Rapid advancements in wireless technology and evolution of a broad spectrum of applications have created a need to develop techniques and algorithms for precise operation of a satellite communication link. This necessitates an investigation of various components involved in a satellite communication. For e.g., channel sharing, data structure, signal specifications, transmitter and receiver processing, etc. are some of the areas in which a research can focus on. Since Time Division Multiple Access (TDMA) is one of the most common multiple access techniques utilized in satellite communication, this thesis focuses on the investigation of some of the critical network management and control processes pertaining to TDMA environment. As the name implies, a TDMA network allows multiple transmitting stations to access the channel by allocating each one
of them different time slots. In other words, multiple earth stations can transmit data intermittently on the same frequency, due to which special steps have to be taken in order to avoid interference among data transmitted by different stations. This is in addition to the Quality of Service (QoS) demands from the network. These requirements have created a critical importance for the development of efficient acquisition and synchronization algorithms. Moreover, the pace at which new applications based on satellite communications are being developed has resulted in rapid changes in satellite technology as well, which in turn has imposed additional constraints on acquisition and synchronization algorithms. This thesis is an investigative study on some of the techniques involved in accomplishing frame acquisition and synchronization.

Data in TDMA communication is formatted in the form of frames which comprises traffic information, in the form of bursts, from all participating earth stations in a network. In addition to traffic data, each burst is prefixed with a preamble that aids frame synchronization as well as carrier synchronization. This thesis focuses on different types of bursts and the role of preamble, Unique Word (UW) in particular, for attaining frame acquisition and synchronization. Most of the widely used algorithms for frame synchronization are based on conventional correlation or maximum likelihood (ML) estimators for the detection of UW. This research is an analysis of the impact of format and length of UW, different types of bursts, on the performance of different synchronization techniques. We have considered PN sequences, Barker codes, Neuman-Hofman codes for studying the performance of correlation detectors and ML estimators, for a QPSK based TDMA system. In addition, ML decision rules that take into
consideration the structural properties of a burst structure to estimate the location of UW were analyzed.

Results show that Barker code of length 13 QPSK symbols produces the best estimate for achieving synchronization, followed by Neuman-Hofman code. Among the different synchronization techniques analyzed the ML estimators delivered the best results in the presence of high frequency and phase offsets. In addition, the structural properties of different types of bursts have an impact on the performance of the decision rules for detecting the UW.
To my Parents: P.K. Sapru and Nalini Sapru
Acknowledgements

I would like to express profound gratitude to my advisor, Dr. Junghwan Kim, for his unstinting support, encouragement, supervision and valuable suggestions throughout this research work. I would also like to thank the entire members of the Communications Lab for their advice.

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Chapter 1

Introduction

Advanced technology coupled with increasing demand for channel resources led to the development of several multiple access schemes in the telecommunications and computer networks domain. These schemes were developed so that multiple terminals connected to the same transmission channel could transmit and share the channel capacity efficiently. Some of the widely popular multiple access schemes are as follows:

- Time Division Multiple Access (TDMA)
- Frequency Division Multiple Access (FDMA)
- Code Division Multiple Access (CDMA)

The multiple access or channel access schemes are based on the principle of multiplexing, which allows signal from different terminals to share the channel.

This research focuses on one of the aspects of a TDMA network. TDMA is perhaps the most popular schemes for implementing a communication network of several stations. It is the basis of most satellite communication networks, leading cellular system (GSM), etc. In communications involving satellites, TDMA enables multiple earth stations or Very Small Aperture Terminals (VSAT) to transmit intermittently on the same frequency. However, transmission from each terminal is separated in time to avoid
interference with data from other terminals. The data transmitted during a single time slot is known as a *burst* and a collection of bursts forms a *frame*. Each station’s burst is synchronized (Frame synchronization) so that, at the time of arrival at the satellite, it is the only signal present and no collision occurs with the traffic burst of any other station and thus is successfully received by the teleport hub modem burst demodulator, as shown in Fig. 1.1. The traffic bursts are amplified by the satellite transponder and retransmitted in a downlink beam which is received by all the participating stations [1]. On receiving the traffic bursts, earth stations synchronize their local carrier (Carrier synchronization) to that of the satellite, eventually helping demodulate and decode the message transmitted. The structure of a TDMA frame, which comprises of bursts from several earth stations, plays a significant role in accomplishing synchronization at network level and carrier level.

![Fig. 1.1 TDMA based satellite communication network](image-url)
1.1 Frame Synchronization

TDMA frame/network synchronization is important because of satellite motion and different propagation ranges which affect the time at which earth stations must transmit so that their bursts do not overlap at the satellite. Synchronization can be viewed as a two stage process [2]:

- Acquisition – refers to the process of positioning a burst into its assigned location in a frame.

- Steady-state Synchronization – refers to the maintenance of a burst in its destined location.

The methods for establishing acquisition and synchronization are characterized as follows:

- Open-loop Acquisition and Synchronization
- Closed-loop Acquisition and Synchronization
- Co-operative feedback control

1.1.1 Closed-loop Acquisition and Synchronization [1]

The closed loop approach relies on the ability of any earth station to see reference and “own” burst retransmission from the satellite, thus enabling the station to adjust its “own” burst timing to occupy an assigned epoch in the TDMA frame. The ability to see its “own” burst allows a terminal to attain acquisition and maintain synchronization by continued loopback error observation and correction cycles.
1.1.2 Open-loop Acquisition and Synchronization [1]

Unlike the closed-loop approach in which a terminal can see its own bursts retransmitted from satellite, the open loop control is applicable for TDMA environments, where the stations do not have the ability to detect the retransmissions from the satellite. Open loop control refers to control of traffic burst position based on the value of propagation time, which is equivalent to the distance between the satellite and earth station. It requires accurate knowledge of the satellite position and the earth scale locations. Open loop control of traffic burst position at an earth station requires the introduction of time delay between reception instant of the TDMA reference burst and the transmission instant of the stations own burst. The value of delay $D_N$ introduced is usually proportional to the frame duration and the distance between the station and satellite.

1.1.3 Co-operative Feedback Control [1]

The cooperative feedback approach for acquisition and synchronization provides considerably precise position control, particularly needed for multibeam systems. This is suitable for systems where traffic stations cannot see their own bursts. It uses open-loop computation for initializing the value of delay $D_N$ for acquisition. On the other hand, for synchronization, it observes the burst position error and feeds back the corrections.
1.2 Motivation

Design of reliable communication systems that deliver the demanded Quality of Service (QoS) aims at approaching the channel capacity, under the assumption of ideal synchronization and parameter estimation [3]. In fact, the use of advanced channel coding techniques has made it possible to reach the Shannon Limit, even at very low Signal-to-Noise Ratio (SNR). Hence, in order to achieve superior performance, it is mandatory that the assumption of ideal synchronization be true. This implies that synchronization and parameter estimation are ever more critical, in order to ensure that the potential advantages of coding techniques are not limited owing to poor timing and synchronization techniques. The structure of TDMA burst plays a significant role in the effectiveness of network synchronization and carrier synchronization technique employed. A TDMA frame, which is a collection of bursts comprising of a preamble portion and a data portion, conforming to the standard structure of satellite network is considered in this thesis. Emphasis has been given to different types of bursts in a satellite network and the nature of Unique Word (UW) portion of the preamble that helps establish frame synchronization.

1.3 Research Contribution

Most of the existing publications provide results validating the performance of various acquisition and synchronization algorithms. The most popular technique for providing frame synchronization in a binary signaling system is to insert a fixed binary pattern or “syncword” periodically into the data stream. Based on the assumption that
symbol synchronization has already been obtained, the receiver obtains frame synchronization by locating the position of the syncword in the received data stream [4]. In a satellite TDMA system, special code patterns called UW are contained in the bursts. Reliable detection of UW is the basis for keeping the stations in synchronism and providing high-quality communication links. Schrempp and Sekimoto [5] studied the influence of miss and false detection of the UW on acquisition and synchronization. The investigation proved that format and length of UW can be chosen so that at system threshold a very reliable UW detection is maintained, which in turn maintained the loss of information at tolerable levels. Barker’s approach for locating the syncword involved a “pattern synchronizer” that scanned the received digital stream [6]. The pattern synchronizer was a device to correlate successive $L$-digit segments of the received sequence with the $L$-digit sync word. The segment giving the maximum correlation would be taken as the location of sync word. Massey later developed an optimum decision rule to estimate the location of the sync word in a burst, taking into consideration the effect of data surrounding the sync word [4]. The Maximum Likelihood (ML) rule was developed for a BPSK modulation scheme with the channel modeled as Gaussian and it was proved that the optimum rule provides a 3-dB advantage over the ordinary correlation rule when signal to noise ratio was closer to unity. Lui and Tan [7] developed an ML decision rule for coherent phase and non-coherent phase signaling systems. Gansman, Fitz and Krogmeier developed optimum frame synchronizers for Additive White Gaussian Noise (AWGN) with a frequency offset and for slow Rayleigh fading, based on ML estimation [8]. The synchronizers developed had a fixed acquisition time and the probability of correct acquisition increased with
increasing SNR. This work was modified by Choi and Lee [9] for obtaining a ML rule based on an operation called double correlation. It was shown that the new rule outperformed several other rules when a frequency offset existed.

All the works described above were pertaining to the core step involved in frame synchronization – UW detection. Kamal presented a Markovian modeling approach for analyzing the performance of sync detector that detects the UW for frame synchronization [10]. These models provided computations for acquisition-time statistics, probability of false acquisition and mean time for loss of sync. These models accounted for the deterministic data pattern immediately preceding the UW. Many other works pertaining to frame synchronization focused on the design of sync pattern or the UW [12, 13, 14].

The UW detection techniques reviewed above considered a simple frame structure comprising of information data prefixed with a syncword. But, satellite communications based on TDMA environment have a well defined frame structure comprising of carrier and clock recovery sequences preceding the sync pattern or UW. Moreover, the system uses different burst structures for time reference and management, transmission of traffic information and acquisition. This research analyses the pattern or structure of each burst for the analysis and development of ML estimation rules that will aid frame acquisition and synchronization.
1.4 Thesis Outline

This thesis consists of six chapters and an appendix. Chapter one gave a brief overview of the motivations behind this research and the contributions made. Chapter two describes the burst TDMA system with emphasis on the preamble portion and different kinds of bursts. This chapter also enlists different types of UW patterns used in this research. Chapter three describes the acquisition and synchronization techniques and illustrates the role of different kind of bursts for the same. In addition, the parameter for evaluating the performance is presented in this chapter. Chapter four has a mathematical derivation of the test metric, which is in turn utilized in the acquisition and synchronization algorithms described in Chapter three. The test metric is derived for different types of bursts, taking their structural properties into consideration. Chapter five discusses the results of network synchronization techniques investigated in this thesis. The performance of different decision rules, for UW detection, derived in chapter four is illustrated here. The effect of the type of burst and the pattern of UW is also presented. Chapter six provides conclusions and makes recommendation for future work.
Chapter 2

Burst TDMA System

TDMA allows multiple stations to share the same channel for transfer of information, by allocating each station an exclusive time slot. The stations are synchronized in such a way that they transmit bursts only during the allocated time slot. The structured arrangement of bursts is defined in terms of units called frames. The structure of a TDMA frame, which comprises of bursts from several earth stations, plays a significant role in accomplishing carrier and network synchronization.

This chapter is devoted to the overview of basic architecture of a TDMA frame and its role in achieving network synchronization and carrier synchronization. The aspects of preamble are briefly discussed for future analysis and modeling.

2.1 TDMA Frame Structure [1,3,15]

TDMA frames are structured to avoid overlap between bursts from different earth stations. Such synchronization may be achieved by one earth station acting as a reference station which then transmits Reference Bursts (RB) used by all other stations to achieve timing synchronization. After this initial reference burst, each earth station transmits its
own Traffic Bursts (TB), which together comprises the frame. Overlap is further prevented by guard time between bursts.

TDMA bursts are organized in a TDMA frame as illustrated in Fig. 2.1 [1]. The frame begins with a reference burst RB₁ and there may be a second reference burst RB₂ for reasons of reliability. The locations of traffic bursts are assumed to be referenced to the time of occurrence of reference burst RB₁ in the case illustrated. Each traffic burst originates from a participating station and carries the traffic from that station to all destination stations in digital format. The position and duration of each traffic burst relative to the reference burst is assigned according to a protocol established for network operations. This may be a preassignment protocol, in which case the position and duration assigned is changed infrequently and only for overall network rearrangement, or a demand-assignment protocol, in which the positions and duration of the bursts may be adjusted almost continuously to meet varying traffic demand. Each traffic burst contains a preamble, which provides synchronization and signaling information and identifies the

---

Fig. 2.1 TDMA Frame Structure [1]
transmitting station, followed by traffic data. The traffic bits constitute the revenue-
producing portion of the burst and the preamble forms the system overhead. The smaller
the overhead, the more efficient a TDMA system is, but the more difficulty it may face in
acquisition and synchronization [16]. Frame efficiency of a TDMA system is defined as
the ratio of number of symbols available for carrying traffic to the total number of
symbols available in a TDMA frame.

In general, the TDMA frame duration may range from as small as 125 µs, typical
of T-carrier and the European Conference of Postal and Telecommunications
Administrations digital PCM transmission standards, and extend to as much as 25 ms for
systems that use demand assignment protocols.

To increase efficiency of a TDMA frame and for synchronization purposes [16], a
number of sequential frames can be combined together to form a TDMA super-frame as
shown in Fig. 2.2. This structure results in efficient utilization of the signaling channel
sequence in the preamble, for management and control [17].

![Fig. 2.2 Structure of a Super-Frame](image)
2.2 Types of Bursts

As mentioned earlier, multiple earth stations transmit data over a frame of time called the TDMA frame. To avoid collision of data transmitted by different earth stations, each frame is split into slots corresponding to each participating earth station, which are in turn synchronized so that they occupy the assigned epochs in a TDMA frame. The data transmitted during each time slot is termed a burst. In addition to the traffic information, each burst consists of frame management and control information called the preamble. This section describes different types of bursts and their structures.

2.2.1 Reference Burst (RB)

Reference bursts are emitted by a reference station and, as previously indicated, constitute the basis for synchronizing all other stations in a network. They do not carry any traffic information and comprises of preamble portion only. The structure of a typical reference burst is shown in Fig. 2.3. This burst contains information necessary for other stations to derive the precise location of their bursts in the frame [15].

![Fig. 2.3 Structure of Reference Burst (RB) or Preamble](image)

<table>
<thead>
<tr>
<th>Carrier and Clock Recovery</th>
<th>Unique Word</th>
<th>Signaling Channel</th>
</tr>
</thead>
</table>

Preamble
In some applications, RB is a combination of two reference bursts – RB₁ and RB₂. The primary RB which can be either RB₁ or RB₂ is transmitted by one of the stations called the primary reference station in the network. The RB automatically switches over to the secondary reference burst in case of primary reference station failure. The reference burst or preamble usually consists of three parts:

- Carrier and Clock Recovery Sequence
- Unique Word
- Signaling Channel

### 2.2.1.1 Carrier and Clock Recovery (CCR) Sequence

Different earth stations have slight differences in the frequency and bit rate. Therefore, the receiving stations must be able to establish accurately the frequency and bit rate of each burst. This is achieved with the help of carrier and clock recovery sequence bits. The length of this sequence usually depends on the carrier-to-noise ratio (CNR) at the input of the demodulator and carrier frequency uncertainty. A higher CNR and a lower carrier frequency uncertainty require a smaller bit sequence for carrier and clock recovery and vice versa. The sequence typically consists of an initial segment of unmodulated carrier followed by phase alternations of the carrier frequency between 0 and $\pi$ radians at the symbol clock rate [1].
2.2.1.2 Unique Word (UW)

Unique word is a sequence of bits that follows the carrier and clock recovery sequence of bits. This bit sequence allows the earth station to locate the position of traffic burst in the received TDMA frame. UWs vary in length and may be as short as 10 QPSK symbols or as long as 24 or longer [1]. At a receiver, the UW is applied to a UW detector. This thesis focuses on the use of a conventional correlation detector and a maximum likelihood estimator as UW detector. The output from a UW detector is information regarding the position of UW in the received data stream. This, of course, gives an accurate indication of the instant of arrival of the burst.

2.2.1.3 Signaling Channel

The signaling channel is used to carry out system management and control functions. The signaling channel of the reference burst has three channels, namely (a) an order-wire channel which carries voice and data traffic, used to pass instructions to and from earth stations, (b) a management channel transmitted by reference stations to all traffic stations, carrying monitoring and control messages in addition to information regarding frame management such as burst time plan change etc., and (c) a transmit timing channel that carries acquisition and synchronization information to different traffic stations, enabling them to adjust their transmit burst timing. This channel also carries a status code that enables the traffic station to identify the primary reference burst between RB₁ and RB₂.
2.2.2 Traffic Burst (TB)

Stations may communicate or transfer information from one station to another in the form of traffic bursts (TB). Different stations accessing the satellite transponder may transmit one or more traffic bursts per TDMA frame and position them anywhere in the frame according to a burst time plan. The timing reference for the location of the traffic burst is taken from the time of occurrence of primary reference burst. The structure of a typical traffic burst is shown in Fig. 2.4 [15]. The traffic information is preceded by a preamble, which in turn comprises of a Carrier and Clock Recovery sequence, Unique Word and a Signaling Channel. The preamble, in most cases, is similar in structure to that of the RB, though the functionality of may have slight variations when compared to that of RB.

Fig. 2.4 Structure of Traffic Burst (TB)

<table>
<thead>
<tr>
<th>Carrier and Clock Recovery</th>
<th>Unique Word</th>
<th>Signaling Channel</th>
<th>Traffic Data</th>
</tr>
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<td></td>
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</tbody>
</table>

2.2.2.1 Carrier and Clock Recovery (CCR) Sequence

The CCR sequence in a TB performs similar functions as that of RB. In order for a receiving station to decode the information with minimal error, it is essential that any shift in the frequency or phase of the incoming signal be rectified before feeding the
sequence to a decoder. This portion of the preamble helps the receiving station to attain carrier synchronization.

### 2.2.2.2 Unique Word (UW)

The UW sequence in the traffic burst provides a timing reference on the occurrence of the traffic burst and also provides a timing marker to allow the earth stations to extract their part of the traffic burst. The timing marker allows the identification of start and finish of a message in the burst and helps to correct decoding.

### 2.2.2.3 Signaling Channel

The signaling channel of TB also has an order wire channel, which performs the same function as in the case of RB. The service channel performs functions like carrying traffic station status to the reference station, carrying information such as high bit error rate or UW loss alarms, etc., to other traffic stations.

### 2.2.2.4 Traffic Data

Traffic information immediately follows the preamble in a TDMA frame. Each station in the network can transmit and receive multiple traffic bursts and sub-bursts per frame. The length of each sub-burst or the data stream in a channel depends on the type of traffic and the number of channels being supported by the burst.
2.2.3 Acquisition Burst (AB)

The acquisition burst (AB) is utilized by a station in its acquisition stage. In other words, a station attempts to acquire its slot in the TDMA frame by transmitting an AB and then making appropriate measurements, which will be described in the following chapters. AB usually consists of only the preamble portion of a traffic burst, and therefore is a very short burst. This minimizes the possibility of collision with other traffic bursts during acquisition.

2.3 Guard Time

Bursts from different stations in a frame are separated from each other by a short duration called the Guard time. This is to make sure that bursts from multiple stations do not overlap while accessing the satellite or a common hub. While designing a frame, the duration of the guard time has to be set to a value so that any inaccuracy in transmit time of traffic bursts does not affect the performance to a great extent.

2.4 Overview of Preamble

At the network level, TDMA requires a method for precise timing of the transmissions from earth stations to avoid overlapping in satellite. In other words, TDMA bursts should be synchronized with satellite switch epochs so that traffic burst are routed from up-beam to down-beam without collision with a switching boundary [1]. Hence, a TDMA burst transmitted by a participating earth station has to enter the TDMA frame in
its assigned location (acquisition) and then maintain its position in the assigned location precisely (synchronization). Moreover, a receiving station has to synchronize its locally generated carrier to that of the transmitting station in order to decode the traffic data with minimal error. As mentioned before, both network and carrier synchronization are aided by the preamble sequence preceding each traffic burst. Preamble-based synchronization techniques are widely used today in communication systems as they have the advantage of utilizing much simpler estimation process and the performance is better at low Signal-to-Noise Ratio (SNR) values or high frequency offsets. It is advisable that a preamble has the following properties:

- Periodically repeating sequences of modulation symbols,
- A data sequence that makes the symbol transitions as obvious as possible,
- A unique word with good correlation properties.

The preamble length needed depends on the estimation algorithm being used for acquisition as well as the required system performance, such as accuracy of the parameter estimates extracted from the preamble. However, the preamble length must reflect the following considerations:

- The longer the preamble, the more accurate the estimate is.
- Operating at higher $E_b/N_0$ allows the preamble to be shorter.
- Using more complex modulations (such as higher orders of QAM) will require longer preambles because estimates of carrier frequency must be more accurate.
2.4.1 Carrier and Clock Recovery

The CCR portion of the preamble, that serves to synchronize the transmitting and receiving carriers and modems, typically consists of a short transmission of unmodulated carrier (equivalent in a BPSK system to a carrier modulated by a string of logical ones or a string of logical zeros) followed by carrier phase transition between 0 and $\pi$ radians at the symbol clock frequency. The preamble is received in the form of a binary phase shift keying (BPSK) modulated wave which is superior to the QPSK modulated wave in point of noise-proof capability. INTELSAT uses 48 QPSK symbols (96 bits) of all ones on both P and Q channels followed by 128 QPSK symbols (256 bits) of alternating zeros and ones (0101…) on both the P and Q channels [16].

The carrier synchronization parameters include carrier frequency offset and carrier phase offset. Carrier recovery occurs in two subsequent phases of acquisition and steady-state tracking. At the start of signal reception, the synchronizer has no knowledge about the synchronization parameter values. After some processing of the received signal, the synchronizer is able to deliver accurate estimates of the synchronization parameters which are needed for reliable data detection. This transition from a large initial uncertainty about the synchronization parameters to a small steady-state estimation error variance is called carrier acquisition [18]. Although this thesis does not emphasize on the concept on carrier and clock recovery, this section briefly explains the general concept of carrier, clock recovery and estimations.

In the burst-mode carrier acquisition, the synchronizer performs the initial frequency and phase offset estimation using the preamble. At the end of the preamble, the acquisition should be completed so that reliable data detection can start in the data
portion of the burst. The performance of the acquisition is critical for any modems, but more so in this case because of the burst-mode setting. The synchronization parameters must be recovered quickly so that detection of the data portion of the burst may begin.

In general, a preamble is used to accelerate acquisition; however, overhead must be kept low in order for the system to be efficient. To do this, the carrier acquisition system must be fast. In the case of short burst communication, where the number of data symbols per burst is small, it may be sufficient to consider the carrier phase as constant over the entire burst. It is sufficient to produce a single carrier frequency and phase estimate per burst, and use these parameters for detecting all data symbols within the burst. However, in the case of long burst communication, the fluctuation of the synchronization parameters over the burst cannot be ignored, because the frequency offset estimated in the acquisition process is not perfectly accurate, and residual frequency error will accumulate phase error with time and cause a loss of phase synchronization. It leads to severe problem in symbol detection. The carrier recovery system, illustrated in Fig. 2.5 [18], must make several estimates per burst so that the
variations of the carrier phase over the burst can be tracked. This process is called carrier tracking. The estimates are extracted from the random data part of the burst in carrier tracking.

A commonly used realization of limiting the transmission bandwidth filter is the root raised cosine (RRC) filter, as shown in Fig. 2.5. Usually a Raised Cosine (RC) filter is split equally into a root raised cosine (RRC) filter pair, with one in the transmitter, performing the pulse shaping to constrain the modulated signal bandwidth, and the other in the receiver, performing matched detection for optimizing the SNR of a known signal in the presence of AWGN. Thus, RRC filter at the transmitter and the receiver will result in the product of these transfer functions resulting in a raised cosine (RC), which in turn will give rise to an output having zero Inter-Symbol Interference (ISI). In the digital receiver, the incoming noise corrupted may be subject to a frequency offset \( f \) and a phase offset \( \phi \). The estimation of these offsets in acquisition is based on the matched filter samples, which are obtained by oversampling of the received preamble sequence (CCR) at sampling rate of \( 1/T_s \), a rate higher than the symbol rate \( k \) is the sampling index in Fig. 2.5). Oversampling has two advantages:

- Symbol timing is not necessary to be recovered first;
- It reduces the number of preamble symbols needed and accelerates the speed of the acquisition, which is the most important issue in burst-mode communications.

After the received signal is adjusted according to the estimates \( \hat{f} \) and \( \hat{\phi} \) made from the CCR, the sampling rate is converted down to the symbol rate \( 1/T \) before the steady-state tracking starts. The symbol timing will be perfectly synchronized during data portion; so
that taking samples at the instants of maximum eye opening gives one sample per symbol
\((n)\) is the symbol index in Fig. 2.5). The phase estimation during the user data portion
keeps reducing the fluctuation of the synchronization parameters and be ready for data
detection.

### 2.4.2 Unique Word

As mentioned earlier, the unique word or UW serves to mark each frame. Hence,
it is essential that UW be a special combination of ones and zeros, capable of providing
timing of traffic burst and information data. For example, INTELSAT defines three 24
QPSK symbols (48 bit) unique words, which can be used in its reference bursts, called
UW0, UW1 and UW2 [16], which are as follows:

- **UW0:**
  - P 0111 1000 1001 0111 1000 1001
  - Q 0111 1000 1001 0111 1000 1001

- **UW1:**
  - P 0111 1000 1001 1000 0111 0110
  - Q 0111 1000 1001 0111 1000 1001

- **UW2:**
  - P 0111 1000 1001 0111 1000 1001
  - Q 0111 1000 1001 0111 1000 1001

Intelsat uses a fourth UW, called UW3, only in the traffic bursts, given as:

- **UW3:**
  - P 0111 1000 1001 1000 0111 0110
  - Q 0111 1000 1001 1000 0111 0110

A typical UW detector is shown in Fig. 2.6, which consists of a digital correlator, and a
threshold detector. At the receiving end of a link, incoming bits are clocked in to a shift
register, and the correlator calculates the Hamming distance between the received vector
(r) and the stored version of expected UW (s). In this case, perfect bit synchronization is assumed, and after demodulation and decision, the received vector is a sequence of ones and zeros. In case the Hamming distance \(d(r, s)\) is less than or equal to a pre-specified threshold \(T\), a UW hit is declared by generating a pulse that triggers data detection. Otherwise, a miss is declared [11].

![Fig. 2.6 A typical UW Detector](image)

According to the detection process described above, there are two types of error events that may occur during the process of unique-word detection. The first one is false alarm, and the other is detection failure. False alarm is the event that the Hamming distance \(d(r, s)\) is less than or equal to the threshold \(T\) even before the actual unique word sequence in the received vector actually resides in the shift register. On the other
hand, detection failure is the event that the Hamming distance is larger than the threshold $T$, when the actual UW does reside in the shift register. In an $N$-bit sequence, there may be $I$ errors and $N - I$ correct bits and the sequence will be acceptable as long as $I \leq T$. For a bit error probability $p$, the probability that an $N$-bit UW will be received correctly is given by [16]

$$P = \sum_{I=0}^{T} \binom{N}{I} p^I (1 - p)^{N-I}$$  \hspace{1cm} (2.1)

where $\binom{N}{I}$ is the binomial coefficient. The probability of a miss $Q$ is given by

$$Q = 1 - P$$  \hspace{1cm} (2.2)

A false alarm will occur when a sequence of $N$ received bits matches the expected UW to within $I$ positions, $I \leq T$. If the incoming bit stream is random, then probability that $N$ successive bits will match the UW is $2^{-N}$. The total number of combinations with $I$ errors is $\sum_{I=0}^{T} \binom{N}{I}$ and hence the probability of false alarm is [16]

$$F = 2^{-N} \sum_{I=0}^{T} \binom{N}{I}$$  \hspace{1cm} (2.3)

During the whole receiving process, the process of detection of unique word is required only for certain period of time. The detection process need not be carried out for the entire duration of frame, for example during carrier and clock recovery. It is obvious that
if unique word detector is fed with the entire frame sequence, the rate of false alarm increases [11]. To that end, in order to reduce the probability of false alarm, a detection window is employed to mask unlikely UW hits to reduce the probability of false alarm. The window timing period is started by the unique word detection pulse and one TDMA frame later an aperture window is formed at the expected occurrence of the unique word detection pulse.

![Fig. 2.7 Positioning of Aperture Window](image)

Fig. 2.7 illustrates the positioning of aperture window relative to the detection pulse resulting from correlation of the carrier and clock recovery sequence that precedes the unique word and the unique word itself, with the stored unique word pattern as they are shifted sequentially into the shift register. The aperture window allows detection of the unique word within the specified time interval. Theoretically, the size of the detection
window has to be only one bit long, i.e., covering the interval when the unique word portion of the received preamble resides in the shift register. In practice, however, the length of the aperture window must be sufficient to compensate for drift of the unique word from its expected position as a result of timing uncertainty in the TDMA system.

In general, it is desirable to choose a sequence with good autocorrelation properties as the UW. In other words, the best choice for a UW would be a sequence that has very minimal side lobes. Since PN sequence has good correlation properties, we use PN sequence as UW. In addition, we also consider a Neuman-Hofman (NH) sequence and three Barker sequences for analyzing the effect of length and format of the UW. The PN sequence required for designing the UW is randomly generated during every simulation. On the other hand, the Barker sequences and the Neuman-Hofman sequence, as listed in Table 2.1, are hard coded in the program.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Polar Binary Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barker 7</td>
<td>[-1, -1, -1, 1, 1, -1, 1]</td>
</tr>
<tr>
<td>Barker 11</td>
<td>[-1, -1, -1, 1, 1, -1, 1, 1, -1, 1, -1, 1]</td>
</tr>
<tr>
<td>Barker 13</td>
<td>[-1, -1, -1, -1, 1, 1, -1, 1, -1, 1, -1, 1, -1]</td>
</tr>
<tr>
<td>NH</td>
<td>[1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1]</td>
</tr>
</tbody>
</table>
Chapter 3

Frame Acquisition and Synchronization

TDMA requires a procedure to make sure that the timings of burst transmission are precise, in order to avoid burst overlapping in the satellite. In other words, it is necessary that the satellite (or any receiver for that matter) should be able to demarcate the bursts from different earth stations. Standard frame synchronization methods involve the insertion of a symbol pattern at the beginning of each burst. Receiver identifies the burst boundaries by detecting these synchronization patterns. The process of establishing time synchronization of the bursts is carried out in two stages:

- Initial Acquisition
- Steady State Synchronization.

Acquisition refers to the process of entry of a TDMA burst into its assigned location in the TDMA frame, and synchronization refers to precise maintenance of a burst in its assigned location.

This chapter discusses different synchronization techniques and provides an analysis of the algorithm used in this research in addition to deriving the metric for evaluating performance of the algorithm.
3.1 Acquisition and Synchronization Methods

The methods for establishing acquisition and synchronization are characterized as follows:

- Closed-loop Acquisition and Synchronization
- Open-loop Acquisition and Synchronization
- Co-operative feedback control

The decision on the method to be implemented in a TDMA system is based on the characteristic features defining the TDMA network being set up. This research focuses on the closed loop approach for acquisition and synchronization, based on the assumption that the earth stations in the network are capable of detecting their own bursts being retransmitted from the satellite.

3.1.1 Closed-loop Acquisition and Synchronization [1]

The loop back control was introduced in the TDMA system designed for use in global and regional beams. This approach relies on the ability of any earth station to see reference and “own” burst retransmission from the satellite, thus enabling the station to adjust its “own” burst timing to occupy the assigned slot in the TDMA frame. This approach cannot be applied for multi-beam systems as they do not allow direct satellite loop-back. To establish a time reference, one station’s burst may be designated as the network reference and all transmissions are timed relative to it. This reference station may be taken over by another station for reliability reasons.
The closed-loop acquisition and synchronization method is illustrated in Fig. 3.1. In *acquisition* phase, the earth station first synchronizes its receiver side to the reference burst *R*, thus establishing a local timing reference. It next transmits an acquisition burst *A* at a time $\Delta_N$ after the instant of reception of each reference burst. The time $\Delta_N$ is a coarse estimate obtained by methods explained later in this chapter. This burst *A* arrives at the satellite in a position, as shown in Fig. 3.1, displaced by an amount $\varepsilon$ from the desired target location (at a time $B_N$ after the receipt of *R*) in the frame (burst position error). The earth station does not see this error until the retransmitted burst returns to the station at a time equal to twice the one way propagation time to satellite. The station is then able to observe the error and adjust its delay value. This correction may be applied to the next
frame, or one or two frames later to allow for processing time. Application of the corrected delay will cause the burst to reside in its assigned slot.

At this point, the station has completed the acquisition phase and may be considered to now enter the synchronization phase, wherein it simply maintains synchronization by continued loopback error observation and correction cycles. It will also stop transmitting acquisition burst and commence transmission of its traffic burst. The acquisition burst consists of only the preamble and therefore is a short burst. This minimizes the chances of collision with traffic bursts from other earth stations.

3.1.2 Open-loop Acquisition and Synchronization [1]

Open loop control refers to control of traffic burst position based on the value of propagation time, which is equivalent to the distance between the satellite and earth station. It requires accurate knowledge of the satellite position and the earth scale locations. Open loop control of traffic burst position at an earth station requires the introduction of time delay between reception instant of the TDMA reference burst and the transmission instant of the stations own burst. The value of delay \( D_N \) introduced is selected so that the time elapsed between departure of the burst from the satellite and the return of a response to the satellite from an earth station is an integer number of TDMA frame periods. The instant of arrival of the reference burst at a station is called the “start of receive frame” (SORF). Elapse of the delay, \( D_N \), from the SORF marks the instant of the “start of transmit frame” (SOTF). Consequently, traffic bursts adjusted to assigned positions relative to the SOTF at the earth station fall at their assigned positions in the TDMA frame at the satellite.
Fig. 3.2 Determination of synchronization delay for Open-loop control

Assuming a multiframe of duration $T_M$, an integer $M$ is selected such that $MT_M$ is greater that the propagation time for the farthest station from the satellite, as shown in Fig. 3.2. Thus, for a station $N$ located nearer (distance $d_N$) to the satellite, a delay $D_N$, is calculated as:

$$D_N = MT_M - \frac{2d_N}{c}$$

This delay must be introduced to mark the SOTF instant and thereby achieve proper frame synchronization at the satellite. To position a traffic burst at its assigned location in the frame, its delay with relative to SOTF must be added to $D_N$. 

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3.1.3 Co-operative Feedback Control [1]

The cooperative feedback approach for acquisition and synchronization provides considerably precise position control, particularly needed for multibeam systems. This is suitable for systems where traffic stations cannot see their own bursts. It uses open-loop computation for initializing the value of delay $D_N$ for acquisition. On the other hand, for synchronization, it observes the burst position error and feeds back the corrections.

3.2 Initial Acquisition

Initial acquisition is the phase when in which the detector has to determine the start of the TDMA frame and locate the slot assigned for the station, an exercise necessarily undergone at terminal power-on or after a lengthy station outage [10]. Acquisition is the most critical phase because it has to be performed in the presence of unknown carrier parameters and large uncertainty regions (up to the whole frame length at terminal startup). Markovian models are used to represent the acquisition algorithm utilized in this research. These models readily quantify key performance variables like acquisition time statistics, probability of false acquisition, etc.

To start with the acquisition process, station $N$ transmits a short acquisition burst (AB) at an estimated time $\Delta_N$ relative to the receive frame timing established by the RB. Any error $\epsilon$ introduced by the estimate $\Delta_N$ would cause the short burst to arrive at satellite, at a position as shown in Fig. 3.1, which is displaced by an amount $\epsilon$ from the desired target location in the frame. The earth station does not see this error until the retransmitted burst returns to the station. The station will then be able to observe the error
and appropriately adjust its delay value from $\Delta_N$ to $\Delta_N - \varepsilon$. Application of the corrected delay value will bring the burst to its destined position in the TDMA frame at the satellite. This correction may be applied to the next frame, or one or two frames later to allow for processing time. The AB being retransmitted by satellite can be identified by the earth station by detecting the unique word. Hence, the most critical step involved in the process of acquisition is detection of UW. Fig. 3.3 presents a flowchart for a three-mode acquisition strategy that is used in this research. In the Scan mode, the UW detector examines the received signal, corresponding to the entire frame, for the desired UW. During the scan mode, the aperture size for UW detection is set to the entire frame size. Provided the UW is not missed, a first detection will occur within an interval of time equal to the frame period $T_F$ seconds. To ensure that the detection was not a false event, the detector enters a Verify mode, wherein an aperture window of duration $A_W$ is setup around expected location of the AB. The detection window is employed to mask a portion of the CCR sequence to reduce the probability of false alarm during UW detection process. The detection window opening has to be long enough to accommodate the time variations in the appearance of unique word due to propagation delay. Once the detector enters verify mode, it resets a counter to count the number of UW hits. When the detector detects UW in say $(L - 1)$ continuous apertures, the acquisition stage is assumed to be completed and the detector enters the Lock-Up stage. Failure to detect UW anytime during the verify mode resets the counter and returns the detector to scan mode.

Thus, it is evident that the design parameters that influence the performance of the acquisition process are:

- Length and format of UW
- Size of Aperture Window
- UW detector design
- Verification count (L)

Fig. 3.3 Three modes of Initial Acquisition Procedure
3.2.1 Markovian Acquisition Model

The acquisition model described in this section defines a number of possible detection events within a frame. The likelihood of these events is mapped on to transition probabilities in the Markov model. Each state in the Markov chain is defined by the state of the detector. This in turn is specified by:

- Detector’s aperture size
- Contents of detect counter
- Whether first detection was true or false

The last characteristic feature enables us to distinguish whether the acquisition has been locked-up on correct UW detection or just any detection which may be correct or incorrect. The transition probabilities are characterized in terms of the following [10]:

- \( P_{FDO} \): probability of false detection occurring in random data while the detector examines the entire frame.
- \( P_{ND} \): probability of no detection, false or otherwise, within a period of one frame length
- \( P_{FDW} \): probability of false detection occurring within the aperture window \( A_W \)
- \( P_{NDW} \): probability of no detection, false or otherwise, within the aperture window \( A_W \).

Fig. 3.4 (a) and (b) illustrate the Markovian model and the transition matrix respectively, representing the acquisition procedure outlined in the flow chart of Fig. 3.3. The detect count value \( L = 2 \) for the acquisition procedure represented by the model. In this particular case, the Markov model state assignments are such that acquisition is declared only for \( L \) continuous detections of the true UW [10].
While the model in Fig. 3.4 completes acquisition only for the detection of correct UW, some scenarios may not require such strict conditions for locking-up acquisition. For such cases, the acquisition can be declared as completed for \( L \) continuous detections.
of UW, which may be true or otherwise. Fig. 3.5 (a) and (b) illustrate the Markov model and transition matrix respectively for such a system.

\[ P = \begin{bmatrix}
  P_{ND} & P_{FDO} & (1-P_{ND}-P_{FDO}) & 0 \\
  P_{ND} (1-P_{FDW}) & P_{FDO} (1-P_{FDW}) & (1-P_{ND}-P_{FDO})(1-P_{FDW}) & P_{FDW} \\
  P_{NDW} & 0 & 0 & 0 \\
  0 & 0 & 0 & P_{FDW} + (1-P_{NDW} - P_{FDW}) \\
\end{bmatrix} \]

Fig. 3.5 (a) Markov Model for correct/false acquisition, (b) Transition Matrix [10]
State 1 in the model represents the detector in its initial scan mode, wherein it scans the entire frame duration for UW (aperture wide open). While scanning the received signal, once the detector exceeds the preset threshold $\xi$, it transits to next state depending on whether the detection was correct one or a false alarm. States 2 and 3 are the intermediate states representing various stages of the detector in verify mode, depending on the value of detect counter and whether the previous detection was a false one. While the former represents the state of the detector due to false detection, the latter represents the detector state following a correct detection of UW. While the detector is in one of the intermediate states (2 or 3), it inserts an aperture window ($A_W$) placed around the expected position of UW. The detector enter lock-up mode once it detects $L$ consecutive hits, and the terminal is said to have acquired the assigned slot in the frame.

Suppose $P[p(k, j)]$ is the transition matrix for the Markov chain, $\vec{X}(0)$ is the row vector of the initial state assignment probabilities, and $\vec{X}(\alpha)$ be the state assignment probabilities after $\alpha$ frame transitions, we have

$$\vec{X}(\alpha) = \vec{X}(0)P^\alpha, \alpha = 1, 2, \ldots$$ \hspace{1cm} (3.2)

Assume that $S$ is a set of non-recurrent states in the chain and $Q$ is the matrix

$$Q = [p(i, j) : i, j \in S]$$ \hspace{1cm} (3.3)

In such case, the mean time to acquire (MTTA) is given by the sum of the first row entries in the matrix.
where $I$ is the identity matrix. Applying the equation (3.4) to the models in Fig. 3.4 and Fig. 3.5 will help estimate the mean time for correct acquisition and mean time for nominal acquisition respectively. A closed form solution for MTTA using Markov analysis with $L = 1$ is given by [10]:

$$\text{MTTA} = \frac{P_{FDO} + (1 - P_{FDW})(1 - P_{FDO})}{(1 - P_{FDW})(1 - P_{ND} - P_{FDO})}$$

(3.5)

In models where the detect count is assumed to be greater than 1 ($L > 1$), the solution for MTTA is given by [10]:

$$\text{MTTA} = \frac{P_{FDO} + (1 - P_{FDW})(1 - P_{FDO}) + (1 - P_{FDW})(1 - P_{ND} - P_{FDO}) \left[ \frac{1 - (1 - P_{NDW})^{L-1}}{P_{NDW}} \right]}{(1 - P_{FDW})(1 - P_{ND} - P_{FDO})(1 - P_{NDW})^{L-1}}$$

(3.6)

### 3.2.2 Estimation of $\Delta_N$

Before the closed loop correction acquisition method can be initiated, a means of obtaining a course estimate of the delay $\Delta_N$ must be provided. This is also part of acquisition phase. Several methods are possible to estimate the delay. In one method, a long-duration, low-power burst of unmodulated carrier is used to search for the desired time slot. Since this low power burst is of long duration (typically equal to the entire length of the assigned traffic burst slot in the frame), a narrow-band filter can be used to enhance its detection. The burst is first scanned through the TDMA frame by applying a
stepping sawtooth function to control its transmission time delay $\Delta_N$ relative to the RB. Once the burst is observed to fall in the middle of the assigned traffic slot, the corresponding value of $\Delta_N$ is used to start the burst position loopback correction procedure.

Instead of using an unmodulated carrier, this research utilizes a phase modulated PN sequence spanning the length of a traffic burst, for the estimation of $\Delta_N$. Each station trying to lock itself into the frame epoch transmits a low-power burst (phase modulated PN sequence) to search for the allocated position in the frame. The peak power of the burst is normally maintained at 20 dB below the nominal traffic burst to avoid interference with other traffic bursts in the frame. The low power short burst is swept through the frame by a different value of the transmit burst delay $\Delta_N$ relative to the receive frame timing. The PN sequence has a remarkably sharp autocorrelation characteristic, and by utilizing this property, the receiver establishes frame acquisition by correlating the received signal with a locally generated PN sequence. Once the low-power short burst is observed to fall into the traffic burst’s assigned time slot, the corresponding value of $\Delta_N$ is employed to start the acquisition process. The correlation peak will be utilized by the new station to determine position in the frame where it has to place its burst with respect to the Reference burst.

3.3 Steady State Synchronization

Post initial acquisition, the terminal enters synchronization phase, wherein it has to maintain its position in the frame in a precise manner. Since this research is based on
closed loop synchronization approach, the terminal maintains synchronization by continued loopback error observation and correction cycles. It stops transmitting the acquisition burst $A$ and commences the transmission of full traffic burst $T$ as depicted in Fig. 3.1. The critical steps involved in each terminal in maintaining sync is the detection of UW in their respective bursts that are retransmitted by satellite and the estimation of error $\varepsilon$. Based on the value of $\varepsilon$, the terminal can adjust its transmit time so that the burst maintains its position in the frame while arriving at the satellite. Fig. 3.6 outlines the functionality of a sync detector in a terminal. The terminal opens up a detection window $(A_w)$ around the expected location of UW and scans the received signal. When the TB UW is detected, it estimates the value of error $\varepsilon$, if any, and adjusts it’s transmit time for the next cycle.

Similar to the use of a detect counter during acquisition, the synchronization procedure uses a miss counter to prevent loss of synchronization before $M$ consecutive reference burst UWs are missed. In the case when value of miss counter is less than $M$, the event of missing a reference burst UW initiates a flywheel unit in the terminal which locally injects a UW detection pulse. This injection allows the terminal to avoid loss of data from other received bursts as a result of infrequent reference burst UW misses or reference station switchover [10]. While designing the detector, one has to keep in mind that the time to detect loss of frame sync increases with the value of $M$. By increasing the value of $M$, the time for which terminal will not be receiving correct data also increases, thereby affecting the performance of the terminal. Worst case, it increases the potential for interference with bursts from other terminals due to increasing timing error $\varepsilon$ in the
transmitted bursts. This situation places an upper bound on $M$ that depends on the duration of the guard time between the bursts.

Fig. 3.6 Steady State Synchronization Procedure
3.3.1 Loss of Frame Synchronism

The terminal loses frame synchronization if it does not detect the position of reference burst UW within the aperture window. A terminal unable to detect the start of frame with sufficient precision cannot correctly receive data bursts nor should it attempt to transmit data bursts as they have high chances of interference with bursts from other terminals. The major events that cause the detector to lose sync are as follows:

- The reference burst UW is within the aperture, but is missed for \( M \) consecutive frames or
- UW drifts beyond the bounds of the aperture window.

The former event of \( M \) consecutive no-detections depends on the UW false detection as well as misses detection. If \( P_{NDB} \) represents the probability of no-detection, then the probability of a terminal losing sync due to \( M \) consecutive no-detection is simple \( P_{NDB}^M \).

The aperture window generated for the detection of UW is positioned based on the detect pulse from the previous UW detection and a local oscillator. Hence, the factors contributing to the displacement of UW beyond the window opening are as follows:

- Asynchronism between the local oscillator and the reference terminal generating the RB
- A false detection preceding the true arrival of reference burst UW

3.3.2 Markovian Synchronization model

The Markovian model considered in this research, for the analysis of synchronization procedure does not consider the asynchronism between the local clock
and the reference terminal. The loss of sync is attributed only to \( M \) consecutive UW misses. Fig. 3.7 illustrates the model used to represent the synchronization process.

By neglecting to consider a tracking aperture and the effect or relative timing errors, the model is simplified to formally defining various detection events. In the Markov chain, state \( i + 1 \) is simply defined by current state of the miss counter \( (0 \leq i \leq M) \).
+ 1). State 2 has been extracted from state 1 to distinguish between true and false detections. Since time is represented in terms of number of frames, the mean time to reach state \((M + 2)\) from the initial state 1 defines the expected time to sync loss in frames, and is given by:

\[
MTBSL = \frac{(1 - P_{NDB}^M)}{(1 - P_{FDB})(1 - P_{NDB})P_{NDB}^M}
\]  

(3.7)

The core functionality involved in acquisition and synchronization process is the detection of UW. the following chapter derives an optimum decision rule for detecting the UW, for different kind of bursts.
Chapter 4

Unique Word Detection

Frame synchronization is achieved with the aid of detection of UW, which is embedded in the preamble portion of a burst. This chapter addresses the problem of robust frame synchronization for a TDMA system, which can withstand frequency and phase errors. Unlike the conventional correlator, decision rules based on ML estimation have been proved to be tolerant to frequency and phase errors. This chapter reviews the ML decision rules for RB, TB and the AB. The performance of these rules is compared to that of conventional correlator.

4.1 System Model

An $M$-ary PSK signal continuously transmitted over an AWGN channel is considered. A simple TDMA frame comprising of RB and TBs is considered and the size of the RB and TB are assumed to be same, as shown in Fig. 4.1. The size of the CCR sequence and UW portion of the preamble for RB and TB are assumed to be the same.
On the other hand, the signaling channel will have difference in lengths owing to the functionality of the same in RB.

![Diagram](image)

Fig. 4.1 Structure of bursts (a) RB, (b) TB, (c) AB

We assume that each TB consists of $L_B M$-ary symbols: the first $L_P$ symbols form the preamble, followed by $L_d$ symbols of traffic data, which can be modeled as random sequence. The random data is followed by a guard time composed by $N_g$ symbol periods. Since UW sequence aids in establishing frame sync, our analysis for deriving the optimum decision rule does not focus on the pattern of CCR sequence. In addition, the data contained in signaling channel do not have any preset pattern as in CCR, nor do they have any constraints unlike the UW. Hence, we assume that the data contained in the
signaling channel portion of the preamble is random, similar to the traffic data portion of a TB. Summarizing, the burst structure we have considered for analysis has a preamble sequence, which can be represented as \( \vec{p} = \{p_k | 0 \leq k \leq L_p - 1\} \). Among the \( L_p \) preamble symbols, the last \( L_{UW} \) symbols constitute the UW, which can be represented as \( \vec{s} = \{s_k | 0 \leq k \leq L_{UW} - 1\} \). \( L_d \) symbols of traffic data are represented as \( \vec{d} = \{d_k | 0 \leq k \leq L_d - 1\} \). On the same lines, the guard time can be represented as \( \vec{g} = \{g_k | 0 \leq k \leq N_g - 1\} \). Overall, in the vector form, the entire burst can be represented as \( \vec{a} = [\vec{p} \vec{d} \vec{g}] \). After pulse shaping, the baseband equivalent of the transmitted signal, can be given as [20]:

\[
x(t) = \sum_{l=-\infty}^{\infty} \sum_{k=0}^{l-1} a_k z(t-kT)
\]

where \( z(t) \) is the Root Raised Cosine (RRC) pulse waveform. The baseband equivalent of the received signal is affected by AWGN, an unknown frequency offset \( f_0 \) and phase offset \( \phi_0 \), which might have been introduced due to inaccuracies in carrier estimation. The signal arriving at the receiving end will have the form:

\[
r(t) = e^{j(\omega_0 + \phi_0)} x(t) + G(t) = \sum_{l=-\infty}^{\infty} \sum_{k=0}^{l-1} a_k z(t-kT)e^{j(\omega_0 + \phi_0)} + G(t)
\]
where $G(t)$ is the complex AWGN process with variance $\sigma_G^2 = N_0 / 2$ ($N_0$ is the one-sided noise power spectral density) and $\omega_0 = 2\pi f_0$. To simplify the derivation of criterion, we assume that the symbol timing estimate is devoid of any inaccuracies. Thus, the $n^{th}$ sample of the received signal is given by:

$$r_n = a_n e^{j(\omega_0^0 T + \phi)} + G_n$$

(4.3)

The normalized frequency offset $\omega_0 T$ and phase offset $\phi_0$ are assumed to be uniformly distributed over $[-\pi, \pi]$. This assumption simplifies the analysis and yields a rule simpler to implement. The rule was developed by Z.Y. Chong and Y.H. Lee [9], and is based on an operation termed *double* correlation. Let us denote the frequency and phase offsets by a vector $\chi = [\chi_0, \chi_1, ..., \chi_{L^n-1}]$, with $n^{th}$ element given by, $\chi_n = e^{j(\omega_0^0 T + \phi)}$. Rewriting equation (4.3), we get

$$r_n = a_n \chi_n + G_n$$

(4.4)

Frame synchronization is attained by estimation of boundary positions (of traffic data transmitted by each earth station) in a segment of received signal, corresponding to a frame. In other words, both acquisition and synchronization stages require identification of start of a burst from an earth station, which in turn can be accomplished by detecting the boundary of UW in each burst. If the UW starts at $\mu^{th}$ position of the received burst, $\mu \in [0, L_B - 1]$, an optimum decision rule is required that provides us with an estimated
position \( \hat{\mu} \), of the UW. Some of the most popular rules for estimating \( \hat{\mu} \) are presented in subsequent sections.

### 4.2 Conventional Correlation

At the receiver, after recovering the timing information, sampled input values are correlated with a stored pattern of the UW. This type of synchronization method, generally referred to as correlation, is one of the simplest ways of achieving synchronization. The correlation rule test function is as follows:

\[
L(\mu) = \left\{ \begin{array}{c}
\sum_{k=1}^{L-1} r_{\mu+k} S_k^*
\end{array} \right\}
\]  

(4.5)

The frame synchronization is declared at a position where the test function is maximized. This rule does give an acceptable level of performance when the frequency and phase errors are minimal. Large value of frequency offset deteriorates the performance of this rule.

### 4.3 Maximum Likelihood (ML) Estimator

Frame acquisition/synchronization can also be accomplished using other optimal rules such as ML Estimation. These rules have an edge over traditional correlation rules at the expense of additional computation. The ML rule which is derived in [8, 9] is based on the assumption that the frequency and phase errors are uniformly distributed and their
tolerance to frequency and phase errors has been tested. This thesis utilizes the influence of structure of different types of bursts involved in acquisition and synchronization procedure, in order to derive the decision rule for an ML estimator. As explained in chapter 2 of this thesis, the bursts can be classified into reference burst (RB), traffic burst (TB) and acquisition burst (AB). RB and TB are assumed to be have similar structure comprising of preamble $\vec{p}$, random data $\vec{d}$ and guard period $\vec{g}$. On the other hand, AB consists of preamble $\vec{p}$ only.

### 4.3.1 ML Estimator for TB/RB

If the UW starts at $\mu^{th}$ position of the received burst, then the ML estimate $\hat{\mu}$ is the integer that maximizes conditional probability density $f(r|\mu)$. In addition to defining the start of traffic information, the ML estimate $\hat{\mu}$ helps the station determine the timing error $\epsilon$, which it uses to adjust the transmit time of subsequent bursts. As stated earlier, the received burst comprises of preamble $\vec{p}$, random traffic data $\vec{d}$ and guard period $\vec{g}$. During the receiving process, there are periods of time when the detection of UW is not necessary, for example, during the process of carrier and clock recovery. In practice a detection window is employed to mask a portion of the CCR sequence to reduce the probability of false alarm during UW detection process. The detection window opening has to be long enough to accommodate the time variations in the appearance of unique word due to propagation delay. The window opening can begin from the instant of $W(\leq$
$L_P - L_{UW}$) tail symbols of CCR sequence, covering the remaining burst [11] thereby having a total duration of $A_W$ symbols. Worst case, we assume that $W$ tail end symbols corresponding to CCR could be composed of the UW, due to timing error. On the same lines, the guard period processed by the receiver is assumed to be composed of random data from adjacent burst. If UW starts at $\mu$th position in the window, $\mu \in [0, A_W - 1]$, the probability density $f(r | \mu)$ can be derived by considering $f(r | \mu, d, \omega_0 T, \phi_0)$, the conditional probability density of the received signal $r$ given $\mu$, $d$ and frequency and phase offset.

$$f(r | \mu, d, \omega_0 T, \phi_0) = \frac{1}{(\pi N_0)^{\frac{N}{2}}} \left[ \prod_{i=0}^{L_{UW}-1} \exp[-|r_i - 2^i S_i|^2 / N_0] \right] \times \left[ \prod_{k=L_{UW}}^{d_U-1} \exp[-|r_k - 2^k S_k| / N_0] \right]$$

Equation (4.6) can thus be modified by omitting all terms independent of $\mu$, obtaining

$$f(r | \mu, d, \omega_0 T, \phi_0) = \frac{K}{(\pi N_0)^{\frac{N}{2}}} \left[ \prod_{i=0}^{L_{UW}-1} \exp[2 |r_i^* \chi_i| / N_0] \right] \times \left[ \prod_{k=L_{UW}}^{d_U-1} \exp[2 |r_k^* \chi_k d_k| / N_0] \right]$$

The term

$$\left[ \prod_{i=0}^{L_{UW}-1} \exp[-|r_i|^2 / N_0] \right] \times \left[ \prod_{k=L_{UW}}^{d_U-1} \exp[-|r_k|^2 / N_0] \right] = K$$

is independent of $\mu$ because it corresponds to the total signal energy in each burst.

Equation (4.6) can thus be modified by omitting all terms independent of $\mu$, obtaining
Since $\vec{d}$ denotes the random $M$-ary data of length $L_d$, which are equiprobable, the dependence of the conditional probability on $\vec{d}$ can be expressed as the weighted sum over all possible data sequences by total probability theorem. Thus, equation (4.7) can be rewritten as:

$$f(\vec{r} | \mu, \omega, T, \phi_0) = \frac{K}{(\pi N_0)^{\frac{d}{4}}} \left[ \prod_{i=0}^{L_d-1} \exp[2 | r_i^* \chi_i s_i | / N_0] \right] \times$$

$$\frac{1}{M^{L_d}} \sum_{\text{all } d} \left[ \prod_{k=L_{cr}}^{A_d-1} \exp[2 | r_k^* \chi_k d_k | / N_0] \right]$$

(4.8)

In order to solve the phase uncertainty $\phi_0$, implicitly incorporated in the term $\chi_n = e^{j(\alpha \omega T + \phi_0)}$, we take the expectation of the above function over $[-\pi, \pi]$. The averaged likelihood function is calculated as:

$$f(\vec{r} | \mu, \omega, T) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(\vec{r} | \mu, \phi_0, \omega, T) d\phi_0$$

$$= \frac{K}{2\pi M^{L_d} (\pi N_0)^{\frac{d}{4}}} \sum_{\text{all } d} \left[ \prod_{i=0}^{L_d-1} \exp[2 | r_i^* \chi_i s_i | / N_0] \right] \times$$

$$\left[ \prod_{k=L_{cr}}^{A_d-1} \exp[2 | r_k^* \chi_k d_k | / N_0] \right] d\phi_0$$

(4.9)
In order to simplify the expression, the integral can be approximated using a modified zeroth-order Bessel function given as:

\[ I_0(x) = \frac{1}{2\pi} \int_{-\pi}^{\pi} e^{x \cos \theta} d\theta \]  

(4.10)

Rewriting equation (4.9) in terms of Bessel function and dropping a few terms that are independent of \( \mu \), we get

\[
f(r \mid \mu, \omega_0 T) = \frac{K}{2\pi M^{1/2} (\pi N_0)^{1/2}} \sum_{a \neq 0} \int_{-\pi}^{\pi} \left[ \frac{2}{N_0} \sum_{i=0}^{L-1} r_i^* e^{j\alpha_0 T} s_i + \sum_{k=0}^{L-1} r_k^* e^{j\alpha_k T} d_i \right] \times \frac{1}{2\pi} d(\omega_0 T) \]

(4.11)

Proceeding with handling the frequency offset on the same lines as phase offset, the expectation of equation (4.11) with respect to \( \omega_0 T \) gives the following:

\[
f(r \mid \mu) = \frac{K}{2\pi M^{1/2} (\pi N_0)^{1/2}} \sum_{a \neq 0} \int_{-\pi}^{\pi} \left[ \frac{2}{N_0} \sum_{i=0}^{L-1} r_i^* e^{j\alpha_0 T} s_i + \sum_{k=0}^{L-1} r_k^* e^{j\alpha_k T} d_i \right] \times \frac{1}{2\pi} d(\omega_0 T) \]

(4.12)

Since the symbols \( s_i \) and \( d_i \) belong to a constellation having cardinality \( M \), we can represent these symbols in terms of \( e^{j\theta} \). In order to simplify the evaluation of the above integration, we rewrite the equation (4.12) as:

\[
f(r \mid \mu) = \frac{K}{2\pi M^{1/2} (\pi N_0)^{1/2}} \sum_{a \neq 0} \int_{-\pi}^{\pi} \left[ \frac{2}{N_0} \sum_{i=0}^{L-1} r_i^* e^{j\alpha_0 T} e^{j\theta} \right] \times \frac{1}{2\pi} d(\omega_0 T) \]

(4.13)
The argument of Bessel function in equation (4.13) is complicated and hence to derive a test function with less complexity, \( I_0(x) \) is approximated by \( (1 + x^2/4 + x^4/64) \) for small \( x \). Therefore,

\[
f(r \mid \mu) = \frac{K}{2\pi M L_0(\pi N_0)} \sum_{all} \left\{ \frac{1}{(N_0)} \right\}^2 \times \sum_{p=0}^{A_W-1} \sum_{q=0}^{A_W-1} r_p^* \exp[j(\theta_p + p \omega_0 T)] r_q \exp[-j(\theta_q + q \omega_0 T)] \times \frac{1}{\sqrt{2N_0}} \sum_{k=0}^{A_W-1} \sum_{l=0}^{A_W-1} \sum_{m=0}^{A_W-1} \sum_{n=0}^{A_W-1} r_k^* r_l^* r_m^* r_n \times \exp[j(\theta_k - \theta_l + \theta_m - \theta_n + (k - l + m - n)\omega_0 T)] \right\} \frac{1}{2\pi} d(\omega_0 T) \tag{4.14}
\]

We know that \( \int_{-\pi}^{\pi} e^{j\mu \theta} d\theta = 2\pi \delta(k) \). In other words, the integration exists only for \( k = 0 \).

Hence, from equation (4.14) only the terms corresponding to \( p - q = 0 \) and the terms for which \( (k - n) - (l - m) = 0 \) remain after evaluating the integral. Therefore, the integration in equation (4.14) will have only the terms corresponding to \( p = q \) and \( k - n = l - m \).

Let \( i = k - n = l - m \). Then \( i \in [-A_W + 1, A_W - 1] \), and the test function can be obtained by dropping the terms independent of \( \mu \), as

\[
L(\mu) = \frac{1}{M L_0} \sum_{all} \left\{ \sum_{i=-A_W}^{A_W-1} \sum_{k=-A_W}^{A_W-1} \sum_{l=-A_W}^{A_W-1} \sum_{m=-A_W}^{A_W-1} r_i^* r_k^* r_l^* r_m \exp[j(\theta_i - \theta_k + \theta_l - \theta_m)] \times \sum_{i=-A_W}^{A_W-1} \sum_{k=-A_W}^{A_W-1} \sum_{l=-A_W}^{A_W-1} \sum_{m=-A_W}^{A_W-1} r_i^* r_k^* r_l^* r_m \exp[j(\theta_i - \theta_k + \theta_l - \theta_m)] \right\} \tag{4.15}
\]
A part of the second term in equation (4.15),
\[
\sum_{d \in \mathcal{L}_{UW}} \sum_{i=1}^{A_d-1} \sum_{k=1}^{A_d-1} \sum_{j=i}^{l_k-1} r_k^* r_{l_k-i}^* r_{k-i} \exp[j(\theta_k - \theta_i + \theta_{i-j} - \theta_{k-i})] = 0
\]
because at least one of the possible symbols in the summation term is not a sync pattern but a random symbol representing traffic data, and the sum of such a symbol for all possible \(M\)-ary symbols (all \(d\) ) is equal to zero, i.e. \(\sum_{m=0}^{M-1} e^{j(2\pi m/M)} = 0\). Therefore (4.15) can be rewritten as:
\[
L(\mu) = \frac{1}{M^{L_u}} \sum_{d \in \mathcal{L}_{UW}} \left\{ \sum_{i=1}^{\mu-1} \sum_{k=1}^{\mu-1} \sum_{j=i}^{l_k-1} r_k^* r_{l_k-i}^* r_{k-i} \exp[j(\theta_k - \theta_i + \theta_{i-j} - \theta_{k-i})] \right\}
\]
\[
+ \sum_{i=1}^{A_d-1} \sum_{m=i}^{A_d-1} |r_m|^2 |r_{m-i}|^2.
\] (4.16)

Applying the fact that \(\sum_{m=0}^{M-1} e^{j(2\pi m/M)} = 0\), equation (4.16) can be further reduced to get:
\[
L_0(\mu) = \sum_{i=1}^{\mu-1} \left\{ \sum_{k=1}^{\mu-1} r_{\mu+k}^* s_k r_{\mu+k-i}^* s_{k-i} \right\}^2 - \sum_{k=1}^{\mu-1} |r_k|^2 |r_{k-i}|^2.
\] (4.17)

where \(s_k\) is the UW pattern and the first term in equation (4.17) is the magnitude square of the correlation between \(r_{\mu+k}^* s_k\) and \(r_{\mu+k-i}^* s_{k-i}\). This correlation is referred to as double correlation, with lag \(i\) between the two correlation terms \(r_{\mu+k} s_k\) and \(r_{\mu+k-i} s_{k-i}\). The second term is a random data correction term. However this test function has been proved to be “unbalanced” in the sense that the difference between the double correlation term and the data correction term is non-zero even when perfect sync is achieved [9]. The imbalance is due to the approximation of the Bessel function \(I_0(x)\). The decision based on
this function has a relatively larger probability of false acquisition. In order to improve the accuracy of decision, the test function can be modified or improved by dropping the squares in equation (4.17), to get:

\[
L_1(\mu) = \sum_{i=1}^{L_{cw}^{-1}} \left\{ \sum_{k=i}^{L_{cw}^{-1}} r_{\mu+k}^* S_k r_{\mu+k-i}^* S_{k-i} - \sum_{k=\mu+i}^{\mu+L_{cw}^{-1}} \left| r_k \right| \left| r_{k-i} \right| \right\} \quad (4.18)
\]

For a specific case where lag \(i = 1\), equation (4.18) becomes:

\[
L_2(\mu) = \left\{ \sum_{k=i}^{L_{cw}^{-1}} r_{\mu+k}^* S_k r_{\mu+k-i}^* S_{k-i} - \sum_{k=\mu+i}^{\mu+L_{cw}^{-1}} \left| r_k \right| \left| r_{k-i} \right| \right\} \quad (4.19)
\]

Finally, dropping the correction term, the test function can be simplified as follows:

\[
L_3(\mu) = \left\{ \sum_{k=i}^{L_{cw}^{-1}} r_{\mu+k}^* S_k r_{\mu+k-i}^* S_{k-i} \right\} \quad (4.20)
\]

For each test function, the estimate \(\hat{\mu}\) is declared to be the position at which the value of test function is maximized. The performance of these test functions were analyzed using simulations and the results are discussed in the following chapter.

### 4.3.2 ML Estimator for AB

In case of acquisition burst, the received signal comprises of preamble only. We assume that data received post preamble is statistically independent zero-mean
Gaussian random variables with unity variance. We consider a window opening for UW
detection, similar to that assumed for TB/RB. If UW starts at $\mu$th position in the window,
$\mu \in [0, A_W - 1]$, the probability density $f(r|\mu)$ can be derived by
considering $f(r|\mu, d, \omega T, \phi)$, the conditional probability density of the received signal
$r$ given $\mu$, $d$ and frequency and phase offset.

$$f(r|\mu, d, \omega T, \phi) = \frac{1}{(\pi N_0)^{4r}} \left[ \prod_{i=0}^{L-1} \exp\left(-|r_i - \chi_s|_r^2 / N_0\right) \right] \times$$

$$\times \left[ \prod_{k=i}^{A_W} \exp\left(-|r_k - \chi d_k|_r^2 / N_0\right) \right]$$  \quad \text{(4.21)}$$

The term
$$\prod_{i=0}^{L-1} \exp\left(-|r_i|_r^2 / N_0\right) \times \prod_{k=i}^{A_W} \exp\left(-|r_k|_r^2 / N_0\right) = \prod_{i=0}^{A_W} \exp\left(-|r_i|_r^2 / N_0\right)$$
is independent of $\mu$ because it corresponds to the total signal energy in each burst.

Equation (4.21) can therefore be modified by omitting all terms independent of $\mu$. The
equation can be rewritten as:

$$f(r|\mu, d, \omega T, \phi) = \frac{K}{(\pi N_0)^{4r}} \left[ \prod_{i=0}^{L-1} \exp\left(2|r_i^* \chi_s| / N_0\right) \right] \times$$

$$\times \left[ \prod_{k=i}^{A_W} \exp\left(2|r_k^* \chi d| / N_0\right) \right]$$  \quad \text{(4.22)}$$
Since $\vec{d}$ denotes the Gaussian data of mean 0 and variance 1, the dependence of the conditional probability on $\vec{d}$ can be expressed in the form of an integral as:

$$f(r | \mu, \omega_0 T, \phi_0) = \frac{K}{(\pi N_0)^{\frac{d}{2}}} \left[ \prod_{j=0}^{L-1} \exp[2 | r_j^* \chi_j s_j | / N_0] \right] \times \prod_{k=L-w}^{d-1} \int_{-\infty}^{\infty} \exp[2 | r_k^* \chi_k d_k | / N_0] \exp[-d_k^2 / 2]d(d_k)$$

(4.23)

On performing the indicated integrations and dropping the terms independent of $\mu$, the equation reduces to:

$$f(r | \mu, \omega_0 T, \phi_0) = \frac{K}{(\pi N_0)^{\frac{d}{2}}} \left[ \prod_{j=0}^{L-1} \exp[2 | r_j^* \chi_j s_j | / N_0] \right] \prod_{k=L-w}^{d-1} \exp[2 | r_k^* |^2]$$

(4.24)

In order to solve the phase uncertainty $\phi_0$, implicitly incorporated in the term $\chi_a = e^{j(\omega_0 T + \phi_0)}$, we take the expectation of the above function over $[-\pi, \pi]$ with respect to the phase offset $\phi_0$. The averaged likelihood function is calculated as:

$$f(r | \mu, \omega_0 T) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(r | \mu, \omega_0 T, \phi_0) d\phi_0$$

$$= \frac{K}{2\pi (\pi N_0)^{\frac{d}{2}}} \left[ \prod_{j=0}^{L-1} \exp[2 | r_j^* \chi_j s_j | / N_0] \right] \prod_{k=L-w}^{d-1} \exp[2 | r_k^* |^2] d\phi_0$$

(4.25)
In order to simplify the expression, the integral can be approximated using a modified zeroth-order Bessel function given as:

$$I_0(x) = \frac{1}{2\pi} \int_{-\pi}^{\pi} e^{i\cos\theta} d\theta$$  \hspace{1cm} (4.26)

Rewriting equation (4.25) in terms of Bessel function and dropping a few terms that are independent of $\mu$, we get:

$$f(r \mid \mu, \omega_0 T) = \frac{K}{2\pi(\pi N_0)^{d_0}} I_0 \left( \frac{2}{N_0} \sum_{i=0}^{k-1} r_i^* e^{i\omega_0 T} \right) \times \prod_{k=L_w}^{d_w} \exp[2 | r_k |^2]$$ \hspace{1cm} (4.27)

The last step is the elimination of frequency offset which affects the decision function in equation (4.27). On the same lines as phase offset, the expectation of equation (4.27) with respect to $\omega_0 T$ will help eliminate the frequency uncertainty, giving an expression as follows:

$$f(r \mid \mu) = \frac{K}{2\pi(\pi N_0)^{d_0}} \int_{-\pi}^{\pi} I_0 \left( \frac{2}{N_0} \sum_{i=0}^{k-1} r_i^* e^{i\omega_0 T} \right) \times \frac{1}{2\pi} d(\omega_0 T) \times \prod_{k=L_w}^{d_w} \exp[2 | r_k |^2]$$ \hspace{1cm} (4.28)

The argument of Bessel function in equation (4.28) is complicated and hence to derive a test function with less complexity, $I_0(x)$ is approximated by $(1 + x^2/4 + x^4/64)$ for small $x$. Therefore, applying the zero order Bessel function approximation, the integration in equation (4.28) will evaluate as:
\[
\int_{-\pi}^{\pi} I_0 \left( \frac{2}{N_0} \sum_{j=0}^{L_{WU}-1} r_j^* e^{i\omega_0 T} s_j \right) \times \frac{1}{2\pi} d(\omega_0 T) = \int_{-\pi}^{\pi} \left( 1 + \left( \frac{1}{N_0} \right)^2 \right) \times \sum_{p=0}^{L_{WU}-1} \sum_{q=0}^{L_{WU}-1} (r_p^* e^{i\omega_0 T} s_p) (r_q e^{-i\omega_0 T} s_q^*) \\
+ \left( \frac{1}{\sqrt{2N_0}} \right)^4 \sum_{k=0}^{L_{WU}-1} \sum_{l=0}^{L_{WU}-1} \sum_{m=0}^{L_{WU}-1} \sum_{n=0}^{L_{WU}-1} r_k^* r_l^* r_m^* r_n^* \\
\times s_k s_l^* s_m^* s_n^* e^{i(k-l+m-n)\omega_0 T} \left( \frac{1}{2\pi} d(\omega_0 T) \right) (4.29)
\]

We know that \(\int_{-\pi}^{\pi} e^{i\theta} d\theta = 2\pi \delta(k)\). In other words, the integration exists only for \(k = 0\).

Hence, performing the integration in equation (4.29) will retain the terms corresponding to \(p - q = 0\) and the terms for which \((k - n) - (l - m) = 0\). In other words, the integration in equation (4.29) will have only the terms corresponding to \(p = q\) and \(k - n = l - m\).

Let \(i = k - n = l - m\). Then \(i \in [-L_{WU} + 1, L_{WU} - 1]\), and the test function can be obtained by dropping the terms independent of \(\mu\), as

\[
\int_{-\pi}^{\pi} I_0 \left( \frac{2}{N_0} \sum_{j=0}^{L_{WU}-1} r_j^* e^{i\omega_0 T} s_j \right) \times \frac{1}{2\pi} d(\omega_0 T) = \left\{ \sum_{i=0}^{L_{WU}-1} \sum_{k=0}^{L_{WU}-1} \sum_{l=0}^{L_{WU}-1} \sum_{m=0}^{L_{WU}-1} r_k^* r_l^* r_m^* s_k s_l^* s_m^* s_i \right\} (4.30)
\]

Therefore (4.28) can be rewritten as:

\[
f(r | \mu) = \left\{ \sum_{i=0}^{L_{WU}-1} \sum_{k=0}^{L_{WU}-1} \sum_{l=0}^{L_{WU}-1} r_k^* r_l^* s_k s_l^* s_i \right\} \times \prod_{k=L_{WU}}^{A_q-1} \exp[- \frac{1}{2} r_k^2] (4.31)
\]
Equation (4.31) can be further reduced to get:

\[
f(r | \mu) = \sum_{j=1}^{L_{uw}-1} \left\{ \left| \sum_{k=1}^{L_{uw}-1} r_{\mu+k}^* s_k r_{\mu+k-i}^* s_{k-i} \right|^2 \right\} \times \prod_{k=L_{uw}}^{A_{uw}-1} \exp\left[ 2 | r_k |^2 \right] \tag{4.32}
\]

Taking natural logarithms on both sides, we get a decision rule as:

\[
L(\mu) = \ln \left( \sum_{i=1}^{L_{uw}-1} \left\{ \left| \sum_{k=1}^{L_{uw}-1} r_{\mu+k}^* s_k r_{\mu+k-i}^* s_{k-i} \right|^2 \right\} \right) + \ln \left( \prod_{k=L_{uw}}^{A_{uw}-1} \exp\left[ 2 | r_k |^2 \right] \right)
\]

\[
= \ln \left( \sum_{i=1}^{L_{uw}-1} \left\{ \left| \sum_{k=1}^{L_{uw}-1} r_{\mu+k}^* s_k r_{\mu+k-i}^* s_{k-i} \right|^2 \right\} \right) + 2 \sum_{k=L_{uw}}^{A_{uw}-1} | r_k |^2 \tag{4.33}
\]

where \( s_k \) is the UW pattern and the first term in equation (4.17) is the magnitude square of the correlation between \( r_{\mu+k}^* s_k \) and \( r_{\mu+k-i}^* s_{k-i} \). This correlation is referred to as double correlation, with lag \( i \) between the two correlation terms \( r_{\mu+k}^* s_k \) and \( r_{\mu+k-i}^* s_{k-i} \). The second term is a correction term contributed by Gaussian data. The square in the first term of equation (4.33) is due to the Bessel function approximation. The test function can be modified or improved by dropping the square in the first part of equation (4.33), to get:

\[
L_2(\mu) = \ln \left( \sum_{i=1}^{L_{uw}-1} \left\{ \left| \sum_{k=1}^{L_{uw}-1} r_{\mu+k}^* s_k r_{\mu+k-i}^* s_{k-i} \right| \right\} \right) + 2 \sum_{k=L_{uw}}^{A_{uw}-1} | r_k |^2 \tag{4.34}
\]
For each test function, the estimate $\hat{\mu}$ is declared to be the position at which the value of test function is maximized. The performance of these test functions were analyzed using simulations and the results are discussed in the following chapter.
Chapter 5

Simulation and Results

This chapter discusses the simulation setup and the results obtained for frame synchronization in a TDMA satellite communication system. The decision rules described in chapter four are tested for different frequency and phase offsets and the results for the same are presented in this chapter. The effect of length and format of UW is also tested for these test functions. The objective of attaining frame acquisition and synchronization is fulfilled using the algorithms outlined in chapter three. The algorithm is tested for various test functions described in chapter four, for UW detection.

5.1 Simulation Setup

In order to investigate the frame synchronization techniques in TDMA satellite communication systems, we have considered a model illustrated in Fig. 5.1 for simulation in MATLAB. The system is based on QPSK modulation scheme.
Symbols generated from the source $a_k$ are fed to a pulse shaping filter, which in turn is a RRC filter with transfer function $z(t)$. After pulse shaping, the transmitted signal will have a form as follows:

$$x(t) = \sum_{l=-\infty}^{\infty} \sum_{k \in I_a} a_l z(t - kT)$$  \hspace{1cm} (5.1)$$

Before arriving at the receiver, the signal gets corrupted by AWGN, frequency error and phase error. The received signal can be expressed as:

$$r(t) = e^{i(\omega_0 t + \phi_0)} x(t) + G(t)$$

$$= \sum_{l=-\infty}^{\infty} \sum_{k \in I_a} a_l z(t - kT)e^{i(\omega_0 t + \phi_0)} + G(t)$$  \hspace{1cm} (5.2)$$

where $G(t)$ represents zero mean AWGN having variance $\sigma_G^2 = N_0 / 2$ ($N_0$ is the one-sided noise power spectral density). $\omega_0 = 2\pi f_0$ is a random frequency offset and $\phi_0$, a random
phase offset. TDMA frames are assumed comprising of bursts having structure as depicted in Fig. 5.2.

UW sequences are 7-bit Barker sequence, 11-bit Barker sequence, 13-bit Barker sequence, 13-bit Neuman-Hofman code and 10-bit pseudo-random noise (PN) sequence, which have good autocorrelation properties. The PN code is simulated in MATLAB for each run, while the other UW sequences are hard coded. Barker code of 7 bits is assumed to be \([-1, -1, -1, 1, 1, -1, 1]\). The same with 11 bits is \([-1, -1, -1, 1, 1, -1, 1, 1, -1, 1]\) and the Barker code of length 13 is \([-1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1]\). The Neuman-Hofman code is also hard coded and the length is assumed to be 13. the sequence being \([1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1]\)

In order to analyze the performance of each test function, 10,000 bursts are run to test the statistical performance. Two levels of testing are performed for UW detection. First, the UW pattern is fixed as PN sequence and the impact of frequency offset is
analyzed for each decision rule, keeping the SNR fixed. In the next level, the performance of each decision rule is studied for changing SNR values. Finally, the best decision rule is tested for different formats of UW sequence, to analyze the impact of UW format and length. The results are presented in following sections.

5.2 Results

This section discusses the results of testing the decision rules discussed in chapter four. The performance is tested on the basis of probability of false acquisition for each decision rule, which plays a key role in correct acquisition of UW.

5.2.1 Effect of Normalized Frequency Offset ($\omega_0 T$)

In the first experiment, the normalized frequency offset ($f_0 T$) is varied from 0 to 0.2, phase offset is a random variable having uniform distribution over $[-\pi, \pi]$ and the value of $E_b/N_0$ is maintained at 6 dB. The UW considered in this experiment is a PN sequence having a length of 10 QPSK symbols. As can be seen, even though the performance of conventional correlator was better than ML decision rules at very low frequency offsets, it worsened with increase in frequency offset, a reason why the technique is not recommended in applications involving large frequency offsets. On the other hand, the ML test functions were tolerant of the frequency offsets.
The performance of $L_1$ and $L_2$ were better when compared to that of $L_0$, proving the statement that $L_0$ is unbalanced. Among $L_1$ and $L_2$, the former has an edge over the latter. Rule $L_3$ was the worst among MLE functions. This can be owed to the fact, though decision rule was developed considering the random data segment following the UW, $L_3$ does not have the correction term contributed by the random data.

### 5.2.2 Effect of Signal to Noise Ratio ($E_b/N_0$)

In this experiment, the effect of SNR on the performance of each decision rule is tested for different ranges of frequency offset. Phase offset is considered to be
uniformly distributed over \([-\pi, \pi]\). The effect of SNR is tested for three different ranges of normalized frequency offset:

- \(f_oT = [-0.1, 0.1]\)
- \(f_oT = [-0.01, 0.01]\)
- \(f_oT = [-0.04, 0.04]\)

Fig. 5.4 depicts the variation of probability of false acquisition with varying SNR. From Fig. 5.4 (b) and (c) it is evident that the performance of conventional correlation detector worsens with increasing frequency offset. At higher frequency offsets, it is \(L_1\) that outscores other ML decision rules.
Fig. 5.4 Prob. of False Acquisition vs $E_b/N_0$ for PN sequence (a) $f_oT = [-0.1,0.1]$, (b) $f_oT = [-0.01,0.01]$, (c) $f_oT = [-0.04,0.04]$
5.2.3 Effect of UW format

This section presents the results of testing the decision rules for different formats of UW and their effect on the probability of false acquisition. Fig. 5.5 gives the simulation results for the performance of different decision rules when different UW formats are chosen. Fig. 5.6 shows the effect of UW pattern of the performance of $L_1$ test function. The simulation was done for a frequency offset uniformly distributed over [-0.1,0.1] and a phase offset uniformly distributed over [-$\pi$, $\pi$]. From Fig. 5.5 it can be concluded that the $L_1$ gives the best performance when compared to the conventional correlator and other ML decision rules.

![Graph showing the effect of UW format on the probability of false acquisition](image)

(a)
Prob. of False Acq. vs Eb/No (Barker 11; foT = [-0.1,0.1])

(b)

Prob. of False Acq. vs Eb/No (Barker 13; foT=[-0.1,0.1])

(c)
Fig. 5.5 Prob. of False Acquisition Vs $E_b/N_0$ for UW of types (a) Barker 7, (b) Barker 11, (c) Barker 13, and (d) Neuman-Hofman codes

Fig. 5.6 Prob. of False Acquisition Vs $E_b/N_0$ for different types of UW
Fig. 5.6 shows that the Barker code of length 13 and Neuman-Hofman code of the same length perform better than other code words. This can be owed to the length of UW, which improves the UW detection. But, one has to note that longer UW causes an increase in the overhead, thereby reducing the efficiency of the frame. Thus, based on the system requirements on the level of precision in synchronization needed, a designed can opt for an appropriate format and length.

5.2.4 Mean Time to Acquire

Mean Time to Acquire (MTTA) is one of the parameters to classify the performance of decision rules discussed in this research for UW detection. Equation (3.6) in chapter three gives an expression for evaluating mean time, in terms of number of
frames, to acquire the correct unique word. In other words, it gives the time taken by a burst to position itself in the destined location. Fig. 5.7 illustrates the performance of the ML estimators and the conventional correlator to acquire the correct UW. In order to evaluate MTTA, 10000 bursts were run to estimate the probabilities of false detection ($P_{FDW}$, $P_{FDO}$) and no detection ($P_{ND}$). The Neuman-Hofman code of 13 symbols was considered as unique word. The simulation was done for a frequency offset uniformly distributed over $[-0.1, 0.1]$ and a phase offset uniformly distributed over $[-\pi, \pi]$. It can be inferred that the performance of ML estimators is considerably better when compared to the conventional correlator. Among the ML estimators, the $L_1$ test function fared better.

Fig. 5.8 MTTA vs $E_b/N_0$ for AB
Fig. 5.8 illustrates the effect of structural properties of a burst in UW detection. As mentioned earlier, a new terminal begins its acquisition process by transmitting an AB. In chapter three we had derive ML decision rules for TB and AB. The performance of these two decision rules for an AB is illustrated in Fig. 5.8. It can be observed that the test function $L_4$ has a slight edge over $L_1$ which is meant for TB. Hence, in systems which demand very low error rate and high QoS, it is advisable to go for different test functions for AB and TB/RB.
Chapter 6

Conclusion and Future Work

The performance of frame acquisition and synchronization has been investigated for different decision rules. The decision rules considered were based on:

- Conventional Correlation
- Maximum Likelihood Estimation

Focus has been placed on the structure of the frame and its role in accomplishing frame acquisition and synchronization. The decision rules were developed for different types of bursts involved in the process of frame acquisition and synchronization. The core step involved in the process is the detection of UW. Hence, the effect of length and format of UW was studied in this work.

6.1 Conclusion

The conclusions made from this study are summarized as follows:

- At very low frequency offsets, the conventional correlator showed better performance when compared to ML decision rules. Hence it is advisable to
opt for a conventional correlator when the frequency offset is very small, as they comparatively simpler to implement.

- At higher frequency offsets, the ML decision rules provided better boundary estimated of the UW. Especially the test function $L_1$ provided the best result among all ML rules.

- Barker code and Neuman-Hofman code displayed good performance when compared to other codewords for UW. This was because of their good autocorrelation properties, as they have very minimal side lobes. With increasing length of the UW, the performance of UW detector also improved. But the designer has to be cautious to avoid drastic increase in overhead which affects the frame efficiency.

- ML estimator for AB delivers relatively better performance when compared to that of TB/RB, during initial acquisition stage. Thus, the structure of a burst does have a significant role in the performance of UW detection process.

### 6.2 Future Work

Some of the areas having scope for further research, based on the outcome of this thesis are as follows:

- This study was performed under the assumption that the symbol timing was precisely recovered from the preamble. The impact of inaccuracies in carrier and clock recovery on the detection of UW can be investigated.
- Other channel models can be considered for the study of frame synchronization for TDMA link.

- Synchronization of the clock at the transmitter and the satellite is itself an area for research. It was assumed that the transmitter clock and the local oscillator in the satellite are in perfect sync for this thesis. The impact of mismatch between the clocks can be studied further.
References


