Advanced Satellite Communication Technology for Oceanic Air Traffic Control

by

Edward H. Kim

Submitted to the Department of Electrical Engineering and Computer Science

in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Electrical Engineering and Computer Science

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ABSTRACT

The current oceanic Air Traffic Control (ATC) system suffers from many inefficiencies, mainly because of infrequent position updates from aircraft. Satellite communication technology shows great promise in solving many of oceanic ATC's problems. In this thesis, we explore available methods for more efficient data transmission in support of oceanic ATC. After examining different types of communication protocols (slotted and random access), multiple access schemes (Time Division Multiple Access and Code Division Multiple Access), bandwidth utilization (spread spectrum and non-spread spectrum), and communication modes (burst and continuous), we separate and identify possible candidate systems, each a unique combination of the previously mentioned communication system concepts, and compare and contrast them in terms of a set of system requirements and criteria deemed critical for oceanic ATC. Throughout the thesis, a special focus is given to CDMA because of its potential capacity advantages. The trade-offs between the candidate systems are considered, and we conclude that TDMA burst systems have a clear advantage over continuous CDMA systems in oceanic ATC. The choice among the various TDMA systems depends on which oceanic ATC criteria are viewed as the most important.

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List of Acronyms

A/C	Aircraft
ARINC	Aeronautical Radio, Inc.
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
BW	Bandwidth
CDMA	Code Division Multiple Access
CW	Continuous-Wave
DS	Direct Sequence
FAA	Federal Aviation Administration
FANS	Future Air Navigation Systems
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
FSR	Feedback Shift Register
GEO	Geosynchronous Earth Orbit
GES	Ground Earth Station
GPS	Global Positioning System
HF	High Frequency
ICAO	International Civil Aviation Organization
INS	Inertial Navigation System
LPD/LPI	Low Probability of Detection / Low Probability of Intercept
ML	Maximum-Length
MP	Multipath
MUI	Multi-User Interference
PG	Processing Gain
PN	Pseudo-Noise
RFI	Radio Frequency Interference
SS	Spread Spectrum
TDMA	Time Division Multiple Access
TRACON	Terminal Radar Approach Control
TOA	Time of Arrival
VHF	Very High Frequency

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1. Introduction

1.1 Overview

The Air Traffic Automation Group, Group 41 at Lincoln Laboratory, is investigating new concepts for using satellite communications in reporting aircraft position while the aircraft are flying over the ocean outside of radar coverage. Unlike domestic Air Traffic Control (ATC), which uses radar to track aircraft, oceanic ATC relies on aircraft to periodically, approximately once per hour, transmit their current position to land-based controllers using High Frequency (HF) radio. This is an inefficient system that results in wasted fuel by the aircraft and less efficient use of the airspace. The next-generation approach for reporting aircraft position uses Inmarsat, a constellation of four satellites in geosynchronous orbit. The communication protocol used by the Inmarsat satellites, however, is inefficient for rapidly reporting the positions of many aircraft.

Frequent transmission of aircraft position data to air traffic controllers may allow aircraft to fly oceanic routes more efficiently. Fleet-wide fuel savings on the order of $220M per year may be possible, along with other savings. Instead of using the current communication protocol, other approaches should be explored. One approach uses Code Division Multiple Access (CDMA) combined with spread spectrum broadcast, and another uses Time Division Multiple Access (TDMA) on a standard Inmarsat communications channel. Chapter 2 describes the Inmarsat satellite system in more detail.

1.2 Basic System Options

Chapter 3 provides a high-level introduction to candidate communication protocols and multiple access schemes. One candidate protocol, called random access, is useful because it does not require aircraft to coordinate amongst themselves. There is no need for a master scheduler activity that coordinates communication resources, nor must aircraft synchronize to the same clock. In a system that uses random access coupled with CDMA, aircraft simply broadcast their positions periodically, with each aircraft having been assigned a separate, orthogonal pseudo-noise (PN) code (Chapter 3) to be used for the CDMA encoding. This allows multiple users to transmit at the same time without the problem of user messages being lost when the messages collide, i.e., overlap in time. Chapter 5 includes explanations and discussions of these candidate systems.

A related approach involves sharing a TDMA channel among several aircraft. The channel would remain continuously open, with aircraft assigned to specific time slots within the channel based on their proximity to other aircraft. This approach requires more coordination among the various aircraft but is worthy of further study because of its simplicity and cost-effectiveness.

1.3 System Requirements

We wish to define a set of system requirements before exploring our candidate satcom ATC systems. Comparing and contrasting the candidate systems in terms of the same set of requirements serves to put all the candidate systems on an equal footing. The following are the major system requirements:

- 500 simultaneous aircraft per satellite
- 150-bit messages with 150 bits of forward error correction (FEC) coding
- 30-second position update interval
- 10 bits/sec average data rate per aircraft
- An average of one bit error in 10,000 bits, i.e., bit error rate (BER) = 10^{-4}

1.4 Thesis Goal

As stated in the overview section, the current oceanic ATC system can be greatly enhanced by using satellite communication technology; we want to explore available methods for more efficient data transmission in support of oceanic ATC. Exactly what type of technology, which communication protocol, multiple access scheme and communication mode should be used, remains to be determined, and this thesis will address each of these issues. The goal of this thesis is to separate and identify a number of possible candidate systems for the current oceanic ATC system, and compare and contrast them in terms of the system requirements we have established in this chapter. The thesis will conduct these comparative evaluations in relation to a set of criteria deemed to be important in oceanic ATC (Chapter 5); the evaluations will be general enough so that a different set of system requirements will simply prompt minor modifications to the thesis results, without having to make drastic changes or redo the evaluations. Throughout the thesis, a special focus will be given to CDMA, a promising technology that has recently seen great success in civilian applications such as cellular phones. Furthermore, we want to describe any trade-off that might exist between the candidate systems.

The thesis is organized as follows: Chapter 2 will introduce the current oceanic ATC system and its procedures – it discusses oceanic ATC shortcomings and areas of potential improvement. This chapter also introduces a concept called "Free Flight," which is seen as one of the ultimate goals in oceanic ATC, and gives explanations as to how a satcom approach would help achieve this goal.

Chapter 3 gets into the heart of the thesis material; it focuses on the communication issues, and introduces the communication multiple access schemes, protocols, and modes that will be used extensively in the comparative evaluations.

Chapter 4 elaborates on TDMA, and concludes by putting the relevant system concepts together in a system architecture tree, which is a taxonomy tree showing the hierarchy and the relationship of all of the communication concepts.

Chapter 5 justifies the choice of the seven most suitable options from the system architecture tree and performs a comparative evaluation of these seven options. Wherever possible, trade-offs between these options will be discussed and illustrated.

Finally, Chapter 6 identifies the best candidate systems for oceanic ATC among the seven options chosen in Chapter 5.

2. Current Oceanic Air Traffic Control Procedures

2.1 Airspace Definitions

Airspace controlled by the Federal Aviation Administration (FAA) falls into three major categories: domestic en route, terminal area and oceanic. The means for tracking aircraft, i.e., surveillance, and communication, vary between each category. This leads to differences in how aircraft are separated to maintain safety.

Most areas of the United States are covered by en route airspace. Radars with a 12-second sweep period continuously monitor aircraft movement, while pilots and controllers communicate instantly using VHF (Very High Frequency) radio. Aircraft at the same altitude are allowed to pass within five nautical miles (nmi) of each other, but if they will pass closer than that, altitude separation must be established. A separation of 1000 feet is adequate below 29,000 feet, but above that altitude a 2000-foot separation must be maintained.

Many busy airports make use of a Terminal Radar Approach Control (TRACON) facility to help organize the traffic flow for efficient use of the runways. A dedicated radar with a five second sweep period allows smaller separations than in en route airspace.

The United States is responsible for operating large areas of oceanic airspace from three oceanic ATC facilities. The Anchorage, Alaska facility is responsible for all aircraft flying in and around Alaska, and relies on radar to provide position data for aircraft in most of that airspace. There is a gap in radar coverage in the airspace leading toward the Far East, and oceanic separation rules apply in that region. Figure 2-1 shows the airspace controlled by Alaska (dashed lines denote radar coverage).

The New York Air Route Traffic Control Center (ARTCC), located in Ronkonkoma (Long Island), New York, is responsible for oceanic airspace in the western part of the North Atlantic (approximately 3 million square miles), as shown in Figure 2-2. Most of this airspace lacks radar coverage, except for an area around Bermuda. The United States Navy used to operate the Bermuda radar, but as part of the military downsizing they have turned responsibility for that radar over to the FAA. Radar data is transferred by telephone line from Bermuda to New York Center for use by air traffic controllers.

The Oakland Air Traffic Control Center located in Fremont, California (south of San Francisco) is responsible for most of the North Pacific airspace (see Figure 2-3). Except for radar coverage around the Hawaiian Islands and Guam, this airspace is operated entirely under oceanic separation rules. Oakland Center is responsible for over 20 million square miles of airspace, nearly 10% of the Earth's surface.

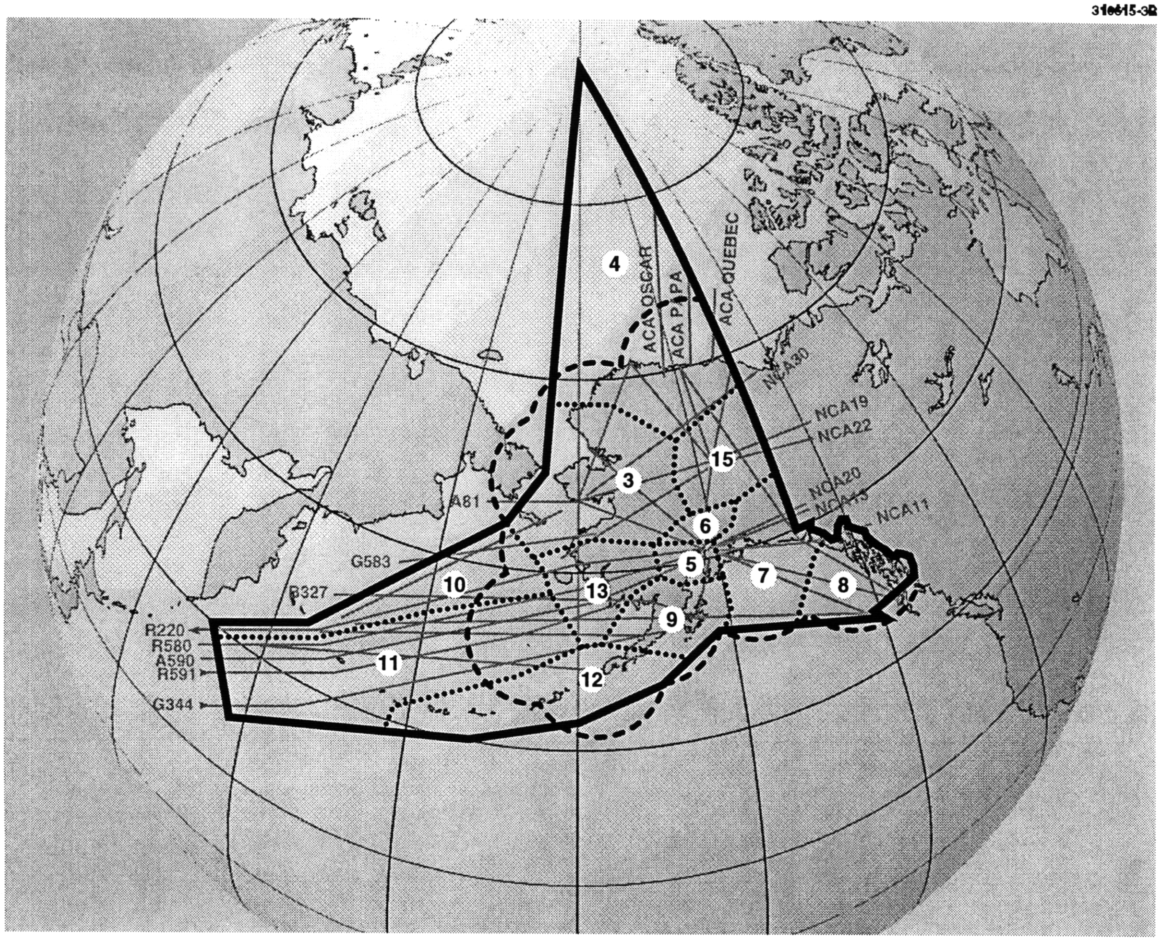


Figure 2-1. Alaskan airspace.

2.2 ATC Communication

Pilots and controllers must communicate using HF (High Frequency) radio, since line-of-sight VHF radio communication is not possible over the ocean. VHF communication is possible around most of Alaska, as well as the islands of Hawaii, Guam, and Bermuda. A non-profit company called ARINC (Aeronautical Radio, Inc.) is responsible for handling the actual HF communications between pilots and air traffic controllers. For example, when a pilot wants to climb to a higher altitude, they make that request to the ARINC HF Radio Operator. If the operator is busy talking with other aircraft, the pilot must wait their turn. The operator takes the pilot's request and logs it into the ARINC Message Data Base, and then relays it via redundant communication channels to the air traffic controllers. The controller, who is also responsible for many aircraft, must deal with the request as time permits. Once the controller determines what to do, the decision is relayed by voice back to the ARINC ATC Operator. This operator accesses the data base to retrieve the original request, appends the reply to it, and sends the package back to the ARINC HF Radio Operator, who relays the reply to the pilot. Several minutes can elapse while this entire process unfolds (see Figure 2-4).

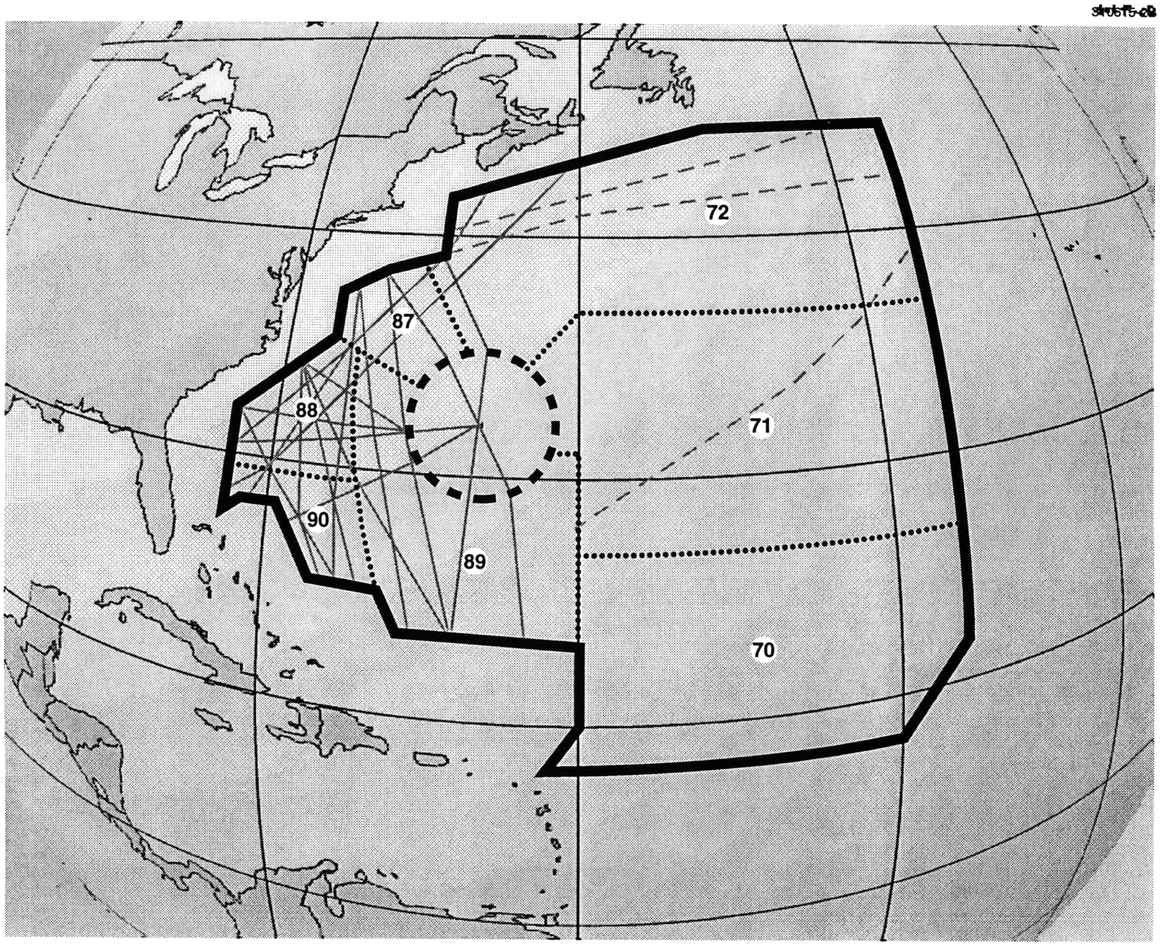


Figure 2-2. New York airspace.

2.3 Shortcomings of Current ATC System

Oceanic travel today is characterized by a track structure which is set up twice daily to take advantage of, or avoid, the prevailing winds. Aircraft are separated procedurally by assigning them to specific tracks at specific altitudes, and separating the tracks so that aircraft are unlikely to drift onto a neighboring track. No radar coverage is provided over the ocean, therefore large separations are established between aircraft as they begin their flights. These large separations help insure that aircraft do not accidentally collide during the course of their journey. The inertial navigation systems (INS) that aircraft use to determine their position "drift" approximately one nautical mile per hour over the ocean, because there are no fixed, ground-based radio beacons available to update the INS. Oceanic travel takes many hours to complete, because of the large distances that must be traveled. For each hour of flight, the distance between an aircraft's actual position, and the INS estimated position, will grow by about one nautical mile. Oceanic tracks are separated horizontally to accommodate this drift rate, and aircraft are metered onto each track to provide adequate along-track separation. A typical North Atlantic eastbound track structure is shown in Figure 2-5.

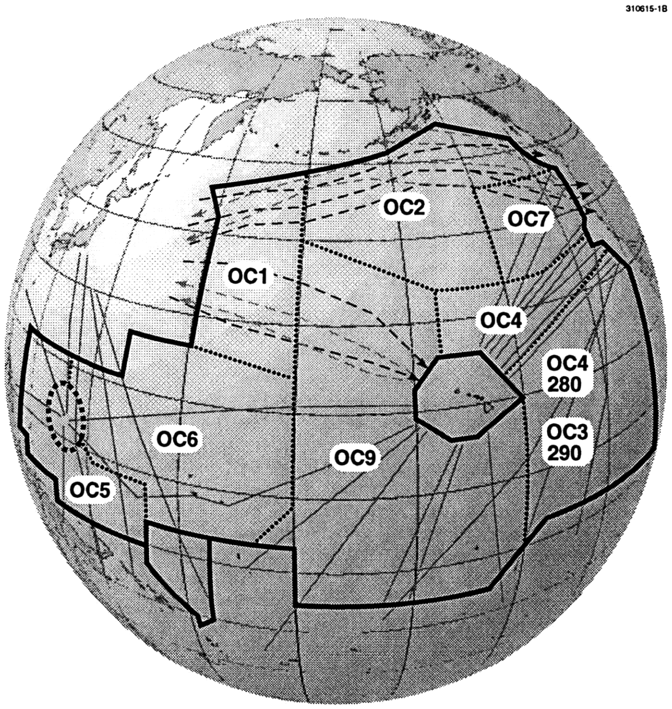


Figure 2-3. Oakland airspace.

The emphasis on safety is clearly justified, but this rigid, procedural approach to oceanic ATC forces aircraft to fly long distances at inefficient altitudes, which wastes fuel. This ATC system has evolved around the limitations of HF radio. The FAA and airlines currently pay over $40 million per year to maintain the HF radio system used to control oceanic aircraft flying in the western Atlantic and the Pacific.

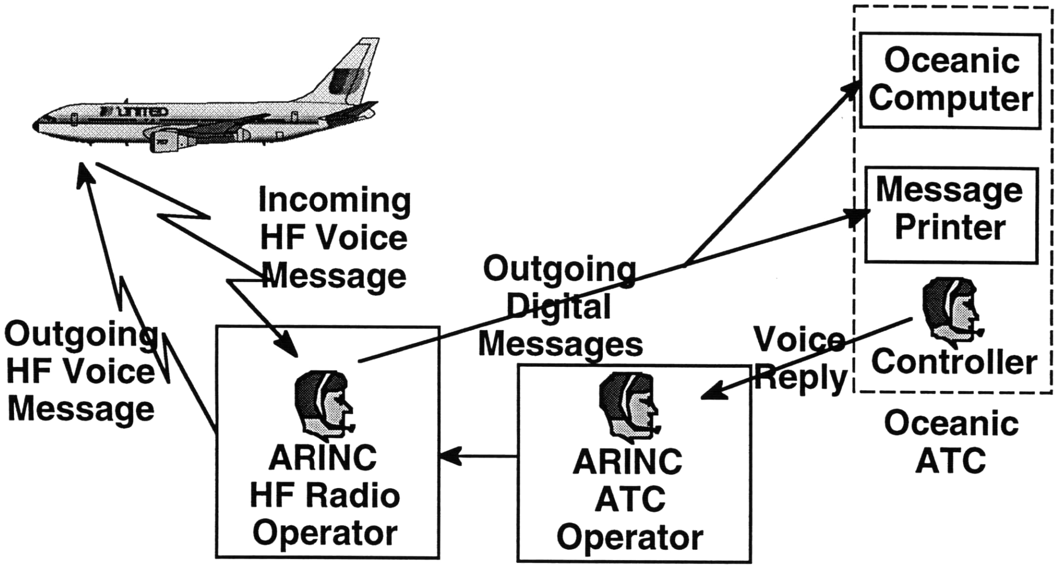


Figure 2-4. ATC-Pilot communication via ARINC.

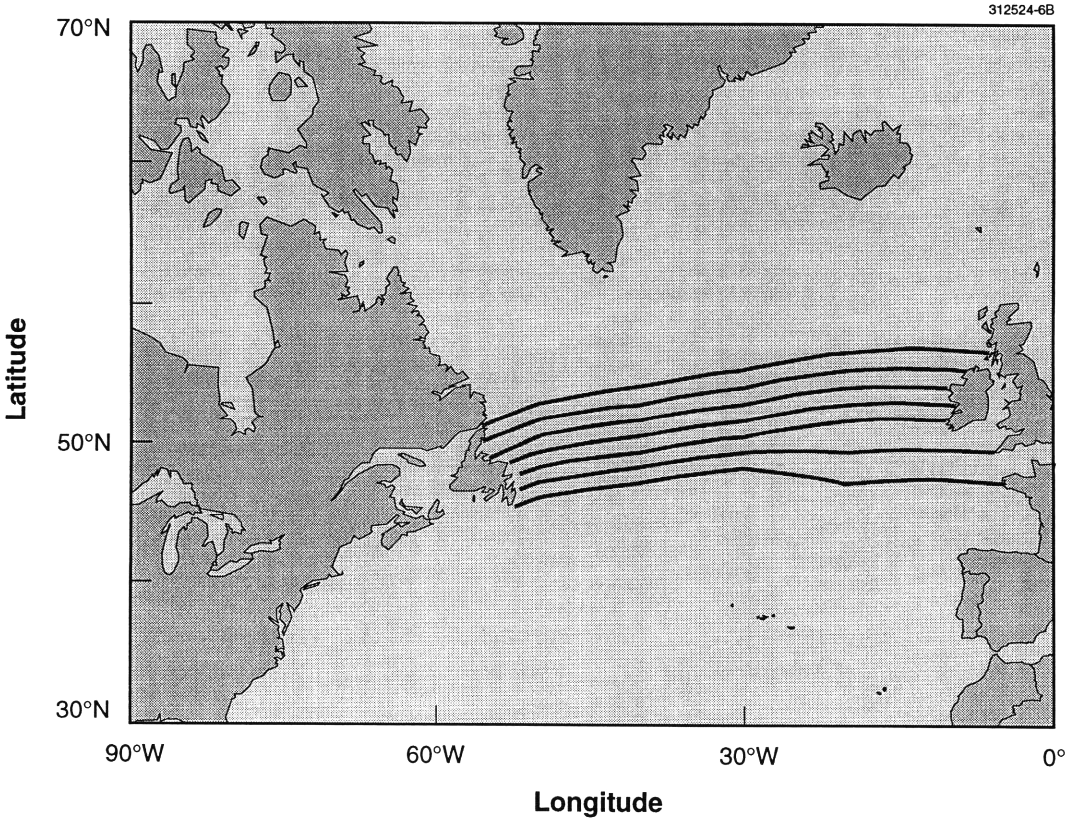


Figure 2-5. North Atlantic eastbound track structure.

2.4 Inmarsat: A Possible Solution

Inmarsat is an international consortium of over 80 countries that operates a constellation of four communication satellites in geosynchronous orbit. The satellites are spaced around the Earth so that they can provide overlapping coverage of the ocean areas up to a latitude of around 70 degrees. Inmarsat recently changed its name from the International Maritime Satellite Organization to the International Mobile Satellite Organization to reflect its intention to compete against Iridium, GlobalStar, and other systems that will offer communication services to mobile users. However, the Inmarsat acronym is so well known that it was decided not to change it.

Inmarsat, whose U.S. signatory is Comsat, has recently launched their third generation of satellites into orbit to replace the second generation equipment. These satellites utilize spot beams to achieve a higher communication capacity by frequency reuse. In order to maintain a minimum of 10° elevation between the satellite and the horizon, aircraft communicating through Inmarsat must be flying within ± 70° latitude, and ± 70° in longitude from the satellite's longitudinal position. The fields of view of these satellites are shown in Figure 2-6 (Note: distances between Earth and the satellites are not to scale).

Communication between satellites and ground stations is conducted at C-band (4.19 - 6.43 GHz), while L-band (1.53 - 1.64 GHz) is used between the satellite and mobile user (ship or aircraft). Over 20,000 ship operators use Inmarsat as an alternative to HF radio, and over 1500 aircraft are also equipped to communicate using Inmarsat satellites.

Satellites provide an alternative to HF radio for ATC-pilot communications. Aircraft could automatically determine their position using Global Positioning System (GPS) satellites, and relay this data via Inmarsat for display on controller's computer screens. This concept of utilizing satellites for air traffic control is called "FANS-1," with "FANS" being an acronym for Future Air Navigation Systems, and "1" signifying that this is an initial effort. FANS is the result of a collaborative effort led by ICAO, the International Civil Aviation Organization, which seeks to promote worldwide standardization of air traffic control.

The FANS-1 system is designed around standard Inmarsat voice and data communication protocols. Voice circuits are allocated by a request channel: this is a pre-defined frequency that is available to all users, and is accessed using a slotted Aloha protocol. Voice circuits can take tens of seconds to set up, and they operate at 10.5 Kbps. Data services can be established at slower data rates of 600, 1200 and 2400 bps, and use either a low or high-gain antenna, depending on the data rate. Packet transmission times can range into the tens of seconds.

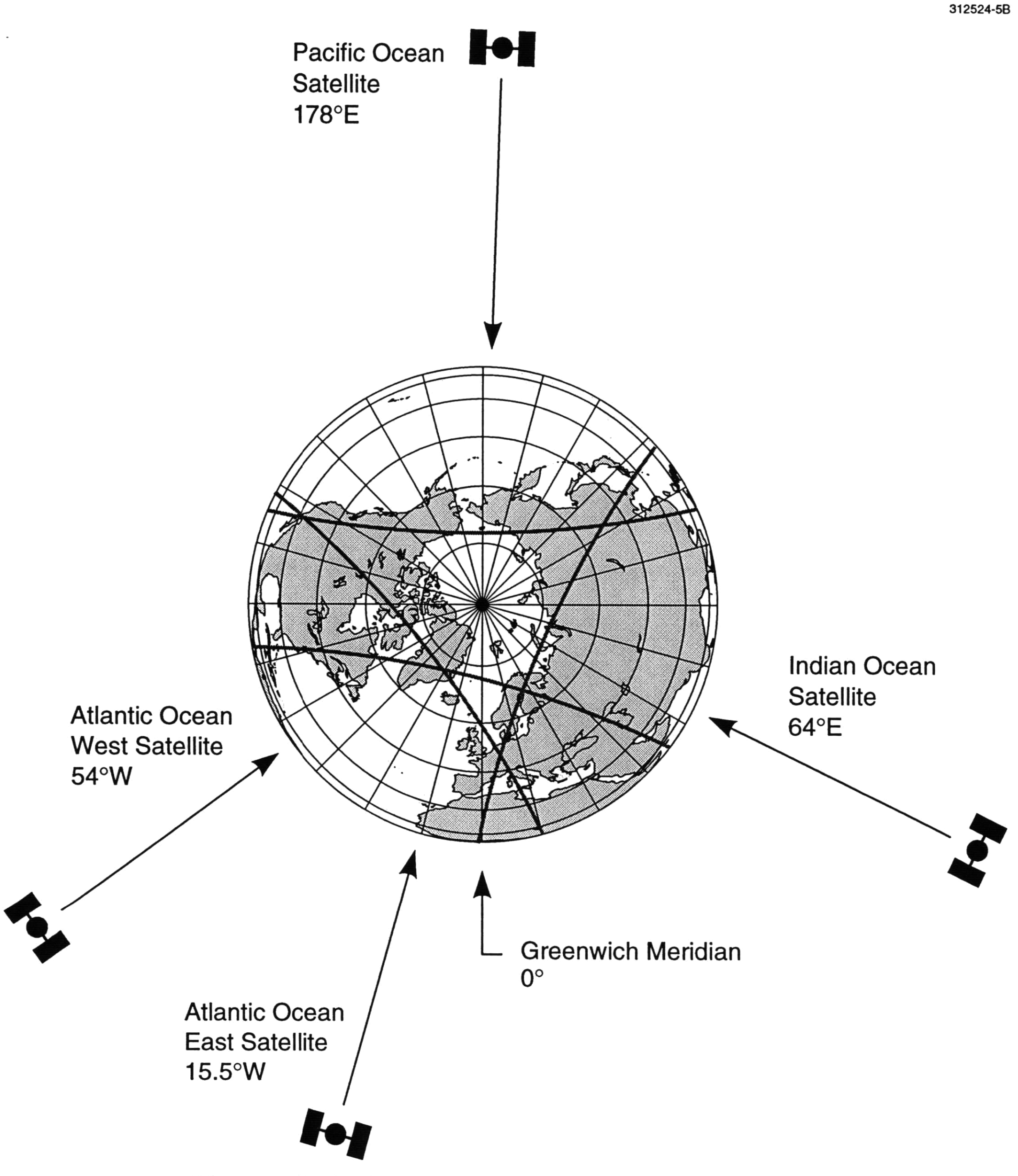


Figure 2-6. Inmarsat satellite fields of view.

Voice circuits require the use of a high-gain (phased array) antenna mounted on the top of the aircraft fuselage. These antennas can support from 2 to 6 simultaneous telephone conversations depending on the equipment complexity, thus making satellite voice service available to both pilots and passengers. The satellite ground station connects the mobile user to the public switched telephone network: pilots can talk with air traffic controllers, and passengers can talk with their office, home, etc. Once a voice channel has been set up between an aircraft and a ground station, it remains active until either party hangs up.

High-gain antennas and their accompanying electronics are costly to install and maintain. Unless the equipment is installed during aircraft construction, it is necessary to take the aircraft out of revenue service for several days while installation occurs. The equipment cost alone is several hundred thousand dollars per aircraft, with the exact price dependent on the number of data and voice channels desired.

To recover the cost of installing and maintaining the satellite communication (satcom) equipment, airlines typically charge their passengers $8/minute for telephone calls. The airline keeps about one third of this, and the remainder goes to Inmarsat for the satellite and ground station services.

2.5 Free Flight

Without more frequent position data, ATC will be reluctant to let aircraft operate with reduced separation distances. Instead, aircraft will be kept on a track system, and will be forced to fly long distances at inefficient altitudes. However, airlines want to operate their aircraft economically, and their approach for doing this is called "Free Flight." Under this proposal, airlines would be free to fly any route or altitude they desire, with ATC only monitoring the situation to help resolve conflicts. This implies tactical control of aircraft instead of the procedural control used now for oceanic flights. Aircraft would fly fuel-efficient cruise-climb profiles that minimize fuel usage. Horizontal separations would be reduced from 50-60 nautical miles down to a few miles to permit better utilization of "best wind" altitudes.

To make Free Flight happen over the ocean, frequent position reports will be required and satcom must replace HF radio. However, as was discussed earlier in the Inmarsat section, the current FANS-1 system doesn't offer the right kind of communication protocol. This thesis explores more promising approaches: Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA).

3. Spread Spectrum and CDMA

3.1 Introduction to Multiple Access and CDMA

Communication costs are minimized when multiple users are allowed to efficiently share a common communication channel. The three most common methods that exist for accommodating multiple access are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA).

In FDMA, each user is assigned a unique sub-channel within the available frequency band (Figure 3-1). There is no need for synchronization of signals among users since each sub-channel is dedicated exclusively for each user. The receiver has a bank of demodulators, with one demodulator assigned to each sub-channel. The sub-channels are separated by guard-bands in order to prevent signals from interfering with those in other sub-channels. This multiple access scheme is the oldest and the most basic of the three, and is still widely used in satellite communication today for its simplicity. Its main disadvantage is that cost increases linearly with the number of users. Also, even with guard-bands there still can be a substantial amount of sub-channel cross-talk, called intermodulation or RF interference.

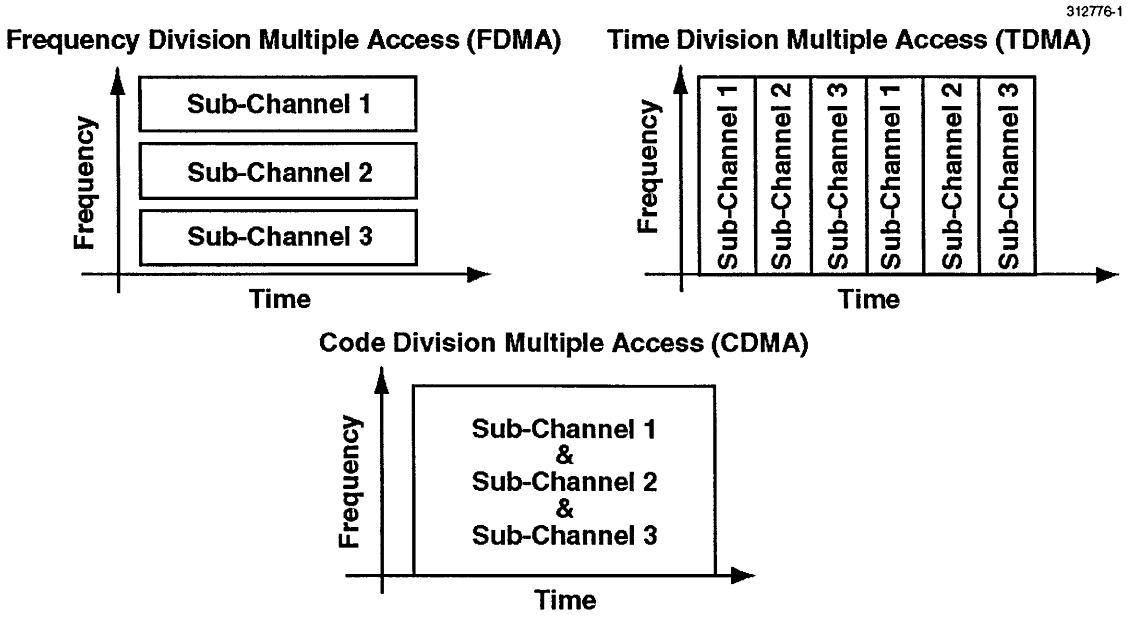


Figure 3-1. Three multiple access schemes.

In TDMA, each user is assigned a time slot during which signals are transmitted. A master scheduler arranges the time slot assignment beforehand, and each user is permitted to transmit their signal only during their assigned time slot. As shown in Figure 3-1, the time slots alternate so that the user can repeatedly send out the same information (such as position reports), or send out segments of a longer message. Segmented messages would be recombined at the ground station receiver. In between the time slots are guard-times which accommodate the unavoidable inaccuracies in timing and synchronization of the time slots. TDMA also avoids FDMA's intermodulation problem.

Compared to FDMA and TDMA, CDMA is unique in that the signals are superimposed on top of each other both in time and frequency. Each user is assigned a unique pseudo-random or pseudo-noise (PN) code, which is a binary sequence of ones and zeroes that serves to identify each user and hence distinguish their message from other users. In order for CDMA to work properly, bandwidth expansion of its signals is required, hence the term "spread spectrum."

PN codes play a crucial role in achieving bandwidth expansion. A PN code is used to expand the bandwidth of a signal by phase modulating the original signal according to the value of the bits of the PN code. The portion of the signal in which the carrier phase is made to correspond to a single digit of the PN code is called a "chip." The chipping rate is the number of PN bits used per unit time to change the carrier phase. The chipping rate thus determines the spreading of the spectrum of the original signal (Figure 3-2).

One important parameter in a spread spectrum system is the processing gain:

$$PG = \frac{T_b}{T_c}$$

where T_b is the bit time of the signal and T_c is the chip time of the PN code [10]. Thus, the shorter the chipping time, which means the chipping rate is high, the greater the processing gain. As we shall see, the processing gain plays an essential role in correctly demodulating the signals at the receiver end.

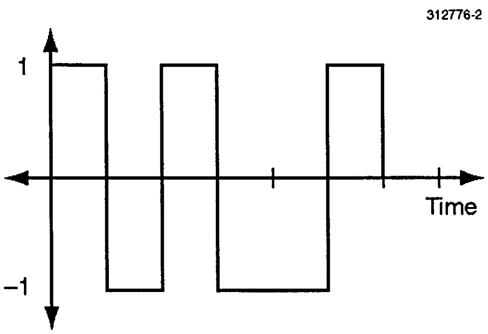


Figure 3-2. A pseudo-noise code sequence.

In the past, CDMA systems have been widely used in military applications because of their security and low probability of detection properties. The key advantage, however, that CDMA has over FDMA and TDMA is its potential for higher capacity. This advantage is shown in Table 3-1, which compares AMPS (an FDMA implementation), TDMA and CDMA telephone systems [2]. A typical AMPS system allows 19 telephone calls per sector. TDMA triples this capacity, and CDMA increases the capacity by a factor of 20. Further increases are not possible because of self-interference issues associated with CDMA [8]. Processing gain is used to suppress the multiple-user interference caused by the PN-encoded signals that reside in the same spectrum. Thus, high processing gain is desired, but it is impractical to build a demodulator with a processing gain greater than 10^4 [19].

Table 3-1 includes frequency reuse constraints, which is why AMPS can accommodate only 19 calls/sector [2].

Table 3-1. Capacity comparison of three multiple access schemes.

	AMPS	TDMA	CDMA
Bandwidth	12.5 MHz	12.5 MHz	12.5 MHz
Frequency Reuse	k = 7	k = 7	k = 1
RF Channel	0.03 MHz	0.03 MHz	1.25 MHz
Number of RF Channels	12.5 / 0.03 = 416	12.5 / 0.03 = 416	12.5 / 1.25 = 10
Channels per Cell	416 / 7 = 59	416 / 7 = 59	12.5 / 1.25 = 10
Usable Channels per Cell	57	57	10
Calls per RF Channel	1	3	38
Voice Channels per Cell	57 x 1 = 57	57 x 3 = 171	10 x 38 = 380
Sectors / Cell	3	3	3
Voice Calls / Sector	57 / 3 = 19	171 / 3 = 57	380
Capacity vs. AMPS	---	3X	20X

3.2 Pseudo-noise (PN) Codes

A PN code consists of a series of bits. The total number of possible PN codes for a series of "n" bits is 2^n. In practice, however, only a small subset of the total number of possible codes can be used for CDMA communication. This is because the codes must exhibit certain features in order to be useful for CDMA. The codes must:

- be easy to generate
- have a long period
- have desireable randomness properties (autocorrelation and cross-correlation)

PN codes must be easy to generate because the ground station receiver needs to generate a local PN code in order to demodulate the signal. A long period (i.e., a large number of bits) is needed to maximize the total possible number of PN codes, so that a reasonably-sized family of codes with suitable properties (as described below) can be extracted. For security reasons, it should not be possible to reconstruct an entire PN code from a short code segment [14].

The ideal autocorrelation would be an impulse function centered around zero. This helps the local PN code synchronize and lock on the incoming signal, and also helps resist multipath interference [14].

User separation is achieved by correlating the received signal with the appropriate locally-generated PN code. Therefore, zero (orthogonal) or low (non-orthogonal) cross-correlation is required to insure that the receiver correctly associates the locally generated PN code with the proper user.

One popular way of generating PN code sequences is by the use of feedback shift registers (FSRs) [10]. Because a desired property of a PN code is a long period, a popular sequence generated by FSRs is the maximum-length (ML) FSR code. The period of a ML code is given by $2^l - 1$, where l is the number of shift registers used. For ML codes of length L, the autocorrelation function, $R(\tau)$, can be shown to be

$$R(\tau) = \begin{cases} 1 & \tau = 0, L, 2L, \ldots \\ \dfrac{-1}{L} & \text{otherwise} \end{cases}$$

The number of ML FSR codes is limited. Additional codes can be generated by adding two different ML codes by modulo-2 addition. The resulting codes are called Gold codes, arguably the most popular codes in use today [14]. Note that Gold codes are nonlinear in nature which makes analysis of these codes difficult.

An important parameter involving PN codes is the ratio of the maximum cross-correlation coefficient and the autocorrelation coefficient [14]. This ratio is important because it is a measure of how well a PN code can reject interference from other users' codes; the smaller the ratio, the better is the rejection of interfering users. For Gold codes, the maximum cross-correlation coefficient is given by

$$K = \begin{cases} 2^{(n+1)/2} + 1 \\ 2^{(n+2)/2} + 1 \end{cases}$$

where n is even. The maximum auto-correlation coefficient of Gold codes is the length of the code. Hence, for a Gold code generated by a 5-stage FSR, the ratio comes out to be 0.29, compared to 0.23 for the corresponding ML code and 0.43 for a corresponding non-ML code [14].

3.3 Spread Spectrum Modulation Techniques

CDMA must use one of the following spread spectrum modulation techniques to achieve bandwidth expansion. It is important, however, to note that the use of spread spectrum does not necessarily imply CDMA. The defining characteristic of a CDMA system is "code division," i.e., the system uses codes to separate the users, and this need for codes requires spread spectrum.

Direct Sequence (DS)

In the DS spread spectrum modulation, the data sequence is directly multiplied by a pseudo-noise (PN) code sequence, and the resulting signal is transmitted (Figure 3-3). The frequency of the PN code, which consists of chips that undergo rapid phase changes, is greater than that of the data sequence. Since the chipping rate is approximately equal to the bandwidth, the transmitted signal occupies more bandwidth than does the original data sequence, hence the term spread spectrum. At the receiving end, the data signal is extracted by multiplying the received signal by a locally generated PN code sequence which is identical to the original PN code. The operations involved in Direct Sequence are thus relatively simple – a simple multiplication of the signal with a PN code is all that is required – which makes it a cost-effective option. Its simplicity and cost-effectiveness have made DS a huge success in the civilian cellular telephony industry, as evidenced by Qualcomm's DS-CDMA cellular phone system.

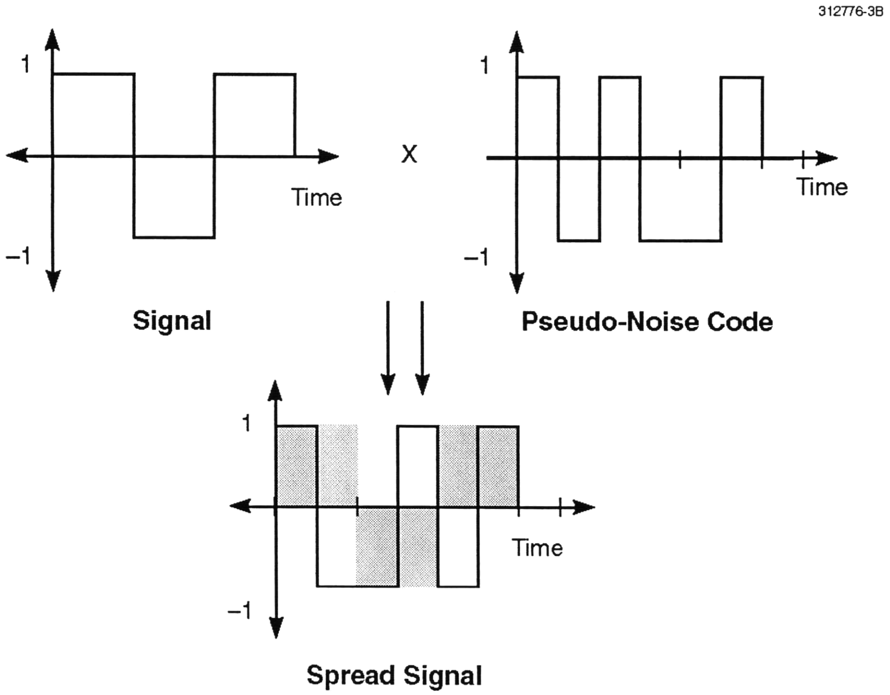


Figure 3-3. Direct sequence spread spectrum modulation.

Frequency Hopping (FH)

The data signal is modulated with a carrier frequency which is not constant but is hopped to different frequencies; the hopping pattern is dictated by the PN code (Figure 3-4). Thus, at any one time, the modulated signal occupies a small portion of the frequency spectrum. FH is spread spectrum since the hop-set, which is the collective set of all the frequencies over which the signal is hopped, ranges over the entire channel bandwidth. There are two types of FH, fast and slow, depending on the rapidity of the frequency change. In fast FH, one bit is transmitted in several hops, whereas in slow FH, one or more bits are encoded in a single hop.

One advantage of FH is in the exponential increase of orthogonal code users that can be achieved with increasing chipping rate [5]. This is superior to DS which has only a linear increase of capacity with increasing chipping rate. The exponential factor in capacity of FH can be seen in the following expression for K, the capacity factor:

$$K \leq 2^{R_c / R_h}$$

where R_c is the chipping rate and R_h is the hopping rate.

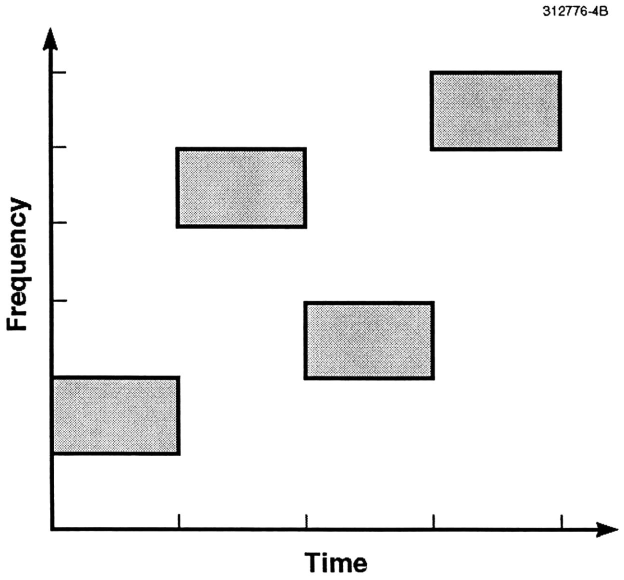


Figure 3-4. Frequency hopping spread spectrum modulation.

However, there are several disadvantages for FH, and that is perhaps why the vast majority of current CDMA systems, at least for civil applications, use the Direct Sequence method. One disadvantage of FH is that it puts a severe constraint on the frequency hopping generators, which must be accurate enough to ensure that there are no errors in decoding. Also, frequency resolution of generators must be quite exact; even a slight deviation from the frequency set can cause errors in decoding. Moreover, the hopping time, which is the time needed for the hopper to make a jump from one frequency to the next, needs to be very short, or otherwise there would be an energy degradation in decoding, given by the expression, $(1-\frac{\varepsilon}{T_\omega})^2$, where ε is the hop settling time and T_ω is the hopping period [5].

Time Hopping (TH)

This approach is similar to FH, but in TH the PN code dictates the time intervals of bursts of the data signal to be transmitted within a frame; the time axis is divided into frames which are, in turn, divided into a certain number of yet smaller time intervals called slots. The transmission occupies the entire frequency spectrum. With synchronization among the users, TH becomes straight TDMA if the PN code doesn't allow more than one user per slot at any one time. As we shall see later, TH is a form of burst mode communication which will provide another set of options for the satcom system.

Hybrid Modulation

This consists of different combinations of the methods mentioned above, for example, a combined DS and FH system. This option is excellent for complementing the advantages of each method, but hardware can get very complex with hybrid modulation.

Looking at the aforementioned spread spectrum modulation techniques, we have decided to explore the Direct Sequence method further, mainly because of its simple yet reliable nature and cost-effectiveness, which are two important qualities for any ATC system. When considering FH as an option for the satcom system, there is a concern of complexity of accurate frequency generators and the need to keep them synchronized for multiple users.

Section 3.2 introduced the concepts of orthogonal and non-orthogonal CDMA. Orthogonal CDMA means that the PN codes have zero cross-correlation with each other. This method of CDMA requires strict synchronization between the received code and the local code to ensure proper demodulation; synchronization is essential for orthogonal

CDMA since even a slight error in synchronization would misalign the chips of the local and the incoming signals and thus lose some of the received energy. An advantage of orthogonal CDMA is that with proper demodulation, other user's signals are orthogonal to the desired signal, which insures correct decoding. For the orthogonal system, capacity increases linearly with satellite power and RF bandwidth [5].

Non-orthogonal CDMA uses codes with low, but not zero, cross-correlation, and has less stringent synchronization requirements. A disadvantage of the non-orthogonal method is that it needs higher power levels to achieve the same level of performance as an orthogonal system [5]. Also, this code family would be hard to construct for a large number of users, and therefore is not of interest to this thesis.

3.4 Multiple User Access Issues

Allowing multiple users to access a communications channel is not simply a matter of choosing a multiple access scheme, such as FDMA, TDMA or CDMA. This section examines several issues that must be addressed when choosing a multiple access approach.

3.4.1 Channel Sharing

Figure 3-5 shows an approach for addressing multiple access issues. The first decision that must be made is whether to dedicate a satellite transponder channel for ATC communication, or instead to allow ATC communication to share transponder bandwidth with other users. These decisions have technical, economic and political implications.

A dedicated channel is attractive because it can be sized to support the expected communication traffic load. If the expected load can be accurately estimated, channel bandwidth can be minimized, which helps reduce costs. Ensuring that the bandwidth is protected for aviation use only, so that position reports and other data can be transmitted without interference, is important from a safety standpoint. A dedicated channel could be operated in either a spread spectrum or non-spread spectrum mode.

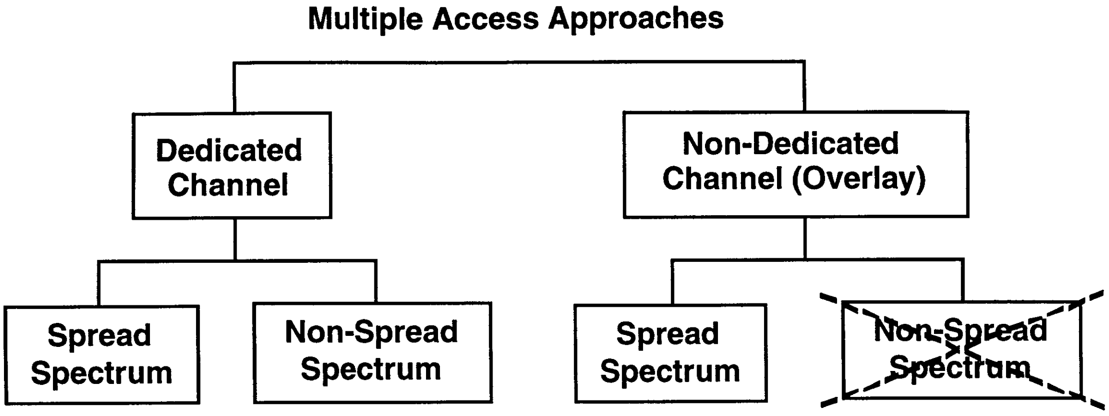


Figure 3-5. Multiple access decision tree.

A dedicated ATC channel will probably require 20 - 50 KHz of bandwidth. This is only a small portion of the 10 MHz aeronautical L-Band bandwidth available on an Inmarsat-III satellite. This bandwidth is currently shared among users of aeronautical voice and data services.

A non-dedicated channel approach would overlay ATC communications on the existing Inmarsat voice and data services. This approach is only feasible if spread spectrum technology is used, because 1) ATC communication must not interfere with the other services, and 2) processing gain is needed to combat the "interference" generated by those other users, to ensure that ATC communication succeeds. The cost of such a service would have to be negotiated with Inmarsat, since it falls outside their existing set of standard services.

3.4.2 Continuous vs. Burst Transmission

Earlier, Figure 3-5 showed three feasible multiple access approaches:

- Dedicated Channel, Spread Spectrum
- Dedicated Channel, Non-Spread Spectrum
- Non-Dedicated Channel, Spread Spectrum

Each of these communication modes may be further subdivided into two types of transmission: continuous and burst. These transmission types are illustrated in Figure 3-6. Continuous transmission uses a low instantaneous data rate, while burst uses a high rate. In the figure, continuous transmission requires almost 30 seconds in which to transmit the message (long latency), while bursts require much less time (short latency). Continuous transmission is sometimes referred to as "continuous wave," or CW.

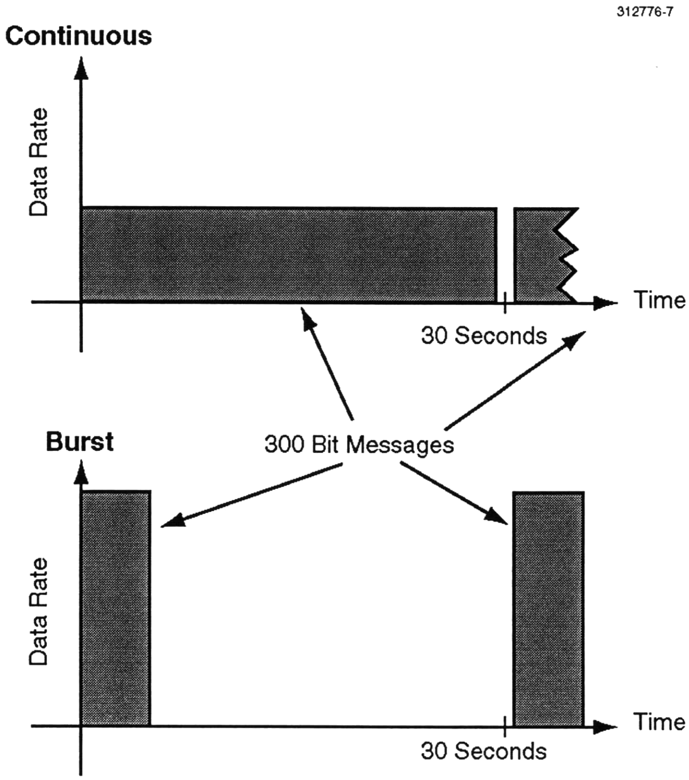


Figure 3-6. Continuous and burst transmission modes.

3.5 Use of Cellular Telephone Technology for ATC

A popular use for CDMA technology is in cellular telephone systems. Qualcomm, the world leader in CDMA cellular systems, has delivered over one million handsets to consumers worldwide. It is reasonable to ask if cellular telephone systems offer an approach that might also be useful for oceanic ATC. Figures 3-7 and 3-8 illustrate the cellular and ATC environments, respectively.

In a cellular telephone system, users communicate via handsets to base stations located throughout the service area. Once a link is established, communication is continuous until either party hangs up. If a similar approach is used for ATC, the aircraft population would communicate via satellite with the ATC facility. Continuous communication would exist throughout the oceanic portion of the flight.

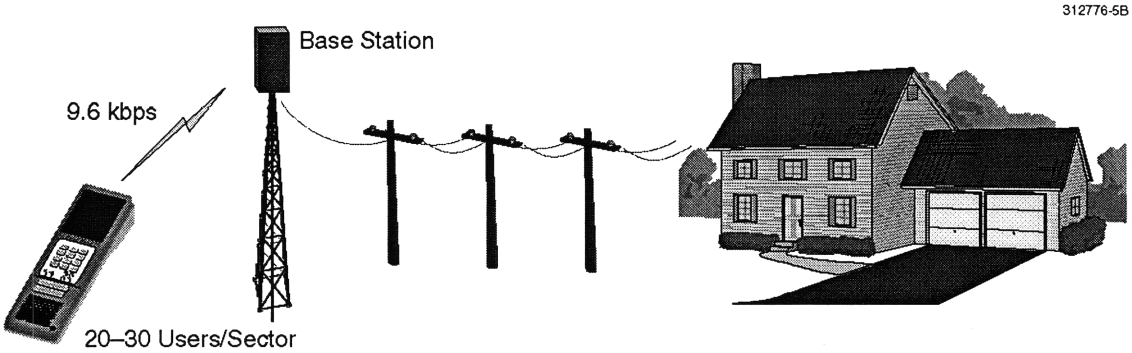


Figure 3-7. Cellular telephone system.

Although these two systems are similar on a conceptual level, there are important differences. Several important communication considerations are listed in Table 3-2, along with a description of how these differ between cellular and ATC.

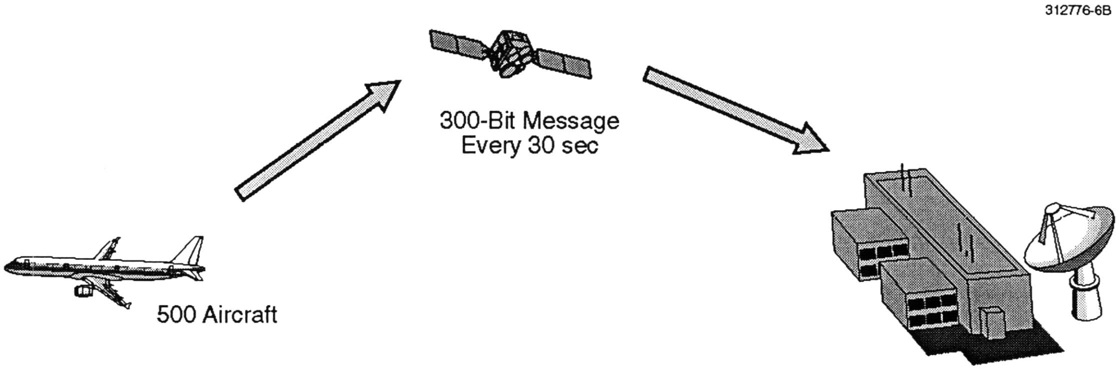


Figure 3-8. Air traffic control system.

Shadowing occurs when an object, such as a building, obscures the direct line of sight between a user and a base station. A related problem is multipath interference, where the signal can bounce off a building, creating multiple signal paths between the user and the base station. The different signals can combine constructively or destructively at the destination. Destructive interference would require that the message be retransmitted.

Table 3-2. Communication considerations.

Considerations	Cellular	ATC
Shadowing	Causes multipath interference and signal loss.	Not a factor.
Multipath interference	Significant in urban environments.	Only one bounce off surface of ocean.
Hand-off	Happens frequently.	Not a factor for GEO global beam; minor factor for spot beam. Would happen frequently with LEO satellite.
Power control	Real-time control (20 ms frame).	Non real-time control (minutes).
Doppler effects	Important factor.	Minor factor for GEO satellites; important factor for LEO satellites.
Link budget	Low power handset, small distances, omni antenna.	High power transmitter, large distances, directional antenna.
PN codes	Need ~32 unique codes/sector.	Each aircraft requires a unique code (500 - 1000 codes).
Message characteristics	Short-term, continuous, highly variable.	Long-term, repetitive (favors burst over continuous).

Shadowing and multipath interference are problems for cellular users in dense urban environments, but are not problems for ATC. Satellite antennas for aircraft are mounted on the top of the aircraft fuselage, and generally have an unobstructed view of the satellite. The aircraft tail may provide some shadowing, but only at extreme (low elevation) view angles. If the aircraft is operating at an extreme northern or southern latitude, it is possible that it will experience a single multipath bounce off the ocean surface, as illustrated in Figure 3-9. However, since the unwanted signal will travel at a negative elevation angle as viewed from the aircraft, this situation can usually be avoided by proper antenna pattern design.

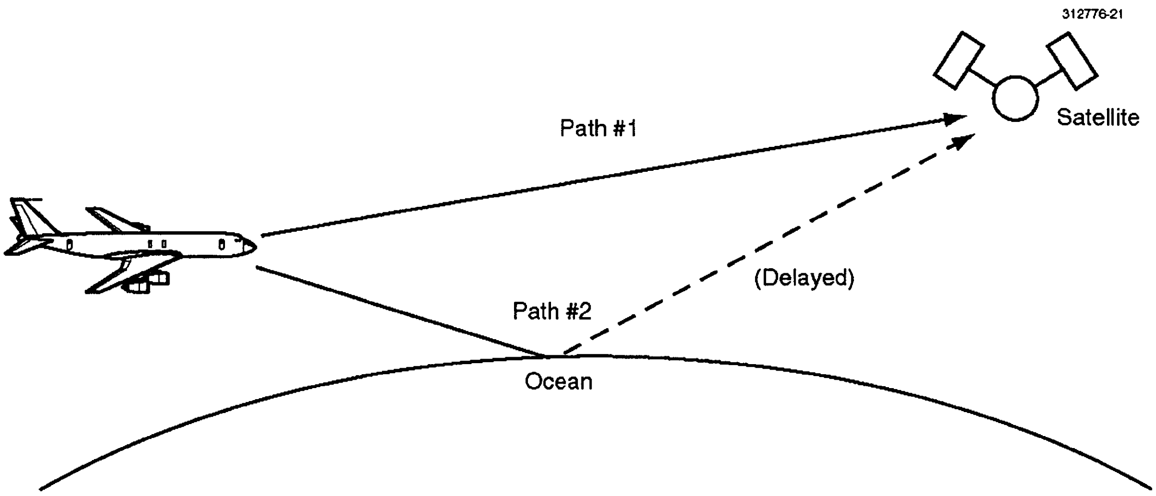


Figure 3-9. Aircraft multipath signals.

Hand-off for cellular telephone users is done when a user moves between sectors and needs to switch from one base station to another. In order to successfully execute a hand-off, the base stations need to carefully monitor the power level of each user to determine which sector they are in. ATC users have the option of using either a global beam, or one of several spot beams. Figure 3-10 shows the Earth as viewed from the geosynchronous Earth orbit (GEO) Inmarsat satellite located in the Atlantic-East orbital position (15° West longitude). The global beam allows communication from roughly ± 70° latitude, and ± 70° in longitude from the orbital longitude. Spot beams, shown in the figure as ellipses, provide additional power to areas of high traffic. If aircraft use the global beam, hand-off is not an issue. If aircraft use the spot beams, hand-off may be necessary, but it will occur on a scale of hours (vs. minutes for cellular telephone users). For low Earth orbit (LEO) satellites such as Iridium or Globalstar, hand-off would be similar to a cellular system because an individual satellite would be within view of an aircraft for only a few minutes.

Power control is done in a much more tightly coupled manner for cellular telephones than would be needed for ATC. Since the distance between a mobile user and a cellular telephone base station can vary quickly, Qualcomm uses a 20 msec cycle for adjusting power levels, so that each user's power at the base station is approximately equal [17]. For an ATC application, the distance between an aircraft and the satellite does not vary rapidly, simply because of the large distance involved (~20,000 nautical miles). Power control would be needed every few minutes. For similar reasons, Doppler shifts are more of an issue for cellular users than they would be for a satellite-based ATC system.

Link budgets are another area of difference. Cellular telephone handsets transmit in the milliwatt to a few watts range, while aircraft transmitters use tens of watts. Cellular base stations have essentially unlimited power available, while satellites are limited by the efficiency of their solar cells and batteries. Satellite systems operate over distances thousands of times farther than cellular systems, and can make use of directional antennas (vs. cellular omni antennas). All of these factors greatly affect link budget calculations.

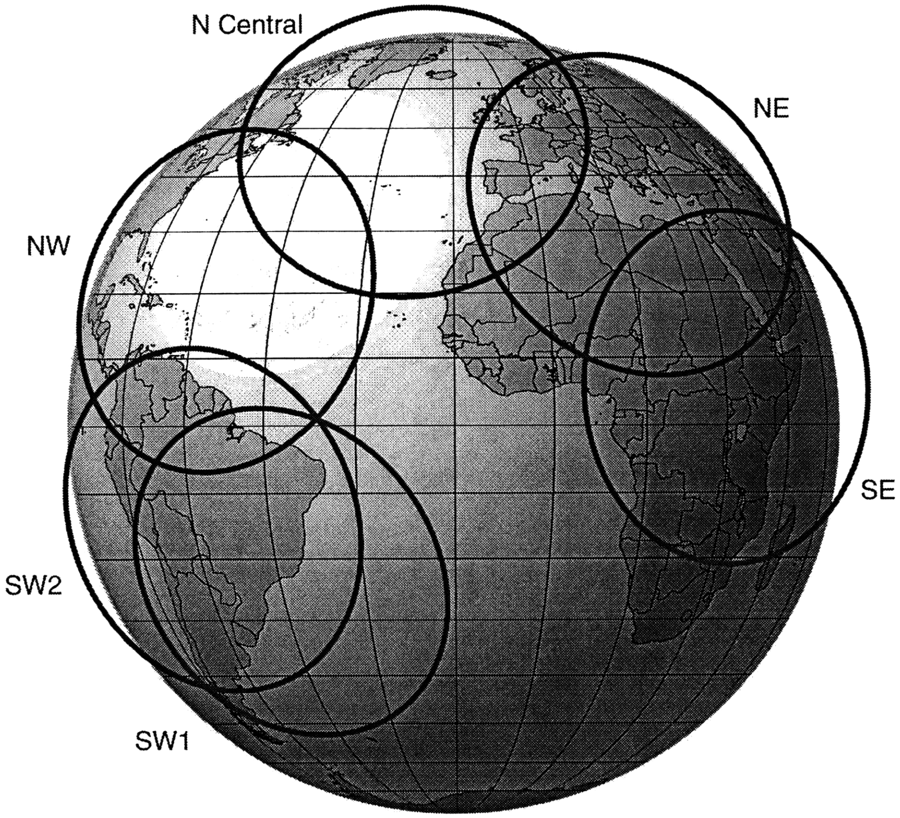


Figure 3-10. Inmarsat satellite spot beams.

For a continuous communication system, the number of pseudo-noise (PN) codes that are needed is the same as the number of users. The user population is divided among cells and sectors (3 sectors / cell) in the telephone system, and since self-interference limits the number of users that can be serviced in a given sector, only about 32 PN codes are required [7]. An ATC system would require as many codes as there are aircraft (500 - 1000), unless spot beams are used, in which case frequency reuse between spot beams would reduce the number of codes.

Finally, there are many differences in message characteristics. Cellular conversations generally last only a few minutes, while oceanic flights travel for several hours. Conversations vary widely in content, whereas ATC messages repeatedly report aircraft ID, position, altitude and time. If ATC messaging were done on a continuous basis, like cellular, this would increase message latency. However, increased latency increases a controller's uncertainty about aircraft location, which would result in an undesirable increase in aircraft separation requirements.

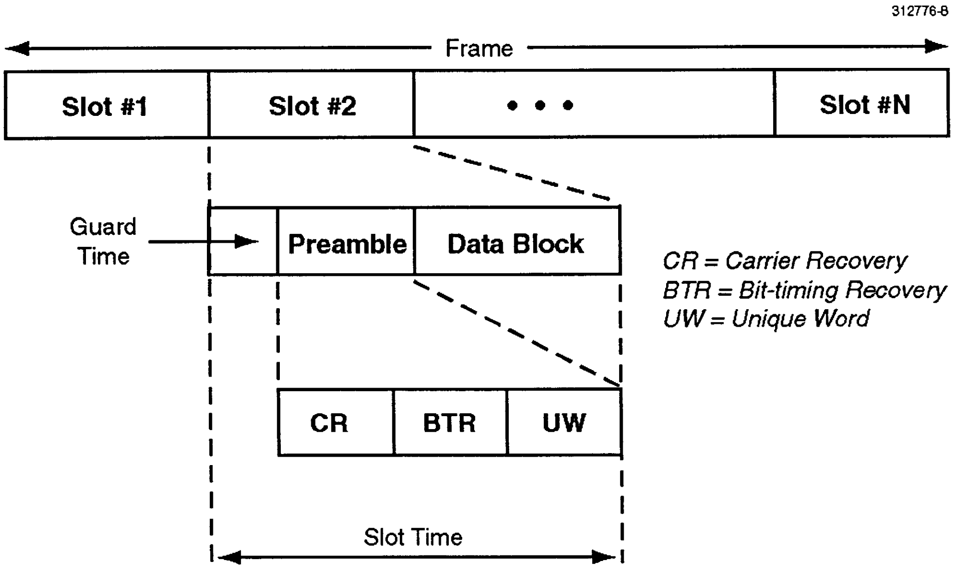
Even though the cellular telephone communication technology, with CW CDMA, does not appear to be compatible with the ATC application, it will be evaluated later in Chapter 5.

4. TDMA

In this chapter, we elaborate on one of the multiple access schemes, TDMA, which was briefly discussed in Chapter 3. At the end of the chapter, we present a system architecture tree that brings together and establishes the hierarchy of the concepts presented in Chapters 3 and 4.

4.1 Preamble Detection for Burst Mode

Unlike the continuous mode of communication, which uses continuous synchronization-tracking (synch-tracking) of the incoming messages, the burst mode requires a mechanism that can detect the arrival of a message – without mistakenly recognizing a non-message as a message – and properly demodulate the message. Such a mechanism must make use of a message preamble, which is a header-like portion of the message that is used to detect the arrival of a message and establish its time of arrival (TOA), and provide the demodulator with bit timing information.



CR = Carrier Recovery
BTR = Bit-timing Recovery
UW = Unique Word

Figure 4-1. A burst message within a time slot.

Figure 4-1 shows a message within a time slot which is divided into its preamble and data parts [5]. The number of bits allocated for the preamble should be shorter than for the actual data block. The preamble efficiency, or overhead, is defined as:

$$\eta_p = \frac{\text{Number of preamble symbols}}{\text{Total number of symbols per slot}}$$

This parameter gives a measure of the efficient use of bits for a preamble, and is around 10 percent or less for typical TDMA systems [5].

The preamble detector is a matched filter that detects the preamble of an incoming message. A matched filter, also called a correlator, is the optimum detector for detecting pulses that have been corrupted by channel noise, and minimizes the effects of noise and enhances detection of the original pulse signal [10]; the name “matched” comes from the fact that the impulse response is the time-reversed and delayed version of the pulse signal, i.e.,

$$h_{opt}(t) = kg(T - t)$$

where $g(T-t)$ is the pulse waveform with the delay T, and k is an arbitrary constant. When a preamble is detected, the matched filter produces a big “spike” that exceeds a preset threshold value, signaling the arrival of a preamble. The time of arrival of the preamble is then estimated from the preamble spike time, and is used to synchronize the demodulation process. After the preamble detection phase, the data stream is sent to the appropriate demodulator to be decoded.

In spread spectrum burst systems, the preamble detector must have the ability to detect preambles that have been decoded with PN codes and thus resemble noise. Two options exist for spread spectrum burst systems: fixed preamble detection and programmable preamble detection (Figure 4-2).

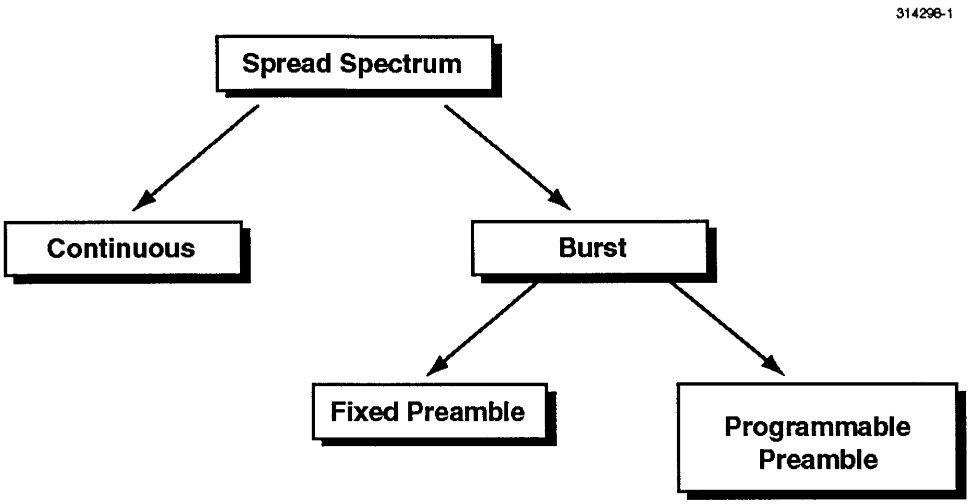


Figure 4-2. Hierarchy of system concepts.

In a fixed preamble system, only one PN code is used for all time. The preamble detector is set up with a PN code that allows it to detect PN-coded preambles. The PN code is used as a spreading mechanism to mitigate the effects of interfering signals, e.g., for an overlay channel with users of other type of services, or in a multiple access mechanism (Figure 4-3).

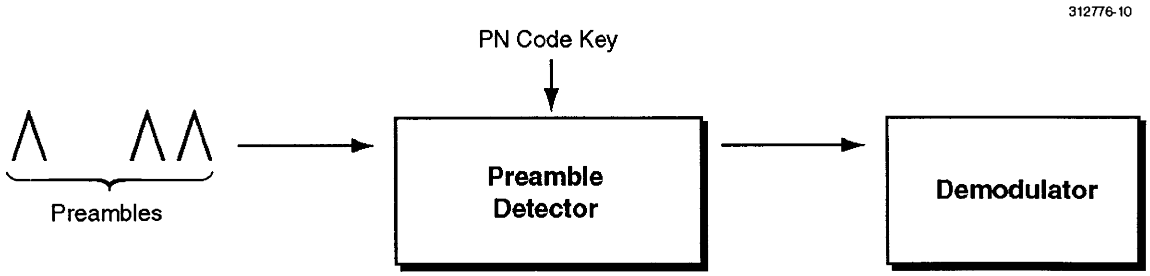


Figure 4-3. Diagram of a fixed preamble detector.

In a programmable preamble system, a number of PN codes are used by the system, each being valid only in a specific time interval. A single, programmable, preamble detector that can be configured with a different PN code for every time period, is used to process all the preambles. Hence, complexity is an issue for programmable preambles because not only must the preamble detector be able to change the PN code, but all of the users must change their PN code as well in each time period. Thus, during any one time period, programmable preamble detection effectively becomes fixed preamble detection, with the next time period simply using a different PN code for all of the users.

If some messages are deemed more important than others, one preamble detector can be dedicated for that particular message or type of messages only, with other detectors being used for other types of messages. Such use of multiple preamble detectors effectively creates additional channels that can improve the system's spectral efficiency.

4.2 TDMA Communication Protocol: Slotted vs. Random Access

In a burst mode system, two or more preambles may collide, or arrive at the receiver at the same time. Unless a way to distinguish these preambles exists, all of the overlapping preambles would go undetected and the subsequent data streams would get lost. With partially overlapped preambles, however, it is still possible to distinguish one message from another. This separation in time, however, must be at least twice the chip duration, which is the minimum time that the preamble detector needs to resume its search for preambles after having detected the first one (Figure 4-4). The chip duration of a signal is a critical factor in preamble detection. The chip duration can be made shorter to reduce the chance of collisions, which is why spread spectrum offers a big advantage in this regard. More discussion on this point appears in the multipath interference section of the comparative evaluation section (Chapter 5).

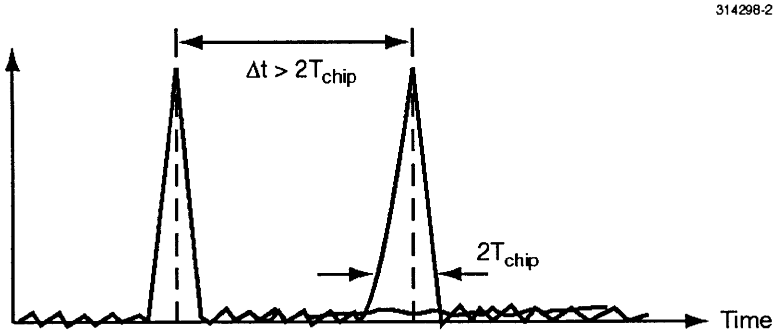


Figure 4-4. Minimum time separation to distinguish two preambles.

Two methods are used to cope with this collision problem: slotted and random access, which are two protocols for time sharing a communication channel. These protocols apply only to TDMA systems since in a CW system, message collisions are occurring all the time at the receiver. In the slotted protocol, each burst is sent in a time slot; only one user is permitted to transmit during any one time slot. In the random access protocol, the bursts are sent randomly, i.e., at any time a user wishes to transmit, without any coordination amongst the users. If the message is received without any collision, then the user gets an acknowledgment of successful transmission from the receiver. If a collision occurs, the acknowledgment is not obtained and the user must re-transmit the message after a certain wait period that is randomized so as to minimize the chances of having a second collision with the same user. The ALOHA system, developed in Hawaii in the early 1970's, is an example of a random access system [9]. A hybrid combination of random access and slotted, the slotted Aloha system, also exists and is used extensively with Inmarsat satellites.

4.3 System Architecture Tree

Figure 4-5 shows a taxonomy tree that brings together all of the system concepts introduced thus far: dedicated vs. shared channels (channel sharing), spread spectrum vs. non-spread spectrum (bandwidth utilization), burst vs. CW (mode of communication), slotted vs. random access (communication protocol), and fixed vs. programmable preamble detection (PN code usage). The use of a shared channel requires spread spectrum, and thus no further branches are connected to the Shared/Non-SS node. The Dedicated/Non-SS/CW leaf node is FDMA. In Chapter 5, we will explore the rest of the leaf nodes by conducting a comparative evaluation study of them.

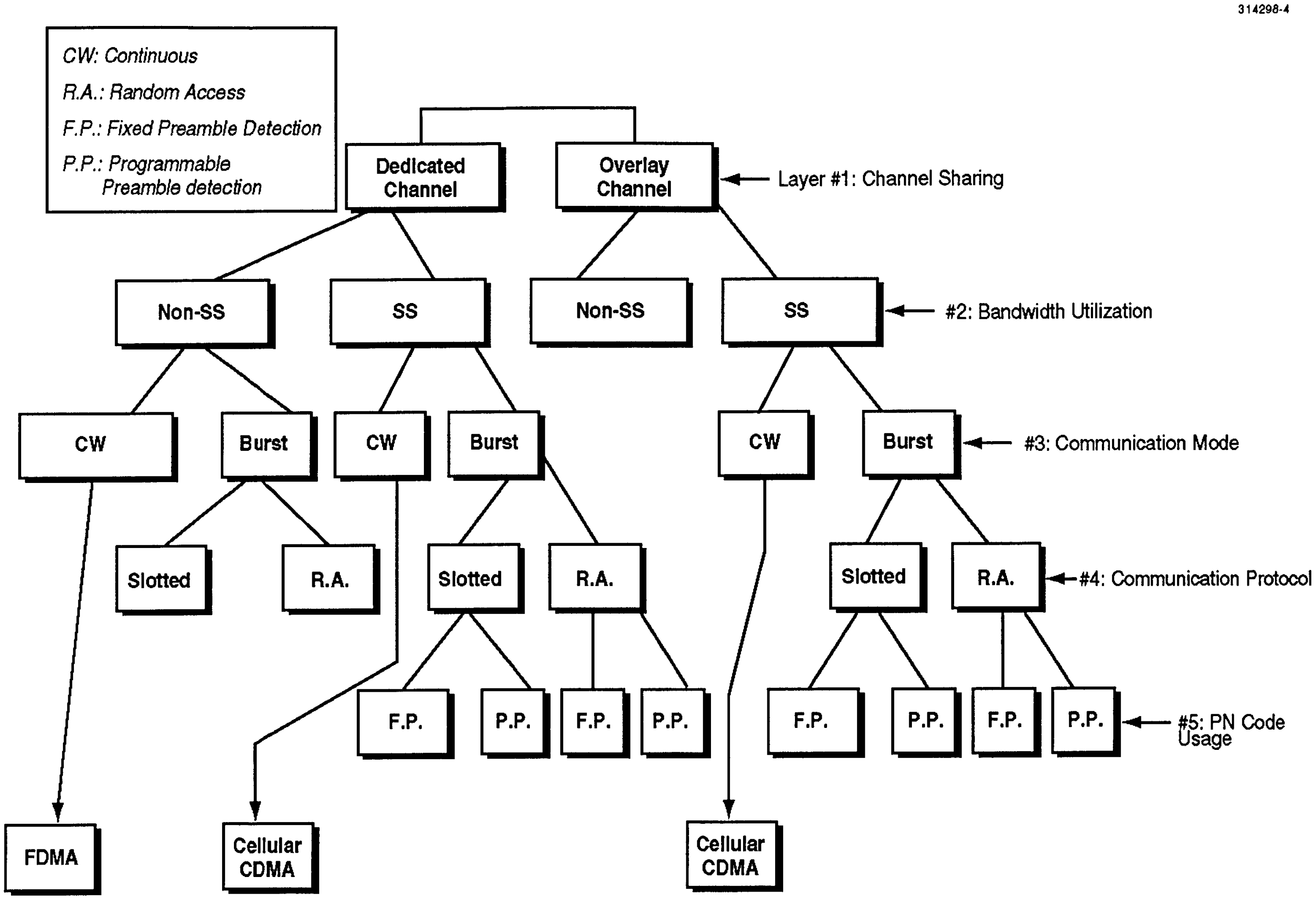


Figure 4-5. System architecture tree.

5. Comparative Evaluations

In this chapter, we take a set of system alternatives from the system taxonomy tree, and define seven different system options that will be considered for oceanic ATC. The evaluation methodology is first introduced. The evaluations are performed with respect to a set of criteria that are critical in oceanic ATC.

5.1 System Options for ATC Satcom Architecture

The system architecture tree, which was presented in Chapter 4, deals with the following issues, each constituting a layer of the tree. We have already indicated preferences for some of these issues that are best suited to the needs and requirements for the ATC system:

- Channel sharing (overlay vs. dedicated channels): both overlay and dedicated channels are explored, even though overlaying would be hard to implement with existing satellite communication systems, such as Inmarsat, because of practical problems
- Bandwidth utilization (spread spectrum vs. non-spread spectrum): spread spectrum preferred for potential capacity and LPD/LPI reasons
- Communication mode (burst vs. continuous)
- Communication protocol (slotted vs. random access - for burst mode only)
- PN code usage (fixed vs. programmable preamble - for spread spectrum only)
- Spread spectrum modulation (DS vs. FH): see Chapter 3 - DS preferred

Using these layers, we can define the following seven system configurations for the ATC system:

1) Non-SS - burst - slotted TDMA (no PN codes)
2) Non-SS - burst - random access TDMA (no PN codes)
3) SS - burst - slotted - fixed preamble TDMA (one PN code)
4) SS - burst - slotted - programmable preamble TDMA (multi-PN codes)

5) SS - burst - random access - fixed preamble TDMA (one PN code)

6) SS - burst - random access - programmable preamble TDMA (multi-PN codes)

7) SS - CW CDMA (multi-PN codes)

5.2 Evaluation Criteria

The candidate systems, i.e., the seven options, will be compared with respect to a number of criteria that are relevant to oceanic ATC. Each evaluation criterion will first be defined and explained in this section. The following parameters are used in all of the comparative evaluations:

- M = number of users = 500 users
- P_M = Probability[500 messages get through with no collision] ≥ 0.9
- T_{update} = message update interval = 30 seconds
- Average data rate = 300 bits / 30 sec = 10 bits / sec
- $\sigma_{\min}$ = minimum energy-to-noise density for reliable communication = 5 (7 dB)
- $n_{\text{data bits}}$ = number of data bits in message = 150 bits
- $n_{\text{bits/slot}}$ = number of bits per slot = $2 \times n_{\text{data bits}} + 100$ bits = 400 bits (Note: we assume 100 bits of overhead, which include preamble bits)
- Jamming margin (i.e., the amount of intentional/incidental interference that the system must be able to withstand) = 100 (Note: a jamming margin of 100 means that the system should operate reliably with $\frac{J}{P} \leq 100$ at the receiver input, where J is jamming power and P is signal power)

The following evaluation criteria will be considered:

- Latency
- Spectral efficiency (total bandwidth)
- Demodulator complexity

- Receiver synchronization
- LPD/LPI
- RFI
- Multi-user interference
- Diversity
- Multipath vulnerability

5.2.1 Latency

Latency is a critical issue for ATC because the controllers need accurate position information in order to assure aircraft safety. Note the distinction between message latency and message update interval; the former is the time it takes a message to travel from the aircraft to the ATC computer system, whereas the latter refers to the parameter that we specified as 30 seconds, the interval between position updates. The longer the latency of a communication system, the farther an aircraft moves from when its position was measured and transmitted. For this consideration, all the burst type systems, except for the random access options, have the same latency since usage of PN codes does not affect latency. The random access protocol's latency is a statistical latency because the latency is not the same for all transmissions due to the possibility of message collision.

In general, latency can be defined as follows:

$$\text{Latency} = T_{\text{prop}} + \text{Max}\left\{T_{\text{msg}}, T_{\text{slot}}\right\}$$

Latency is the sum of the total propagation delay of the message, and either the message length or the slot duration, whichever is greater; we want the greater of the two, since latency is a worst-case parameter. In oceanic ATC, the propagation delay includes: 1) the uplink and downlink delay, which for GEO satellites is approximately 250 ms total, but will vary, by up to 20 ms, depending on the location of the aircraft with respect to the satellite, and 2) the ground network delay, T_{net}, a design parameter that differs from one network to another. We assume T_{net} can be limited to 100 ms latency. Although the full expression for latency will be determined for each of our options, we will disregard the propagation delay for the comparative purposes since it is the same for all of the options.

Using this definition, we find the latency expression of the slotted burst TDMA (Option 1) to be 2×125 ms + $T_{\text{net}} + T_{\text{slot}}$. Because the propagation delays are largely predictable, slots that are shorter than 250 ms can be used. The slot duration, T_{slot}, is determined by dividing the message update interval by the total number of users, i.e.,

$$T_{slot} = \frac{T_{update}}{M} = \frac{30\ \text{s}}{500} = 60\ \text{ms}$$

Thus, we take the latency for Option 1 as 60 ms.

For the random access burst TDMA system (Option 2), the latency is a statistical variable because there is not just one latency for all transmissions, but different latencies that can occur with different probabilities. If the first transmission goes through without any collision, the latency would simply equal 2×125 ms + $T_{\text{net}} + T_{\text{msg}}$ (in random access, there are no time slots). However, if a collision does occur, the message is lost and the GES cannot acknowledge the message, and so the aircraft concludes it must re-transmit the message. In this case, one or even multiple re-transmissions of the message becomes necessary; the length of the wait period between the initial burst and the re-transmission is random, usually a few times the message length. Thus, the latency depends on the number of re-transmissions needed and the random delays chosen. Figure 5-1 illustrates a scenario in which a message collision occurs and a re-transmission of the message becomes necessary.

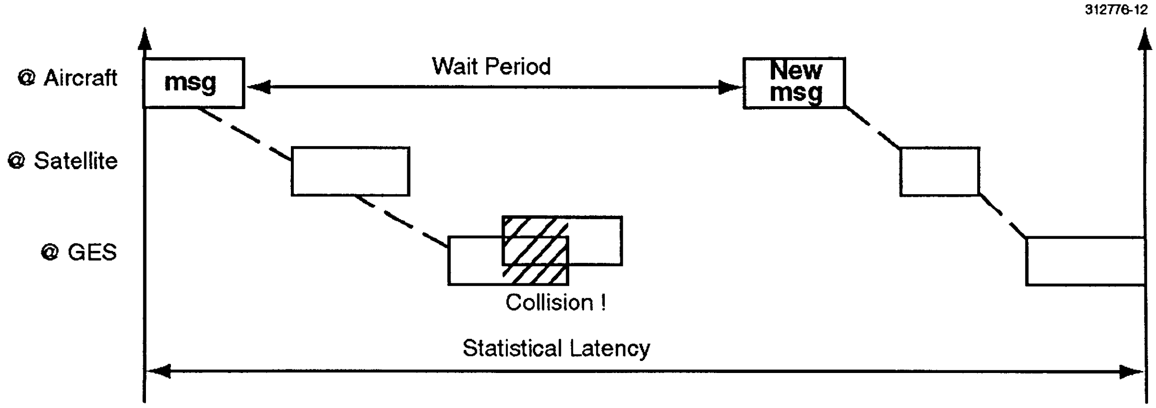


Figure 5-1. Statistical latency of the random access protocol.

Because of this dependency on the number of collisions, we need to modify the previous definition of latency and define the average latency as:

$$\text{Average latency} = \bar{L}$$

$$= P[\text{zero collision}]\cdot\left(T_{prop} + T_{msg}\right) + P[\text{one collision}]\cdot\left(T_{delay1} + T_{prop} + T_{msg}\right) + \ldots$$

The average latency is difficult to calculate and depends on the details of the re-transmission protocol. Instead, we take as a latency requirement that the probability of a collision of two messages is kept less than 10%. Hence, we need to determine the expression for the probability of the N^{th} message arriving at the receiver without a collision with any of the previous $N-1$ transmitted messages. Then, we want to calculate or bound the probability that the N^{th} message is transmitted at a randomly selected time within the 30 second reporting interval without colliding with any other message. Figure 5-2 shows a generic relationship between the number of users and the probability of collision-free transmission; as more users transmit messages, the probability of message collision increases. For example, with one user in the system, the probability of message collision is zero, or the probability of collision-free transmission is one.

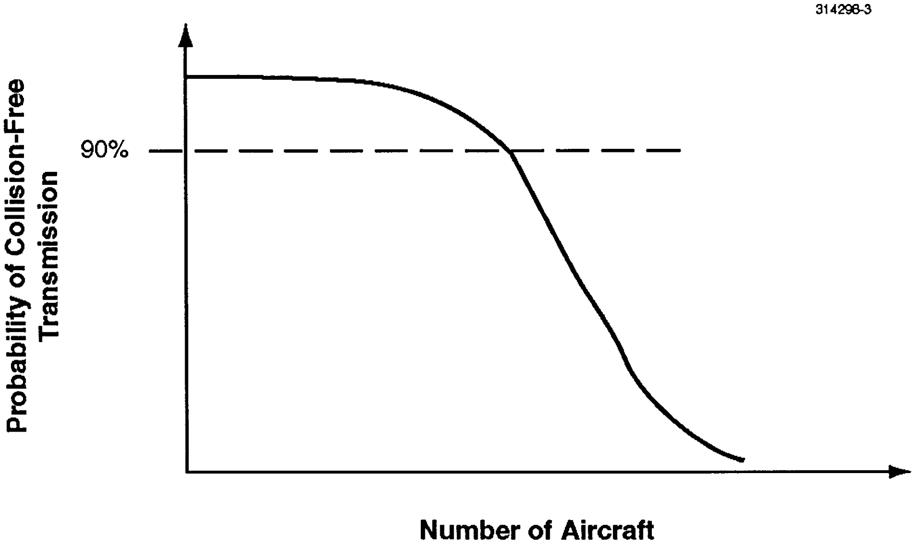


Figure 5-2. Relationship between the number of users and the probability of collision-free transmission.

The probability of the first message colliding with another message is zero since there are no other messages; hence, $P_1 = 1$. The second message can either overlap entirely with the first message, i.e. the times of arrival for both are the same, or it can catch the tail end of the first message (Figure 5-3).

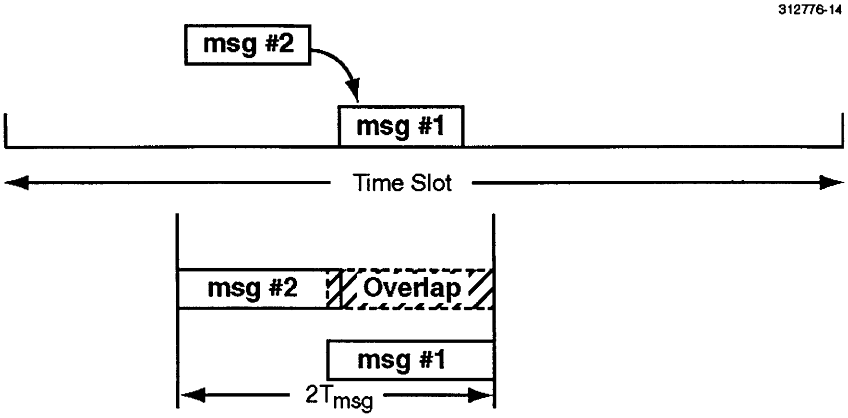


Figure 5-3. Overlap of two messages resulting in possible data loss.

Thus, the window of time that will cause a collision is $2T_{\text{msg}}$ out of the 30 second message update interval, and so the probability that the second message does NOT collide is:

$$P_2 = \frac{T_{\text{update}} - 2T_{\text{msg}}}{T_{\text{update}}} = 1 - \frac{2T_{\text{msg}}}{T_{\text{update}}}$$

Similarly, we find that:

$$P_3 = 1 - 2 \cdot \frac{2T_{\text{msg}}}{T_{\text{update}}}$$

The probability that all M (=500) messages do not collide is the product of all these probabilities:

$$P_{\text{M}} = P_1 \cdot P_2 \cdot P_3 \ldots \cdot P_{\text{M-1}} = 1 \cdot \left(1 - \frac{2T_{\text{msg}}}{T_{\text{update}}}\right) \cdot \left(1 - 2 \cdot \frac{2T_{\text{msg}}}{T_{\text{update}}}\right) \cdot \ldots$$

Simplifying, we arrive at the following expression for P_{M}:

$$P_{\text{M}} \approx 1 - M \cdot \frac{2T_{\text{msg}}}{T_{\text{update}}}$$

According to the performance requirements adopted for this study, we want M messages to go through with a 90% chance of no collision. Hence, we have the inequality relation:

$$\left(1 - M \cdot \frac{2T_{\text{msg}}}{T_{\text{update}}}\right) \geq 0.90$$

Solving this inequality for T_{msg}, we find T_{msg} to be 3 ms. This is a significant decrease from the TDMA slot duration, which is 60 ms; the message duration has to be that much shorter to ensure that a message collides with another message only once out of ten times. This implies that the timeline in a 30 second update interval is largely empty, i.e., free of messages. We shall revisit this issue in the spectral efficiency calculations. In conclusion, the latency for Option 2 is $\mathrm{P[zero\ collision]} \cdot \left(T_{prop} + T_{msg}\right)$, with a 90 % chance of zero collision and ignoring the propagation delay, or 2.7 ms. Note that if the probability of zero collision were any higher than 90%, for example, 99%, the message duration would have to be decreased to further reduce the channel occupancy, and thus further reduce spectral efficiency.

Figure 5-4 illustrates the propagation of a CW message from aircraft to ground station (GES). Because CW is a continuous mode, the message occupies the full 30 second update interval, and thus its latency is $2 \times 125\ \mathrm{ms}\ +\ 30\ \mathrm{s}$. That is, the latency for a CW system is essentially equal to the message length, which is equal to the update interval. Thus, ignoring the propagation delay, the latency for CW is 30 seconds.

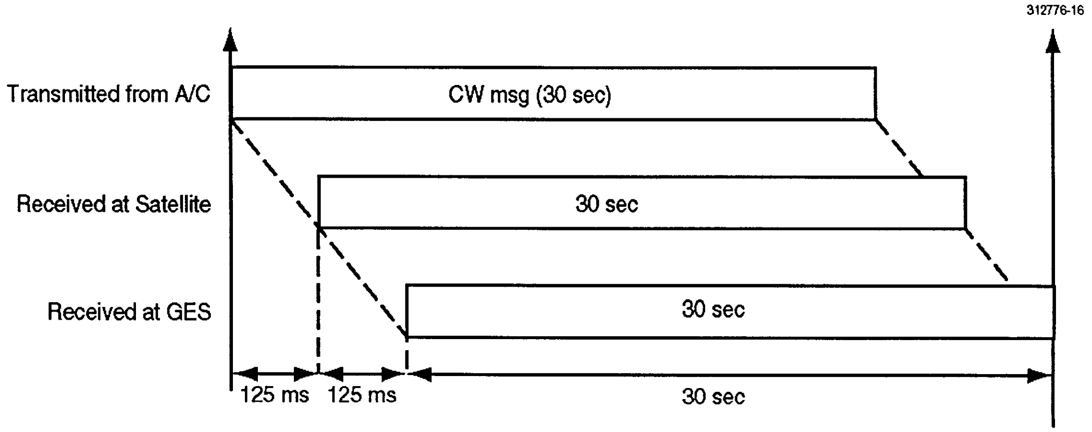


Figure 5-4. Latency of a CW mode message.

The CW mode's latency of 30 sec is longer than the system reaction time of 15-20 seconds, and thus it makes effective control of aircraft for safety much more difficult. Thus, the burst mode has a clear advantage over the CW mode in latency. Position updates sent by the CW mode suffer from "message staleness," which means that when the latest position update is received, it is already 30 seconds old and does not give accurate position information since the aircraft has traveled during the time it took the message to arrive. However, if the message update rate can be reduced to 10 seconds, CW CDMA may become a viable option, since 10 seconds is now shorter than the system reaction time of 15-20 seconds.

Table 5-1 summarizes the results from this section by listing the latency for each system option, ignoring the propagation delay.

Table 5-1. Latency of Each System Option.

System Options	Latency
Option 1: Non-SS/Burst/Slotted TDMA	60 ms
Option 2: Non-SS/Burst/Random Access TDMA	2.7 ms
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	60 ms
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	60 ms
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	2.7 ms
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	2.7 ms
Option 7: SS/CW CDMA	30 s

5.2.2 Spectral Efficiency

Each option requires a certain amount of bandwidth in order to accommodate 500 simultaneous users - the more bandwidth needed, the higher is the cost of the option, and hence, options requiring less bandwidth are clearly more attractive.

We define bandwidth, BW, as the portion of the spectrum between the first negative and positive zero-crossings. Figure 5-5 shows a "sinc" function, $(\sin x)/x$, which is the frequency domain representation of a "box-car" function in time domain; a burst of RF carrier is essentially a box-car in time domain. Thus,

$$BW = \frac{2}{T_{chip}},$$

where T_{chip} is the chip duration.

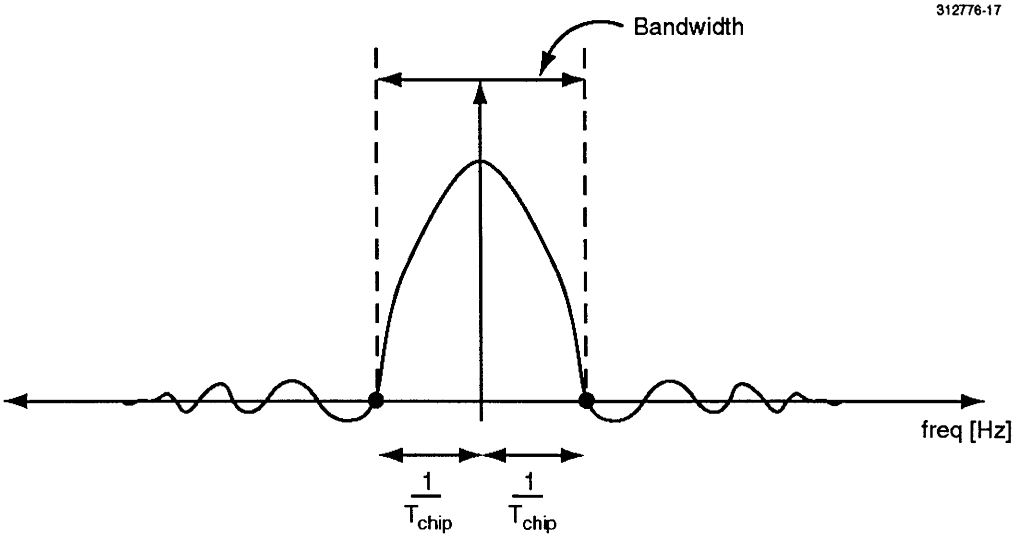


Figure 5-5. Definition of bandwidth.

For slotted TDMA (Option 1), there is no spreading in bandwidth, hence $T_{chip} = T_{bit}$. In the latency discussion, we determined the slot duration, T_{slot}, to be 60 ms. Since each slot contains 400 bits,

$$T_{\mathrm{bit}} = \frac{T_{\mathrm{slot}}}{n_{\mathrm{bits/slot}}} = 0.15 \text{ ms},$$

and so BW is simply twice the inverse of the bit duration, or 13 KHz.

Similarly, for random access TDMA (Option 2), we calculate the chip duration, which is again the bit duration, by dividing the message length by $n_{\mathrm{bits/slot}}$, and find it to be $T_{\mathrm{bit}} = 7.5\mu s$, or 7.5 microseconds. The bandwidth is 260 KHz, an order of magnitude increase from the slotted TDMA bandwidth, necessitated by the low collision probability requirement.

A few things to note about the bandwidth for random access TDMA: the bandwidth went up because of the inefficiency of the random access protocol relative to slotted TDMA, as was mentioned in the latency discussions. In random access systems, the message time has to be reduced significantly in order to meet the system requirement of 90% certainty of no collision, which proportionally increases the bandwidth -- the shorter the burst duration, the greater the inverse of that duration and greater the bandwidth. However, a trade-off exists in the flexibility of the system -- in slotted TDMA, each user can only send one burst in the allotted time slot, whereas in random access, it can be sent at anytime. Slotted has more rigorous constraints, such as the pre-arrangement of the slot scheduling. But it requires less bandwidth, hence the equipment is more complex but the channel cost will be less.

Next, consider CW CDMA. We can develop an expression for the capacity of a CW CDMA system from a fundamental law of digital communication, which, when met, ensures a reliable communication link between the ATC controller and the pilot of an aircraft:

$$\frac{E_b}{N_0^*} \geq \sigma_{\min}$$

The ratio of the bit energy E_b to the noise power spectral density N_0^*, must be greater than some minimum threshold value, $\sigma_{\min}$, which is usually in the range of 4 to 5 (~7 dB). The N_0^* term in the denominator consists of multiple sources, namely, thermal noise (N_0), self-interference noise (I_0, for a dedicated channel), and noise from other users (J_0, for an overlay or shared channel):

$$N_0^* = N_0 + I_0 + J_0$$

If we assume that we are using a dedicated channel and the self-interference noise is the predominant source of noise, then the energy-noise density formula simplifies to the following expression:

$$\frac{E_b}{N_0^*} \approx \frac{E_b}{I_0} = \frac{P_s T_b}{\sum_{i=1}^{M} P_i \Big/ W_{ss}}$$

where energy per bit, E_b, is the product of bit time T_b, and the power level of the signal at the satellite, P_s. W_{ss} is the spread spectrum bandwidth and P_i is the power level of each user. If we further assume that the power levels of the users are equal at the satellite due to a power control scheme, then the summation in the denominator reduces to $M P_s$, and the power term P_s cancels. We then solve for the system capacity, M, and derive the following expression:

$$M \approx \frac{T_b W_{ss}}{\sigma_{\min}}$$

As an example, we can perform some quick preliminary calculations using this system capacity formula to see how much bandwidth is needed to meet one of our system architecture goals of 500 simultaneous aircraft. Using 0.1 seconds as bit time and the value of 5 for $\sigma_{\min}$, we see that a 5 KHz channel and a 10.5 KHz channel, two common Inmarsat channels, yield 100 and 210 users, respectively, which does not meet the capacity specification. The minimum bandwidth needed for 500 users is 25 KHz. Note that because of the assumptions made to arrive at the capacity formula, we are only considering dedicated channels; if we were to use an overlay channel with other users of a different service, then the bandwidth must increase to provide more processing gain to combat interference from those other users.

The system capacity expression is a function of T_{chip}, from which the bandwidth can be calculated:

$$M \approx \frac{T_b W_{ss}}{\sigma_{\min}} = \frac{PG}{\sigma_{\min}} = \left(\frac{T_{\text{bit}}}{T_{\text{chip}}} \right) \cdot \frac{1}{\sigma_{\min}}$$

Substituting in values for M, T_{bit}, and $\sigma_{\min}$:

$$\text{BW} = \frac{2}{T_{\text{chip}}} = 50 \text{ KHz}$$

This is a three to four-fold increase in bandwidth over slotted TDMA, but significantly less than random access. Note that in this CW case, all of the PG, which is 2500, is used to mitigate interference from other ATC users, called self-interference. None of the PG is used for mitigating jamming or incidental interference.

Finally, for spread spectrum burst TDMA, we simply scale up the results we obtained for non-spread spectrum burst systems, slotted and random access, by the appropriate processing gain; unlike in the non-SS options, $T_{chip} \neq T_{bit}$. It is important to note that for the burst case, we cannot use the previously calculated PG for the CW case. In burst, there is no self-interference; instead, all of the PG can be used to suppress jamming or incidental interference, meaning a more secure, robust system for SS-burst. In order to find the new PG for SS-burst, we use the jamming margin specification, which is 10^2 and can be defined as:

$$\frac{J_0}{P_s} = \frac{PG}{(E_b/N_0)_{\min}}$$

This result comes directly from the capacity calculations for CW CDMA, with I_0, the self-interference term, being replaced by J_0, the "other-user" interference term. Thus, PG is found to be 500, i.e., $T_{\text{bit}} = 500\,T_{\text{chip}}$.

If RFI protection is needed by a CW system, this extra PG of 500 is necessary to combat the "other-user" interference. Thus, with a PG of 3000, we find that the BW of an anti-jam CW system is 60 KHz.

Using the value of 500 for PG, we find that the resulting bandwidths for burst systems are very large: 6.5 MHz for SS-burst-slotted (Options 3 and 4) and 130 MHz for SS-burst-random access (Options 5 and 6).

Table 5-2 summarizes the results from this section by listing the required bandwidth for each system option.

Table 5-2. Bandwidth of Each System Option.

System Options	Bandwidth
Option 1: Non-SS/Burst/Slotted TDMA	13 KHz
Option 2: Non-SS/Burst/Random Access TDMA	260 KHz
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	6.5 MHz
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	6.5 MHz
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	130 MHz
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	130 MHz
Option 7: SS/CW CDMA	50 KHz (60 KHz for RFI protection)

The appeal of spread spectrum might well be questioned since it costs so much more in bandwidth. As we will see, however, SS does offer advantages in better security, lower probability of interception, lower probability of detection, and resistance to incidental interference.

5.2.3 Demodulation Complexity

Demodulation is the process of recovering the message bits from the received waveform. Proper demodulation techniques are essential in correctly decoding the messages. Demodulation complexity is a burst vs. CW issue because the number of demodulators needed depends on the number of overlapping messages that must be simultaneously demodulated. That is, zero overlap of messages (as in burst communication, if we assume zero collisions) means minimum demodulation complexity, while 500 overlaps (as in CW) implies maximum complexity.

Figure 5-6 shows the receiver diagram for burst mode. Once a preamble is detected by the preamble detector, the demodulator is fed with the preamble itself and a series of sampling impulses generated by the bit strobe generator. After the message is demodulated, the extracted data is put in a buffer where decoding of the forward error correction (FEC) coding is done and the final bit decisions are made. Note that there is only one demodulator shown in the diagram since we have assumed no message overlap. As was mentioned before, a complete overlap results in a loss of messages, but with a minimum time separation of $2T_{chip}$, the preamble detector can separate out the preambles. However, in this case, more than one demodulator would be necessary, and thus the demodulation complexity is increased. The demodulation complexity for random access will be greater than slotted if overlapped messages are to be processed. Even though PN code usage is generally not a factor for this consideration, programmable preamble detectors and demodulators are more complex than the ones that use a fixed PN code.

For CW CDMA, all user messages overlap each other, and CDMA handles this by assigning a different PN code to each user. Each user's message must be decoded using a separate demodulator; hence, the number of demodulators needed is equal to the number of users, which is 500 in this case.

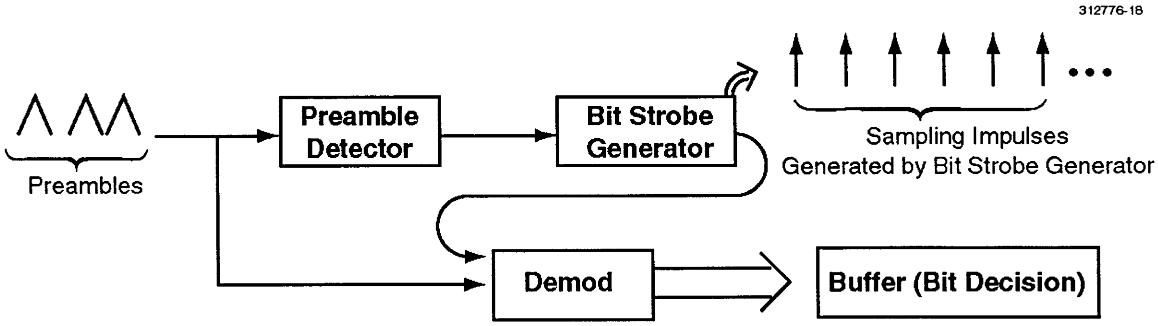


Figure 5-6. Diagram of a burst mode receiver.

Table 5-3 summarizes the results from this section by listing the number and the type of required demodulators for each system option.

Table 5-3. Demodulator Complexity of Each System Option.

System Options	Number of Demodulators
Option 1: Non-SS/Burst/Slotted TDMA	1 non-SS demodulator
Option 2: Non-SS/Burst/Random Access TDMA	1 non-SS demodulator (more if message collision is to be resolved)
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	1 fixed SS demodulator
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	1 programmable SS demodulator
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	1 (or more) fixed SS demodulators
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	1 (or more) programmable demodulators
Option 7: SS/CW CDMA	1 SS demodulator per user

5.2.4 Demodulator Synchronization

Accurate demodulator synchronization at the receiver is essential to recover the data from messages. For the CW system, once the initial synch lock-in is performed, the synch-tracking process is used, and constant re-synchronization, which is needed in burst, is not necessary [5]. For this reason, synch-tracking is used and is generally easier to perform than preamble detection. Figure 5-7 shows the receiver diagram of CW CDMA.

As discussed, all of the burst TDMA options use a preamble detector.

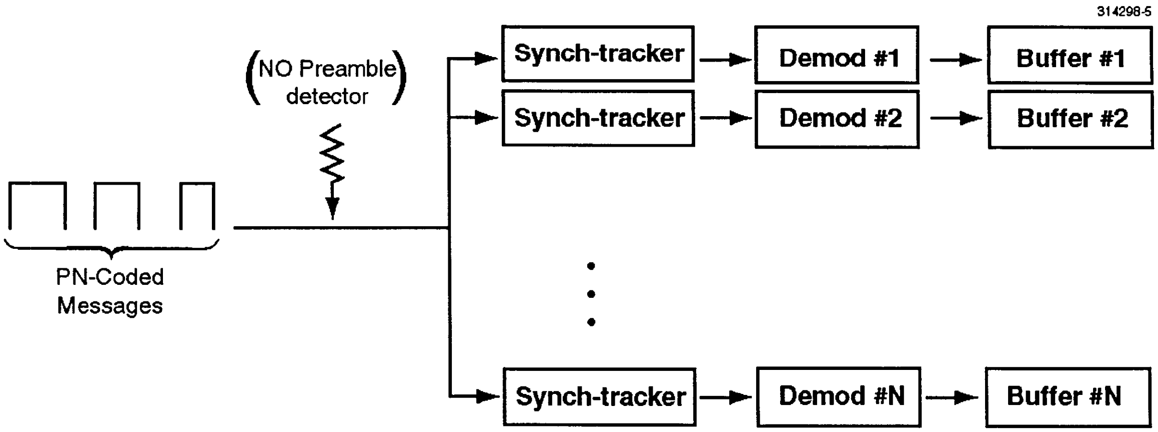


Figure 5-7. Diagram of a CW mode receiver.

Table 5-4 summarizes the results from this section by listing the type of receiver synchronization used by each system option.

Table 5-4. Receiver Synchronization of Each System Option.

System Options	Receiver Synchronization
Option 1: Non-SS/Burst/Slotted TDMA	Non-SS preamble detection
Option 2: Non-SS/Burst/Random Access TDMA	Non-SS preamble detection
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	Fixed SS preamble detection
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	Programmable SS preamble detection
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	Fixed SS preamble detection
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	Programmable SS preamble detection
Option 7: SS/CW CDMA	Synch-tracking

5.2.5 Message Security

Message security can be divided into three categories: low probability of interception (LPI), low probability of detection (LPD), and a listener actually deciphering the data bits. LPD refers to a listener being aware of a transmission. LPI refers to a listener being aware of a transmission and knowing enough about the nature of the transmission to record - intercept - or jam the signal. Because they are closely tied, we will consider LPI and LPD together.

Although the threat of an interception or jamming of a civil ATC message is not likely, the issue of message security is explored for the sake of completeness and comprehensiveness. For a military ATC system, message security may be an important consideration.

LPD/LPI depends on the degree of user coordination and usage of spread spectrum and PG (use of PG to shield messages from noise and make them noise-like). In general, short pulses are more easily detected than SS signals, and thus are more vulnerable to detection and interception. For slotted TDMA, once the slot assignments are known, it is easy to track the message bursts of a particular aircraft. Random access TDMA has better LPI than slotted TDMA because coordination among the users is less and so a listener cannot predict when an aircraft will transmit its burst. The SS-burst-random access option has these advantages, plus the added protection of spread spectrum; it will be harder for a listener to record a SS message because it is noise-like. However, the best option is Option 7, CW CDMA, because with all 500 users' messages being transmitted simultaneously, it is virtually impossible for a listener to separate the signals.

The actual decoding of the data bits by a listener can be prevented by simply using cryptography, regardless of the method of transmission. There is an important distinction to be made between the uses of cryptography and SS -- SS reduces a listener's capability to listen in or record the message, whereas crypto scrambles the data bits so that even if the listener succeeds in recording the message, he would not be able to figure out the meaning of the data stream.

Table 5-5 summarizes the results from this section by describing the LPD/LPI vulnerability of each system option.

Table 5-5. LPD/LPI of Each System Option.

System Options	LPD/LPI Vulnerability
Option 1: Non-SS/Burst/Slotted TDMA	Vulnerable
Option 2: Non-SS/Burst/Random Access TDMA	Vunerable
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	SS protection
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	SS protection
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	SS protection
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	SS protection
Option 7: SS/CW CDMA	SS multi-user protection

5.2.6 RF Interference

The RF interference (RFI) issue is somewhat related to LPD/LPI. It refers to a system's ability to suppress incidental or purposeful RF interference. As was mentioned in 5.2.5, it is unlikely for instances of jamming to occur in a civil ATC system, but the topic of RFI is discussed here for completeness.

Immunity from RF interference is one of spread spectrum's main advantages; the military has used SS systems mainly because of their anti-jamming quality. Thus, this criterion is a non-SS vs. SS issue. Non-SS has no processing gain to suppress interfering users, but the FEC coding helps in recovering the message bits correctly if only a small percentage of bits are incorrectly demodulated because of interference.

For a DS-SS system that uses phase shift keying, we can define the jamming margin as:

$$\frac{J}{P} = \frac{PG}{\left(E_b/N_0\right)_{\min}}$$

where J is the interference power [10]. Expressing both sides in dB, we get:

$$(\text{Jamming margin})_{dB} = (\text{Processing gain})_{dB} - (\sigma_{\min})_{dB}$$

For example, a system with a jamming margin of 33 dB implies that even in the presence of an interfering signal with power 2000 times greater than the signal power, the message can still be processed at the required signal-to-noise density ratio, and hence, at the desired bit error probability.

Table 5-6 summarizes the results from this section by describing the RFI vulnerability for each system option.

Table 5-6. RFI Vulnerability of Each System Option.

System Options	RFI Vulnerability
Option 1: Non-SS/Burst/Slotted TDMA	Vulnerable
Option 2: Non-SS/Burst/Random Access TDMA	Vulnerable
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	SS protection
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	SS protection
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	SS protection
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	SS protection
Option 7: SS/CW CDMA	SS protection (need 60 KHz)

5.2.7 Vulnerability to Multi-User Interference

This criterion is a multiple access issue; all multiple access schemes must address the issue of multi-user interference (MUI), i.e., suppressing the effects of other ATC users that share the same communication channel. MUI is synonymous with system self-interference. In order to suppress the effect of other users, a system can use PG (spread spectrum), time gaps (burst mode), or both. CW CDMA can only rely on PG to mitigate MUI because of the nature of the communication mode. Assuming no message collisions, burst communication is immune from any MUI.

A slotted TDMA system has complete immunity from MUI given that the slot assignments include only one user per slot; however, slotted TDMA gives up flexibility within the system since coordination among the users is necessary. Random access TDMA may or may not use SS, but it would need SS to allow message reception in case of message collisions. There are possibilities of even second and third collisions – random access cannot guarantee that all the messages will safely be decoded at the receiver – instead, it can only guarantee a certain percentage of the messages will go through without collision. Fixed preamble systems, i.e., use of the same PN code for all times, do use SS and the PG can still suppress users of other types of service in an overlay channel.

Table 5-7 summarizes the results from this section by describing the multiple-user interference vulnerability for each system option.

Table 5-7. MUI Vulnerability of Each System Option.

System Options	MUI Vulnerability
Option 1: Non-SS/Burst/Slotted TDMA	None
Option 2: Non-SS/Burst/Random Access TDMA	10% chance of collision
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	None
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	None
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	10% chance of collision
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	10% chance of collision
Option 7: SS/CW CDMA	Critical design factor

5.2.8 Satellite Diversity

Satellite diversity refers to the transmission of a single message via multiple satellites in order to achieve some redundancy. The signal transit time from an aircraft to a GEO satellite can range from 120 to 135 ms, depending on their relative positions (Section 5.2.1). If a slotted TDMA system is used, it can only be optimized for one GEO satellite: signals that arrive sequentially at one satellite will overlap at the other. If satellite diversity is to be achieved using GEO satellites, larger guard times will be needed, reducing spectral efficiency.

The distance from aircraft to a LEO satellite (such as Iridium or Globalstar), is much smaller than it is to a GEO satellite, which reduces the signal transit time. LEO satellites also have a smaller communication coverage area, therefore only a fraction of the 500 aircraft will be within range of any given LEO satellite at a time. This means that efficient channel sharing is less of an issue for LEO satellites than it is for GEOs. LEOs provide some diversity simply because multiple satellites are needed to serve the entire aircraft population. Beyond that, LEOs can provide some overlapping coverage of the same aircraft at non-equatorial regions.

The advantage of using satellite diversity is that it can be used to increase message reliability. If only a single satellite is used to relay messages from an aircraft to a GES, the aircraft antenna may be shielded by a part of the aircraft during turning manuevers. Message reliability would decrease during such manuevers because of the decrease in antenna gain of the aircraft antenna in certain directions. However, if two satellites (in two different directions relative to the aircraft) can relay the message, it is unlikely that both satellites would be shielded simultaneously (Figure 5-8).

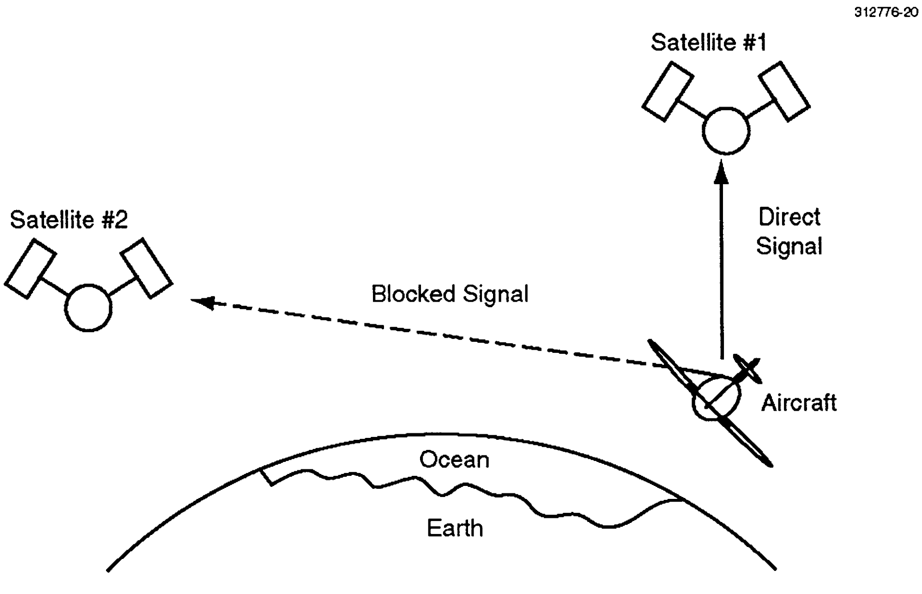


Figure 5-8. Satellite diversity.

Table 5-8 summarizes the results from this section by describing the feasibility of satellite diversity in each system option.

Table 5-8. Satellite Diversity of Each System Option.

System Options	Satellite Diversity
Option 1: Non-SS/Burst/Slotted TDMA	Difficult
Option 2: Non-SS/Burst/Random Access TDMA	Possible
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	Difficult
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	Difficult
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	Possible
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	Possible
Option 7: SS/CW CDMA	Possible

5.2.9 Multipath Interference

Multipath (MP) interference refers to a type of interference that occurs when a signal reaches its destination via not one, but a number of different paths, resulting in the delayed signals interfering with the direct signal at the receiver. MP interference can be a serious problem in environments with many obstacles between the transmitter and the receiver. The oceanic environment eliminates the multipath interference issue that is so prevalent in the cellular domain, except for one significant case: a signal from an aircraft flying over the ocean has two paths – one is a direct path up to the satellite, and the other bounces off the surface of the ocean and then reaches the satellite – and these two paths create two signals that arrive at the satellite at slightly different times and could thus interfere with each other (Figure 5-9). The degree of interference depends on the time separation of the two signals upon their arrival and the relative power levels of the signals. The more separated they are, the easier it is for the detector to detect the first signal and then just discard the second one. But if the two arrive almost at the same time, with almost the same power, they cannot be easily separated and confusion can occur.

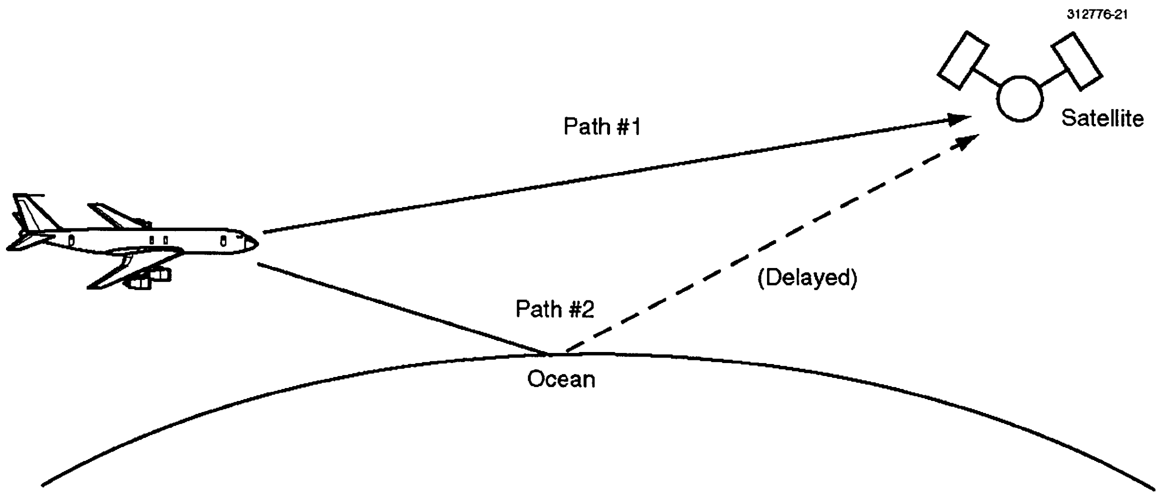


Figure 5-9. Multipath interference in oceanic ATC.

The key in distinguishing between the two versions of the same message is the chip duration: the shorter the chip duration, the greater the chance of separating the two versions. Figure 5-10 shows a histogram of the chip durations of the system options. The SS burst options are clearly superior, but the cost is that they require larger bandwidth.

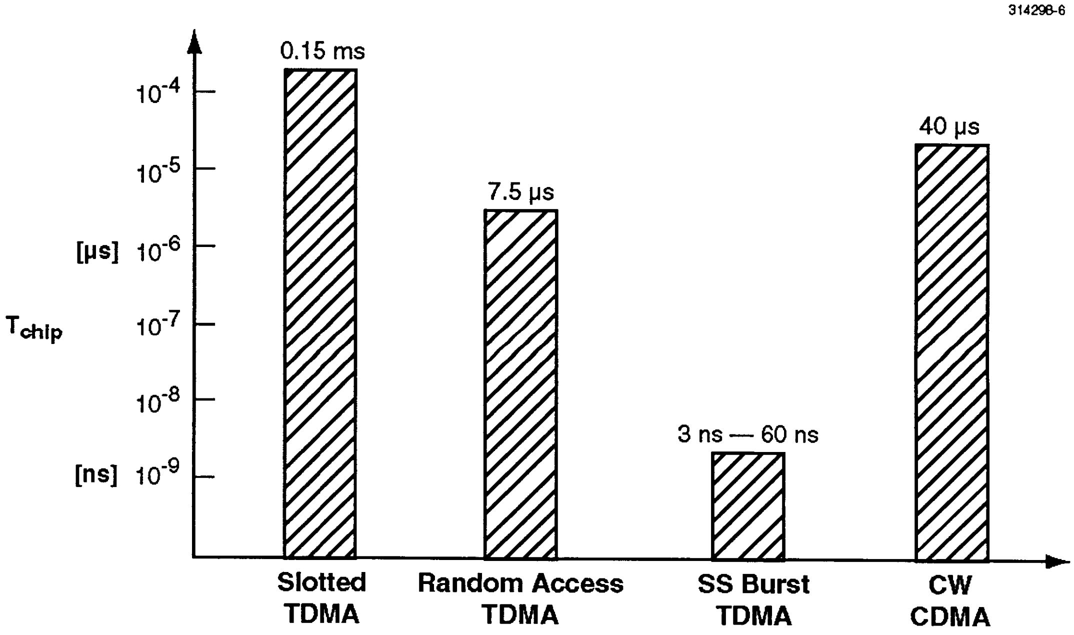


Figure 5-10. Histogram of chip durations (Note log scale).

Table 5-9 summarizes the results from this section by listing the multipath vulnerability and the chip duration of each system option.

Table 5-9. Multipath Vulnerability of Each System Option.

System Options	MP Vulnerability (Chip duration)
Option 1: Non-SS/Burst/Slotted TDMA	Vulnerable (0.15 ms)
Option 2: Non-SS/Burst/Random Access TDMA	Vulnerable (7.5 μs)
Option 3: SS/Burst/Slotted/Fixed Preamble TDMA	SS protection (60 ns)
Option 4: SS/Burst/Slotted/Prog Preamble TDMA	SS protection (60 ns)
Option 5: SS/Burst/Random Access/Fixed Preamble TDMA	SS protection (3 ns)
Option 6: SS/Burst/Random Access/Prog Preamble TDMA	SS protection (3 ns)
Option 7: SS/CW CDMA	SS protection (40 μs)

6. Evaluation of Candidate Systems and Conclusions

In this chapter, we conduct a careful assessment of the candidate systems with respect to the evaluation criteria discussed in Chapter 5.

6.1 Evaluation of Candidate Systems

Table 6-1 summarizes the results from Chapter 5 by combining Tables 5-1 through 5-9 into a single comprehensive table. Based on these results, we perform a relative rank evaluation (3: best, 2: medium, and 1: poorest). Table 6-2 shows this relative ranking for the case of equal weighting of all evaluation criteria. Note that because it depends on the type of satellites used in a system, satellite diversity was omitted from the ranking process.

The first step in determining the most suitable communication approach for oceanic ATC is to identify any candidates that do not meet the critical requirements, or are clearly impractical. These critical requirements include:

- Minimum latency of much less than 15-20 seconds
- Maximum required bandwidth of 10 MHz (on a fully overlaid channel available on an Inmarsat-III satellite)

Candidate systems that do not meet the critical requirements are eliminated from the evaluation process. As for impractical systems, the programmable preamble options require the most complex signal processing to obtain protection from a sophisticated and deliberate jamming attack. This approach has been widely used in military systems which must consider such an attack, but this protection is not required for a civil ATC system.

Next, we consider each candidate and identify its strengths and weaknesses as an ATC satcom system. For the purposes of comparative analysis, we take Option 1 as the baseline system and compare it to Options 2 through 7.

Option 1, Non-SS/Burst/Slotted TDMA, meets the critical requirements, and with a total rank of 18, is one of the highest ranked options. Its strength lies in latency, bandwidth (cost), demodulator complexity, and receiver synchronization. However, because it is not an SS option, Option 1 is vulnerable to jamming, and thus ranks low in the areas of LPD/LPI, RFI, and MUI. After an initial examination, Option 1 appears to be viable for the ATC satcom system.

Table 6-1. Comparative evaluation of system candidates.

	Option 1 Non-SS/Burst/ Slotted TDMA	Option 2 Non-SS/Burst/ Random access TDMA	Option 3 SS/Burst/Slotted/ Fixed preamble TDMA	Option 4 SS/Burst/Slotted/ Prog preamble TDMA	Option 5 SS/Burst/Random access/Fixed preamble TDMA	Option 6 SS/Burst/Random access/Prog preamble TDMA	Option 7 SS/CW CDMA
Latency	60 ms	2.7 ms	60 ms	60 ms	2.7 ms	2.7 ms	30 s
Spectral efficiency (Total BW)	13 KHz	260 KHz	6.5 MHz	6.5 MHz	130 MHz	130 MHz	50 KHz (60 KHz for RFI protection)
Demod complexity	1 non-SS demod	1 non-SS demod (or more to resolve msg collision)	1 fixed SS demod	1 prog SS demod	1 (or more) fixed SS demod	1 (or more) prog SS demod	1 SS demod per user
Receiver synch	Non-SS preamble detection	Non-SS preamble detection	Fixed SS preamble detection	Prog SS preamble detection	Fixed SS preamble detection	Prog SS preamble detection	Synch-tracking
LPD/LPI	Vulnerable	Vulnerable	SS protection	SS protection	SS protection	SS protection	SS multi-user protection
RFI	Vulnerable	Vulnerable	SS protection	SS protection	SS protection	SS protection	SS protection (need 60 KHz)
Multipath vulnerablity	Vulnerable	Vulnerable	SS protection	SS protection	SS protection	SS protection	SS protection
Multi-user interference	None	10% chance of collision	None	None	10% chance of collision	10% chance of collision	Critical design factor
Diversity	Difficult	Possible	Difficult	Difficult	Possible	Possible	Possible

Ranking system:
3 : Best
2: Intermediate
1: Poorest

Table 6-2. Comparison of Relative Ranking of Candidate Systems.

	Non-SS/Burst/ Slotted TDMA	Non-SS/Burst/ Random access TDMA	SS/Burst/Slotted/ Fixed preamble TDMA	SS/Burst/Slotted/ Prog preamble TDMA	SS/Burst/Random access/Fixed preamble TDMA	SS/Burst/Random access/Prog preamble TDMA	SS/CW CDMA
Latency	3	2*	3	3	2*	2*	1
Spectral efficiency (Total BW)	3	2	1	1	1	1	2.5
Demod complexity	3	3	2	2	2	2	1
Receiver synch	3	3	2	1	2	1	3
LPD/LPI	1	1	2	2	2	2	3
RFI	1	1	2	2	3	3	3
Multipath vulnerablity	1	2	3	3	3	3	2
Multi-user interference	3	2	3	3	2	2	1
TOTAL	**18**	**16**	**18**	**17**	**17**	**16**	**16.5**
AVERAGE RANK	**2.25**	**2**	**2.25**	**2.12**	**2.12**	**2**	**2.06**

* Random access is ranked lower than slotted because of its statistical latency.

Option 2, Non-SS/Burst/Random Access TDMA, has a low overall rank, but has most of Option 1's strengths; it ranks lower than Option 1 mainly because of the extra bandwidth required and the statistical latency, which result from the 10% chance of message collision. Even though its latency of 2.7 ms is considerably lower than Option 1's latency of 60 ms, Option 2 was given a lower rank than Option 1 because of the chance of message collision and the resulting loss of data - in which case, the latency would increase (Table 6-2). Nevertheless, Option 2 remains a possible option since it allows for user scheduling flexibility. Users would not have to send messages in assigned time slots, and this could reduce the cost of avionics.

Option 3, SS/Burst/Slotted/Fixed Preamble TDMA, ranks high overall. It is a complementary system to Option 1 since its SS protection can decrease or eliminate Option 1's vulnerability to jamming. In comparing it to Option 1, a system trade-off must be made: Option 3 eliminates Option 1's vulnerability to jamming by adding SS protection to it, but in doing so, it has to give up Option 1's advantages in cost, demodulator complexity, and receiver synchronization, the latter two to a lesser degree. Thus, the choice between Options 1 and 3 depends on whether SS protection or cost is considered more critical.

Option 4, SS/Burst/Slotted/Programmable Preamble TDMA, is a programmable preamble system, and thus will not be pursued further as an option.

Option 5, SS/Burst/Random Access/Fixed Preamble TDMA, does not meet the bandwidth requirement - it requires 130 MHz - and thus will not be pursued further as an option. The bandwidth requirement can be met by either increasing the message duration or simply decreasing the amount of bandwidth spreading, but both of these measures would violate the other system requirements. Even if it meets all the requirements, Option 5 still has a lower relative ranking than Options 1 or 3.

Option 6, SS/Burst/Random Access/Programmable Preamble TDMA, is a programmable preamble system and does not meet the bandwidth requirement, and thus will not be pursued further as an option.

Option 7, SS/CW CDMA, does not currently meet the latency requirement. However, because the CDMA cellular telephone technology is such a successful system, consideration should be given to finding a way to meet the latency requirement. For example, the 30 second message may be split into three successive 10 second messages, each containing the least significant bits of latitude-longitude position measured just as each short message is formatted for transmission. This would shorten latency of position updates down to 10 seconds, which might be acceptable in a system with 15-20 second reaction time. However, a 10-second latency is still only marginal for this application, and there is still the demodulator and receiver complexity issue in CW CDMA of having one demodulator per aircraft user. Unless a custom VLSI implementation is done just for such a low data rate CDMA application, the receiver complexity would still be prohibitive, thus eliminating the use of CDMA in this way for oceanic ATC.

6.2 Conclusion

The relative comparisons show three candidates of approximately equal rankings, but with different strengths:

- Option 1 - Non-SS/Burst/Slotted TDMA
- Option 2 - Non-SS/Burst/Random Access TDMA
- Option 3 - SS/Burst/Slotted/Fixed Preamble TDMA

Of these three candidates, the big difference is in the areas of LPI/LPD, RFI, and multipath vulnerability. If these three factors are outweighed by spectral efficiency, synchronization and demodulation complexity, then the clear winner is Option 1. Otherwise, if LPI/LPD and RFI vulnerability are more important than spectral efficiency and receiver complexity, then the SS option, Option 3, would be superior to the non-SS candidates. Option 2, the random access approach, requires more bandwidth than Option 1 and permits message collisions, but reduces costs of avionics equipment as a result of more flexibility amongst the system users.

In conclusion, the best answer for oceanic ATC is TDMA with burst messages, transmitted in assigned time slots or at random, as in an ALOHA protocol. The pivotal requirement then becomes the sensitivity to RFI. Protection from incidental RFI dictates the use of spread spectrum waveforms. In that case, the receiver processing can be kept relatively simple by using a PN code which is fixed for all time, and therefore, hardwired into the receiver processing circuits. The selection between slotted vs. random access TDMA protocols will be strongly influenced by the feasibility and cost of obtaining greater bandwidth for the random access system.

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