly greater capacity performance than Figure 1 for the pseudo random technique. This result follows from the fact that the TDMA technique slightly reduces channel interference for squitter reception since the squitters are timed to be non-interfering. The dotted curve shows the maximum TDMA aircraft capacity as determined by the number of transmissions per aircraft per second. Thus, at a squitter rate of once per second, the TDMA system has 600 time slots.

For Case 1, the TDMA slot capacity is always in excess of the maximum number of aircraft that can be handled and still meet the requirement of greater than or equal to 95% probability of a successful reply reception every 5 s. For the other interference cases, the TDMA slot capacity restricts the aircraft capacity to less than the number determined by the requirement for a 95% probability of reception every 5 s.

6.5 CAPACITY COMPARISON

In order to compare capacity for equivalent performance, the TDMA capacity was calculated using an update rate of twice per second. Capacity for the pseudo random and the TDMA techniques applied to GPS-Squitter is presented in Table 6, based on the use of a 2-Hz squitter rate, the same as for the pseudo random case. This rate provides the best overall TDMA capacity, as indicated in Figure 9.

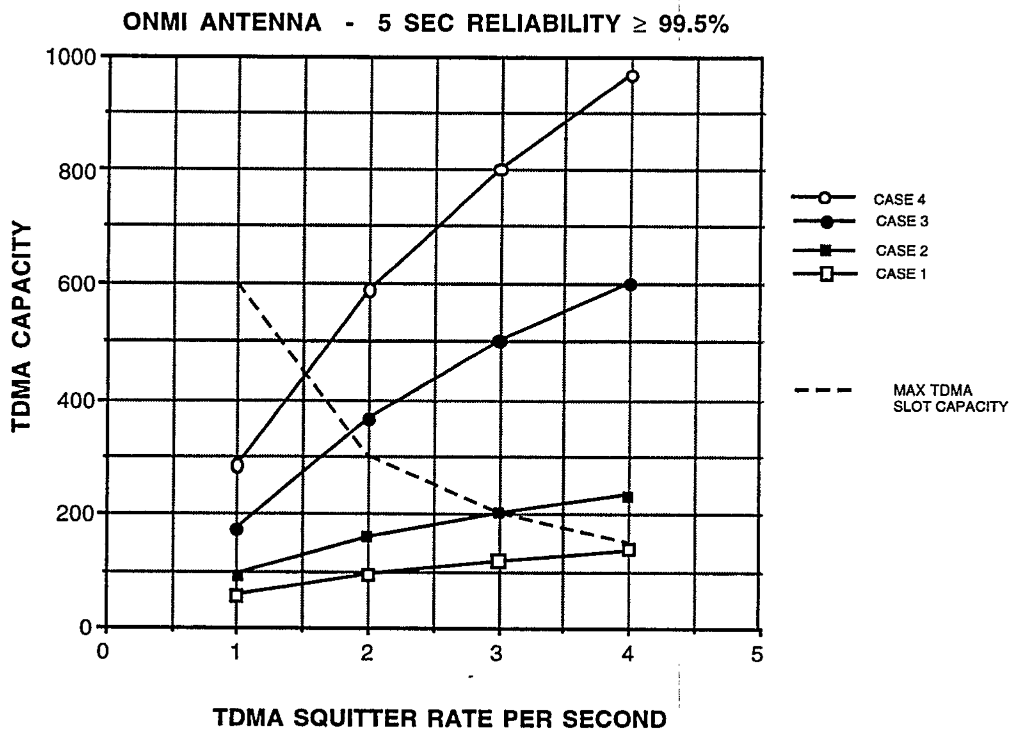

Figure 9. TDMA capacity vs. ADS transmission rate.

TABLE 6

Airborne Capacity Comparison, 2-Hz Squitter Rate

TECHNIQUE	CASE 1	CASE 2	CASE 3	CASE 4
FIXED RATE PSEUDO RANDOM				
OMNI	85	140	280	410
6-SECTOR	215	350	695	1015
9-SECTOR	325	525	1050	1525
12-SECTOR	425	700	1400	2030
TDMA	95	160	300	300

7. SUMMARY

7.1 MAXIMUM SQUITTER RATE

In the environment foreseen for GPS-Squitter, an ADS broadcast rate of 2 Hz provides the best operating point in terms of traffic capacity and interference caused by the squitter transmissions. Further increases in squitter rate do not provide a significant capacity increase.

7.2 USE OF A VARIABLE SQUITTER RATE

The use of a variable squitter rate is beneficial on the airport surface since squitter is the dominant channel activity. A variable squitter rate does not provide worthwhile benefits for the airborne case.

7.3 TDMA VS. PSEUDO RANDOM SQUITTER

Because GPS-Squitter shares the channel with other activities, a structured time line (such as TDMA) for the squitter activities is not effective in improving capacity. A second consideration is that the high data rate together with the maximum range requirement leads to a very low link utilization, since guard time is the dominant channel activity.

From Table 6 it can be seen that for the omni case, the TDMA approach provides a very small improvement in capacity for Cases 1 to 3 and less capacity for Case 4. Of greater importance is the fact that TDMA provides significantly less capacity than the pseudo random technique applied to sector beam antennas.

In the GPS-Squitter operating environment a pseudo random technique is ideal since it is a simple approach that can be implemented by a small modification to current Mode S transponders, it is compatible with the use of sector antennas and it automatically satisfies the different update rate requirements of TCAS and ATC surveillance.

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