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I, Ananta Vidyarthi, hereby submit this original work as part of the requirements for the degree of Master of Science in Electrical Engineering.

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Digital AM Radio Navigation using differential Time Difference of Arrival Principle

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Committee member: Xuefu Zhou, PhD
Digital AM Radio Navigation Using differential Time

Difference of Arrival Principle

Submitted in partial fulfillment of the requirements for the degree of

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By

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B.E., Anna University, India

Committee Chair

Dr. Howard H. Fan
Abstract

With today's technologies, the global positioning system (GPS) is widely used to assist mankind to find locations and help people to reliably commute from one place to another. However, the GPS signal is weak and is therefore subject to interference and blockage due to obstruction. Jamming and spoofing of GPS signals can have a detrimental effect on military applications. Hence, there is a need to resort to Signals of Opportunity (SoOP) which have relatively greater signal power than GPS. Signals of Opportunity are those signals which have been dedicated for other purposes such as communication, but are utilized here for navigation. The foremost advantage of SoOP is that they are plentiful in occurrence, relatively resistant to blockage and jamming compared to GPS and often impose no requirement to reconstruct existing hardware. This thesis employs Digital AM radio signal which exists in the (540-1700) kHz region of the frequency spectrum to track unknown receiver locations. A technique called differential Time Difference of Arrival (dTDOA) which is one step beyond the Time of Arrival (TOA) and Time Difference of Arrival (TDOA) methods is employed to solve for locations. It is assumed that the locations of AM transmitters are known prior to localization. The dTDOA principle will require a minimum of two receivers to operate together. Problems due to clock offsets and clock synchronization in receivers are overcome by using the method of dTDOA. The relatively long symbol durations (narrow bandwidths) of the digital AM radio signal poses a problem as it gives rise to potentially huge timing errors, thereby greater localization errors. To improve the accuracy of Digital AM radio, simulations were carried out using methods like curve fitting and time averaging to show that the location accuracy can be enhanced greatly on par to the current navigation standards. Moreover, real time problems such as poor signal reception, signal
attenuation, zone change of AM transmitters while in transit, different noise levels in the signal have also been simulated. Although the setting and the actual data obtained in a real world environment may be different, an attempt has been made to simulate them in this thesis as much as possible. A very simple approach has been employed for multipath mitigation, which could be a suitable area for future work.
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I wish to extend my heartfelt gratitude to my Grandfather and Parents for believing in me and supporting me during all the decisions I took with respect to my academics and my life. I also wish to extend my utmost thanks to my family and friends for understanding me. Thank you for your untiring support, ideas and encouragement.
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Chapter 1 Introduction

Navigation in Latin is usually used to describe travel through sea. But in today’s world, navigation can be extended to air, space, land and sea travel. Navigation is the guide which will aid the traveler to successfully travel from one place to another. In case if the traveler is lost, the role of navigation will be to find the precise location of the traveler and help in directing the person to the required destination, with specific routes and time required to reach the destination.

With the tremendous growth in infrastructure and technology, means of navigation has gone to a different level. People use satellite based navigation today predominantly for commuting from one place to another. Global Navigation Satellite System (GNSS) is a satellite based navigation system which transmits precisely synchronized signals to the earth from satellites orbiting around the earth. It thus provides global coverage and allows users with the appropriate receivers to determine their position. The GNSS of the United States is the Global Positioning System, familiarly referred to as the GPS.

The GPS technology is outstanding in providing navigation for travelers and vehicles on and around the earth. The time delay the GPS signal creates to travel the distance from multiple satellites to a receiver on the earth is multiplied by the velocity of light. This gives the distance between the satellites and the receiver. Therefore the principle is based on computing the range from a receiver to at least four satellites, and hence the location of the receiver can be found. The entire functioning of the GPS receiver involves much signal processing in both analog and digital forms [1]. GPS receivers are used almost by every household in the United States today to help in travel.
1.1 Shortcomings of GPS

Despite being advantageous in many aspects, GPS signals may be disrupted by a wide variety of reasons. The GPS signals are very weak due to the large distance of the GPS satellites to the earth. The signals therefore may easily be subject to interference from radio frequency emitters and may suffer from signal blockage [2]. At the same time, if the vehicle with a GPS receiver is in motion in the downtown area of a city, with huge tall buildings, the signal will be reflected and hence delayed, resulting in a less accurate location. This is referred to as multipath. GPS signals may be subjected to signal attenuation when they encounter trees or buildings and their performance degrades indoors [3]. In this case the number of transmitters is reduced from four and the receiver will be unable to find its location [4]. Also, natural disruptions like ionospheric scintillations and solar flares can affect the signal in the polar and equatorial regions during some parts of the day [5]. Moreover, GPS signals are also subjected to jamming and spoofing. All this can be attributed to the fact that GPS signals are of low power $10^{-16}$ Watt when they reach the Earth’s surface [2]. Apart from these errors, there is an error due to atmospheric delay and clock errors [6]. Although the above mentioned errors can be corrected by a principle called differential GPS (dGPS), the error due to multipath and the effect of noise on the GPS error still pose a problem [7].
1.2 Background and Motivation

1.2.1 Signals of Opportunity

To overcome the shortcomings as mentioned in Section 1.1 there is a need to resort to signals which have relatively higher power and which are capable to provide indoor localization as well. This will be of great advantage for users trying to locate a shop inside a shopping mall, or a specific room in a building. For this we resort to signals of opportunity. Signals of opportunity are those signals which are not primarily dedicated for the purpose of navigation. They are radio frequency signals usually intended for the sole purpose of communication. Signals of opportunity may be AM or FM broadcast signals, TV broadcast signals, 3G/4G wireless communication signals, provided by different service providers. They are robust and have a very good received power level relative to GPS and are capable of penetrating through buildings. The main advantage of using these signals is that they are readily available, cheap and there is no need for any extra installation of devices or infrastructure. The frequency spectrum of these signals range from a few tens of kilohertz to tens of gigahertz. Although these signals extend over a large span of frequencies on the frequency spectrum, most of the signals are not robust for navigation. The signals in the higher end of the frequency spectrum are subject to a higher path loss whereas the lower end frequency signals are subject to interference [8]. Navigation is achieved in these signals by ranging techniques which are based on the time of flight. This can be explained as the time difference between the signal transmitted at the transmitter and the time of arrival of the signal at the receiver. If the ranging is unidirectional i.e., from the transmitter to a receiver, the time of arrival can be estimated using a clock at the receiver [9].
Localization algorithms such as Received Signal Strength Indicator (RSSI) [10][11], Time of arrival (TOA), Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) aid in ranging techniques [12][13]. Angle of Arrival requires an antenna array and is not cost effective. Although RSSI does not add to the receiver hardware, simulations have been run and it is found that RSSI ranging technology has poor accuracy [14]. TDOA is a better method that can achieve good position accuracy [15]. TDOA estimates the difference of the arrival time of the signals between the synchronized nodes and does not require knowledge of the absolute time of the transmission [16]. Based on the difference between two arrival times multiplied by the velocity of light, the distance error can be calculated. The TOA method, on the other hand, is based on one way ranging by measuring the time of arrival at the local clock in the receiver. TOA is well resistant against multipath and is capable of achieving meter level accuracy. However, these techniques of TOA and TDOA, even if they provide meter level accuracy in distance measurements, require tight synchronization of the receiver nodes [17]. This is because of the problem of unknown clock offsets in receivers, while measuring TOA. In addition, in the case of signals of opportunity, there is only one way ranging available because the transmitters of the signals of opportunity are usually not synchronized. In order to eliminate the unknown receiver clock offsets and the unknown transmission time, a method of localization that is one step beyond the TOA and TDOA, called the differential Time Difference of Arrival (dTDOA), is utilized.

The differential Time Difference of Arrival (dTDOA) method requires at least two receiving nodes to work with signals of opportunity. The time of arrival of a signal from a transmitter is measured at two receivers. The difference between these two TOAs is found as a TDOA. This will eliminate the unknown transmission time. The same procedure is repeated with another
transmitter. The difference between the two TDOAs eliminates the clock offset and hence a dTDOA is found. Now this dTDOA is multiplied by the velocity of light to obtain the distance differences. The main advantage of this method is that there is no tight synchronization required between receivers. The principle of dTDOA is explained more in Chapter 4.

Localization using Digital TV broadcast signals was studied in [18] [19]. Digital TV signals are usually available with a number of transmitters spaced around a city and have reasonable powers of transmission. Transmission coverage usually encompasses a large area and also the symbol rate is fast enough to achieve good ranging accuracy. Localization using Digital TV and AM radio signals is presented in [20]. Apart from that, localization using 3G cellular signals has also been presented in [8]. These signals are wideband and have significantly better advantages like higher transmit power and a number of transmitting stations covering a wide area than ultra wide band signals. Although UWB signals have a wider bandwidth, the drawback of UWB is that it is very weak and cannot be received over a not so large a distance and hence is useless for long distance navigation. With the advent of recent technology like WiMax and LTE, these signals of opportunity could likely be used for navigation to obtain better accuracy in future.

The history of simple analog AM radio signal based navigation systems existed even before the First World War. The methodology of using AM radio signals for navigation is evolving based on technology, demand and competition with satellite based navigation systems. In the 21st century, modern algorithms and advanced processors have made it easier to implement new and complex techniques. The concept of using of phase locked loop (PLL) to measure phase differences in the AM signal and thereby aid in navigation was extensively studied in [20]. A detailed study was done on AM signal navigation using cross correlation and TDOA techniques [20]. Results were tested on AM signals by running simulations and by using a navigation
hardware kit in [21]. The AM signal used was analog AM radio. For an SNR of 60 dB, the accuracy obtained was around 1.5 meters in simulation. However, real world locations of transmitters were not mapped and simulated. Although AM signal can propagate over longer distances, analog AM suffers from adjacent co-channel interference. This intriguing AM navigation system is a good encouragement to pursue AM signal for navigation.

Digital AM is one area which has not been explored extensively. Digital AM radio has higher power than analog AM and is less susceptible to co-channel interference. However, the bandwidth of the signal has an effect on timing error as mentioned in [22]. Digital AM radio has narrow bandwidth and longer symbol durations, and will not be an ideal choice for accurate position estimation. However, in this thesis, an effort has been made to utilize digital AM signals to obtain a good level of location accuracy.

1.3 Thesis Outline

This thesis is organized as follows. The next chapter, Chapter 2 gives information about the nature of the digital AM broadcast signal used, its transmission and the modulation process. Chapter 3 provides information on the strategy used to acquire TOA. Chapter 4 explains about the implementation of the principle of dTDOA for the localization process and the parameters used in tracking the receivers. Chapter 5 discusses the Simulation and Results of Localization and Chapter 6 concludes with the pros and cons of AM digital radio and scope for future work.
Chapter 2 Signal Format of Digital AM Radio

IBOC is an acronym for In-Band-On-Channel digital radio. It is a kind of terrestrial radio broadcasting. It employs sophisticated digital radio waveforms which can deliver compact disc-like quality sound, free of interference and noise to radio listeners. It utilizes existing AM and FM analog broadcasting band and channel schemes to transmit digital signal [23], and is handled by a company called iBiquity Digital Corporation. The IBOC digital radio transmitter system encodes incoming analog sound into binary form for transmission. With IBOC radio, a digitally modulated signal shares the radio station’s channel with the existing analog signal.

2.1 Service modes and Spectra

The design provided by IBOC AM radio has two service modes with two new waveform types: Hybrid and All Digital. The Hybrid Waveform retains the analog AM signal, while the All Digital waveform does not [23]. There are two service modes possible in AM radio. They are given as

1. Hybrid service mode denoted by MA1
2. All Digital service mode denoted by MA3

In the Hybrid service mode, the bandwidth of the analog audio signal waveform can be 5 kHz or 8 kHz. Therefore the digital signal is transmitted on both sides of the analog host signal in the primary and secondary sidebands. It is also transmitted on the tertiary sidebands which are beneath the analog signal as shown in Figure 2.4. For the 8 kHz configuration, the secondary
sidebands are also beneath the analog host signal. The greatest system enhancements are realized with the All Digital system. In this system the analog signal is replaced with the primary sidebands whose power is increased relative to the Hybrid system levels. Secondary and tertiary sidebands’ powers are also increased to the level of the Hybrid waveform. Reference subcarriers are also provided to convey system control information as mentioned in [24]. The end result is a higher power digital signal with an overall bandwidth reduction. The power spectral density of IBOC AM radio is measured by averaging the power spectral density in a 300-Hz bandwidth. The power spectral density of the Hybrid AM radio with the analog component and the All Digital radio without the analog component are shown in Figure 2.1 and Figure 2.2

![Figure 2.1 AM Hybrid Waveform Power Spectral Density and Spectral Emission Limits for 5 kHz Analog Bandwidth][25]
Digital radio offers distinct advantages over analog, including mitigation of transmission artifacts and audio quality apart from bandwidth reduction. These changes provide a more robust digital signal that is less susceptible to adjacent channel interference, thereby reducing the noise in the system [24]. Also the All Digital AM system has lesser bandwidth than the Hybrid signal. If reasonable localization results are obtained for the All Digital system, we can predict that better localization results may be obtained with the Hybrid signal which has relatively a larger bandwidth. The overview of the AM digital system for both the service modes MA1 and MA3 is given in the following section. However, we focus more on the signal generation and transmission of All Digital AM (MA3) as that is the signal which is used in this thesis. The overview of the AM digital system for both the service modes MA1 and MA3 is given in the following section.
2.2 Functional Block Components of the AM System

The description in this section aims at providing a brief introduction to the creation and generation of AM HD Radio signals for transmission over the air to a receiver. This subsection includes a high-level description of the Physical Layer 1 L1 functional block and the associated signal flow.

Figure 2.3 shows the functional block diagram of the Layer 1 processing. The system control channel (SCCH) transports control and status information. The service mode control (PSM), analog audio bandwidth control (AAB) and power level control (PL) are input to Layer 1 from Configuration Administrator, while status information is sent from Layer 1 to Layer 2.

![Figure 2.3 AM Air Interface L1 Physical Layer Functional Block Diagram](image-url)
In Figure 2.3, P1, P3 and PIDS are the logical channels. A logical channel is a signal path which transfers data from Layer 2 through Layer 1 and can be configured based on the service mode, Hybrid or All Digital. Logical channels P1 and P3 are dedicated for general purpose audio and data transfer while PIDS carries information with respect to each station. Timing and synchronization information is provided by a separate system control administrator. Each logical channel corresponds to a sideband on the frequency spectrum. The logical channel spectral mapping for the Hybrid and All Digital modes is given in Figure 2.4 and Figure 2.5. Once the AM All Digital radio signal is created, it is transmitted through logical channels to different phases like scrambling, channel encoding, interleaving and signal mapping before transmitting on air. The bits in each logical channel are scrambled to randomize the time domain data and aid in receiver synchronization. Channel encoding improves the system performance by increasing the robustness of the signal in the presence of interference and channel impairments. Once the data in the signal is channel encoded, the next phase is interleaving where the logical channels are dissolved and the output of interleaving is a matrix containing training symbols [24]. The purpose of interleaving is to mitigate the occurrence of burst errors. After interleaving, interleaver matrices are formed and symbols of the matrices are mapped on to OFDM sub-carriers.

Each OFDM sub carrier channel has a spacing of 181.7 Hz. The Hybrid MA1 service mode comprises of 163 sub-channels indexed from -81 to 81 over a total bandwidth of 29.4 kHz as shown in Figure 2.4. The All Digital MA3 service mode has only 105 sub-channels indexed from -52 to 52 over a total bandwidth of 18.9 kHz as shown in Figure 2.5. Therefore when compared to All Digital mode, Hybrid mode contains more training symbols per symbol duration. Importance of training symbols will be discussed in the next Section 2.2.1. We predict that since
Hybrid mode contains more signal matching information than the All Digital mode, the time of arrival (TOA) detection accuracy will be higher for the Hybrid mode. Hence choosing All Digital MA3 service mode for the localization will be a challenge and this is another reason to support our choice to use the same. Demonstrating the capability of All Digital MA3 service mode for localization would imply that Hybrid mode could also be used for the same.

Figure 2.4 Logical Channels and the sidebands on the Frequency Spectrum- Hybrid mode with 5 kHz analog signal bandwidth.

Figure 2.5 Logical Channels and the sidebands on the Frequency Spectrum- All Digital mode.
To utilize digital AM for the purpose of navigation, we take advantage of the way the system is designed. Specifically, we make use of the known training symbols, which will be mentioned in Section 2.2.1, in signal detection at the receiver. Since, the thesis entirely relies on training symbols; interleaving section is explained in detail in the next Section.

### 2.2.1 Interleaving

Interleaving in time and frequency is used to mitigate the effects of burst errors. After interleaving, the logical channels lose their identity. The interleaver output is a structured matrix. Each interleaver matrix consists of information associated with a specific portion of the transmitted spectrum. The interleaver matrix maps onto primary, secondary and tertiary sidebands. Each interleaver matrix consists of 8 interleaver blocks and each block has a size of 32x25. Hence each block has 800 symbols to be filled. The interleaver matrix designations reflect the spectral mapping. “PU” and “PL”, for example, map to primary sidebands while S and T map to secondary and tertiary sidebands respectively. The AM digital radio has five interleaver matrices namely PU, PL, S, T and PIDS.

The equation which provides the index of symbols to be filled in the k\(^{th}\) position in the interleaver matrix and is given in Equation (2.1) and Equation (2.2)

\[
Row(k) = \left[11\left(\frac{(k)MOD_{25}}{25}\right) + 16\left(\frac{k}{50}\right) + 11\left(\frac{k}{50}\right)\right] MOD_{32}
\]

\[
Column(k) = (9k) MOD_{25}
\]

For k=0,..., 749
The Equations (2.1) and (2.2) fill only 750 symbols of the total 800 symbols. The remaining 50 points are the training symbols which are denoted by ‘T’ in Figure 2.6.

The training symbols are known a priori and we will be taking advantage of this information to correlate the received signal with a locally generated copy. Figure 2.6 shows the image of the interleaver block based on Equations (2.1) and (2.2). From the Figure it is evident that the training symbols have a period of 16 rows.
Matrix $\text{PIDS}$ has two columns in contrast to the other matrices which have 25 columns. The equation providing the index of the symbols of PIDS is different from Equations (2.1) and (2.2). It is defined by

$$\text{Row}(k) = \left[ 11k + \text{INT}\left( \frac{k}{15} \right) + 3 \right] \text{MOD}_{32} \quad (2.3)$$

For $k=0,\ldots, 29$

Of the total 32 symbols in the PIDS interleaver, there are two training symbols denoted by ‘T’.

In the AM All Digital service mode MA3, the $\text{PU}$, $\text{PL}$, $\text{S}$, $\text{T}$ and $\text{PIDS}$ interleaver matrices are populated for input to the OFDM subcarrier mapping. The training symbols ‘T’ have a bit definition as given by Table 2.1

<table>
<thead>
<tr>
<th>Interleaver Matrix</th>
<th>$\text{PU}$</th>
<th>$\text{PL}$</th>
<th>$\text{S}$</th>
<th>$\text{T}$</th>
<th>$\text{PIDS}$</th>
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<tr>
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<td>100101</td>
<td>100101</td>
<td>100101</td>
<td>1001</td>
<td></td>
</tr>
</tbody>
</table>

2.2.2 System Control Processing

System control processing receives system control data from the Configuration Administrator via the SCCH as shown in Figure 2.3. To aid in receiver synchronization, the system control administrator provides control data, synchronization data and parity bits. These are eight 32 bit sequences and are carried by a vector $\text{R}$. Each symbol of the vector consists of one bit. The system control data sequence is given by Figure 2.7.
2.2.3 OFDM Subcarrier Mapping

Before transmitting the digital signal it is necessary to modulate the data. The digital signal is modulated using Orthogonal Frequency Division Modulation (OFDM). OFDM is a parallel modulation scheme in which the data stream modulates a large number of orthogonal subcarriers that are transmitted simultaneously. OFDM is robust against channel interference, low sensitivity to synchronization errors and its structure reduces inter-symbol interference greatly [26].

OFDM subcarrier mapping transforms rows of interleaver matrices into scaled 16 QAM, 64 QAM and BPSK symbols and then maps them to specific OFDM subcarriers on an output vector $X$. This is illustrated in Figure 2.8. The inputs to OFDM subcarrier mapping are the interleaver matrices $PU$, $PL$, $S$, $T$, $PIDS$ and $R$. Matrices $S$, $T$, $PIDS$ and $R$ map to the secondary, tertiary, PIDS and reference subcarriers respectively. Matrices $PU$ and $PL$ are mapped to the primary upper and lower subcarriers respectively. One row of each active interleaver matrix and one bit of the system control vector $R$ is mapped into each OFDM symbol, (every $Ts$ seconds) to produce one output vector $X$. $Ts= 5.805 \times 10^{-3}$ second as given in [24].
The output of the OFDM subcarrier mapping for each OFDM symbol is a single complex vector $X$, the symbols of which are indexed on to different subcarriers. Thus for a Digital AM system, one row of $PU$, $PL$, $S$, $T$, $PIDS$ and $R$ matrices are mapped to 105 subcarriers for one OFDM symbol duration. The bandwidth of the system is 18.9 kHz, all of this available bandwidth is utilized in this thesis. This is because, more the training symbols or information known a priori, the better timing information can be obtained for localization and navigation purpose.

### 2.2.4 OFDM Signal Generation and Transmission Subsystem

OFDM signal generation receives complex frequency domain OFDM symbols from the output of the OFDM subcarrier mapping and outputs a time domain representation of the digital signal. If
$X_n[k]$ denotes the complex scaled constellation points for the subcarrier mapping for the $n^{th}$ symbol, where $k= 0, 1, \ldots, L-1$ is input to the signal generation for transmission. The input vector $X$ is transformed into shaped time-domain baseband pulse $y_n(t)$ defining one OFDM symbol as

$$y_n(t) = W(t-nT_s) \sum_{k=0}^{L-1} X_n[k]e^{j2\pi f_{\Delta} \left( \frac{k}{2} \right) (t-nT_s)} \quad (2.4)$$

Where $n=0, 1, \ldots, \infty$, $0 \leq t \leq \infty$, $n$ indexes consecutive OFDM symbols, $L=105$ is the maximum number of OFDM subcarriers and $T_s$ and $\Delta f$ are the OFDM symbol period and OFDM subcarrier spacing, respectively.

The pulse shaping function $W(\zeta)$ is defined in the time-domain as

$$W(\zeta) = \begin{cases} 0 & \text{for } \zeta < 0 \\ \frac{1}{\sqrt{3\sqrt{2\pi}}} \int_{-\infty}^{\pi} e^{\frac{-4050(\zeta)}{\pi \alpha}} H(\zeta-\tau) d\tau & \text{for } 0 \leq \zeta \leq \frac{348}{270} T_s \\ 0 & \text{for } \zeta > \frac{348}{270} T_s \end{cases} \quad (2.5)$$

where

$$H(\zeta) = \begin{cases} 0.5 \left[ 1 + \cos \left( \frac{\pi \alpha T - \zeta}{\alpha T} \right) \right] & \text{for } 0 < \zeta \leq \alpha T \\ 1.0 & \text{for } \alpha T < \zeta < T \\ 0.5 \left[ 1 + \cos \left( \frac{\zeta - T}{\alpha T} \right) \right] & \text{for } T \leq \zeta \leq (1+\alpha)T \\ 0 & \text{otherwise} \end{cases} \quad (2.6)$$
and $T=1/\Delta f$, $\alpha$ is the cyclic prefix time duration as given in [24]. The pulse shaping is given by Figure 2.9.

![Pulse Shaping Function](image)

**Figure 2.9 Pulse Shaping Function**

Once the signal is converted to time domain, before transmission all the symbols are concatenated and up converted to higher frequencies for transmission. The functional block diagram is shown in Figure 2.10
Figure 2.10 All Digital Transmission Subsystem Functional Block Diagram.
Chapter 3 Time of Arrival (TOA)

Acquisition

3.1 Correlation

Correlation between two signals gives the degree to which two signals are similar to each other. This degree to which they are similar may be helpful in finding useful information which is application specific. In the application of this thesis correlation is used to find time of arrival (TOA) information. There are two types of correlation, cross correlation and auto correlation [23]. If there are two signal sequences x(n) and y(n), cross correlation between these two sequences is given by a new sequence \( r_{xy}(l) \) which is given by

\[
r_{xy}(l) = \sum_{n=-\infty}^{\infty} x(n)y(n-l) \quad l=0, \pm 1, \pm 2, \ldots \tag{3.1}
\]

In the special case when signal x(n) is correlated with a noisy and or delayed version of x(n), we get the auto correlation of the sequence which is given by Equation (3.2)

\[
r_{xx}(l) = \sum_{n=-\infty}^{\infty} x(n)x(n-l) \quad l=0, \pm 1, \pm 2, \ldots \tag{3.2}
\]

3.1.1 Coarse Peak Detection

On the receiver side, the received signal is first converted to the baseband. The baseband analog signals are then sampled at a suitable sampling frequency. To satisfy the Nyquist criterion, a
sampling frequency more than 1100 kHz is chosen as mentioned in [23]. Our objective is to detect the time of arrival of the transmitted signal at the receiver.

Each receiver is equipped with an internal clock with its own local time since there is no time synchronization among any receivers and or transmitters. This internal clock is used to measure and record the time of arrival (TOA) of the received signal. This is achieved by correlating the received signal with a local copy of the signal at the receiver and recording the TOA of the first peak in the correlator output. Correlation is done in the time domain after converting the received signal to baseband and before OFDM demodulation. Based on the equations given in Section 2.2.4 a received signal is created for simulation. At the receiver end, a locally generated waveform is created.

The local copy in terms of interleaving is easy to understand and one row of an interleaver block is shown for reference in Figure 3.1 which is used for local signal generation.

<table>
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<th>Row (k)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>“T”</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 3.1 Local Copy Interleaver : Interleaver row and Column indices vs k, here k=0**

<table>
<thead>
<tr>
<th>Row (k)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td></td>
<td>0</td>
<td>0</td>
<td>“T”</td>
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<td>631</td>
<td>595</td>
<td>534</td>
<td>498</td>
<td>437</td>
<td>376</td>
<td>340</td>
<td>279</td>
<td>243</td>
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<td>146</td>
<td>85</td>
<td>49</td>
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<td>702</td>
<td>666</td>
<td>605</td>
<td>569</td>
<td>508</td>
<td>472</td>
</tr>
</tbody>
</table>

**Figure 3.2 Transmitted signal Interleaver : Interleaver row and Column indices vs k, here k=0**

Figure 3.1 shows only one row of the interleaver block for a local copy. Since only the training symbols are known, all other symbols are set to zero in the local copy when compared to the
format of the signal designed for transmission as shown in Figure 3.2. The local copy shown in Figure 3.1 is mapped to a complex number associated with the training symbol value and a time domain waveform is also created for the local copy using the signal generation formulas mentioned in Section 2.2.4.

The first peak at the correlator output corresponds to the line-of-sight (LOS) signal which is the direct path signal and the TOA is calculated from the position of the peak and the time recorded in the internal clock. Additive white Gaussian noise is added in the system and can give rise to spurious peaks other than the arrival time of the line-of-sight (LOS) signal, and the signal can be corrupted if the SNR is relatively low. Apart from additive white noise, multipath propagation such as reflection from buildings may cause measurement errors in TOA. In this case the non-LOS (NLOS) signal may overshadow the LOS signal and hence the probability of detecting a wrong peak is possible. To avoid this kind of erroneous detection, we set a threshold for the correlator output with a condition that the first peak which crosses the threshold is considered as the LOS signal and its position should be taken as the TOA of the received signal [27]. This is coarse peak detection by using a threshold to avoid multipath. By simulations, with various levels of SNR in the signal, we choose a suitable threshold to detect the LOS peak.

The transmitted signals from different transmitters will have different delay time based on the distance between the transmitter and the receiver. The correlation output of a received signal and a local signal with a threshold is shown in Figure 3.3.

One vector $X$ which is one OFDM symbol duration long is transmitted every 5.805 ms as given in [24]. Once the received signal is sampled, it is correlated with the local copy of the signal to determine the exact TOA. As mentioned in Section 2.2.1, the period of the training symbols in the interleaver block is 16 rows. Correlation was done with lesser than 16 rows and it was found
that there were false peaks of almost same magnitude as the actual peak making it unreliable for detection. Hence the safer choice was to choose 16 rows for correlation to obtain the TOA. The TOAs of all the transmitter signals recorded in the internal clocks of all receivers are transmitted to a processing station for further processing.

![Correlation Curve and Threshold for Peak Detection](image)

**Figure 3.3** Output of the Correlator with a threshold to detect a peak- Zoomed view.

### 3.1.2 Time of Arrival (TOA) Acquisition

Measuring TOA accurately from the correlation peak is crucial, since the error in each TOA measurement amplifies and results in a large localization error. The accuracy of TOA error in AM HD radio is affected by a number of factors. The AM signal has a large symbol period which further worsens the TOA accuracy. Since the bandwidth of the AM signal is narrow, and due to the longer symbol duration, sampling at very high frequencies will virtually have no effect as it will not aid in measuring the TOA accurately. Further, to detect exact TOA, it is necessary for the training symbols to match. Hence the problem of detecting TOA depends on correlation,
i.e., matching training values of the received signal and the local signal. Moreover, unlike GPS receivers which receive a known signal from satellites, in the case of radio receivers, only the training symbols and their positions are known, other data in the digital AM signal is random and cannot be used for correlation. Considering longer correlation vectors therefore may help in detecting peaks as there will be more number of training symbols matching. These complications prove to be quite challenging in measuring the TOA promptly.

If a sampling frequency of \( f_s = 10 \text{ MHz} \) is considered to sample the received signal, after correlation, if we choose to detect peaks and record it as TOA only at the sampling interval, a maximum distance error of \( c/2f_s \) can occur, where \( c \) is the velocity of light and \( f_s \) is the sampling frequency. This turns out to be 15 m for \( f_s = 10 \text{ MHz} \). This is the ranging error which occurs between one transmitter and one receiver. In order to use dTDOA equations to solve for the unknown location of receivers, five or more transmitters have to be considered. Hence it is necessary to calculate the error for each of the transmitters and receivers used. This error of 15 m magnifies to the order of a few kilometers while solving for the location of the receivers. Further, the locations of radio transmitters are predominantly in downtown regions of cities to ensure good reception. Since the transmitters are more or less clustered closer to each other, the detection of the receiver is in a huge error band. Hence, if we are detecting TOA of the signal at sampling intervals, the dTDOA method and the clustering of transmitters in a city worsen the accuracy of detecting the position of a receiver using digital AM radio for navigation. Since sampling at higher rates will not help in improving accuracy, there is a need to detect TOA of a signal between two adjacent samples, i.e., interpolation, to achieve a reasonable error as far as navigation is concerned. The interpolation method is discussed in the next subsection, while details and methodology of dTDOA method to find locations is explained in Chapter 3.
3.2 Method of Curve Fitting for TOA Acquisition

In order to calculate the TOA between two adjacent samples, we propose the idea of curve fitting to fit the correlation data and to estimate the TOA by solving polynomial functions. This is referred to as interpolation. This idea is derived from the Early, Prompt and Late concept to estimate TOA of the received signal in GPS [28]. We use a similar concept to detect peaks in between samples using curve fitting. The intention to use curve fitting is to improve the accuracy of the system. Thus the TOA time resolution due to sampling interval as mentioned in Section 3.1.2 will be reduced greatly as a result of interpolation and detecting TOA in between samples. The details of which are provided in this section.

3.2.1 Curve Fitting

It was observed that the correlation peak is asymmetric, so the correlation curve is shaped differently to the right and left of the peak value. This is illustrated in Figure 3.4. Therefore, we need to fit two curves on each side of the correlation peak. This is necessary, since the usage of one curve may not fit the values close to the peak which is the focal point of the fitting. By a trial and error process we determined that a quadratic polynomial is sufficient to fit the correlation values close to the peak. Therefore two simple quadratic functions are fitted for the correlation data points to the left and right of the maximum (peak) excluding the maximum point.
Figure 3.4 Asymmetric Correlation peak denoting different slopes on both sides.

\[ P_L = A_L x^2 + B_L x + C_L \]  \hspace{1cm} (3.3)

\[ P_R = A_R x^2 + B_R x + C_R \]  \hspace{1cm} (3.4)

Where, \( P_L \) and \( P_R \) are the quadratic curve fit for the left side and right side of the correlation peak respectively. \( A_L, B_L, C_L \) and \( A_R, B_R, C_R \) are coefficients of the quadratic Equations (3.3) and (3.4) and \( x \) is the variable. The few correlation data points very near to the peak value on either side of the peak are used for the fitting. Method of linear least squares is used to fit these data and thereby to calculate the coefficients. Once both the polynomials are calculated, they are solved together, to find out where the curves intersect. For a polynomial of degree 3 or more, the intermediate value theorem can be used to solve for the intersection easily [29]. In case of a quadratic function, the solution can be found easily by using the direct formula for the roots of a quadratic function.

The quadratic function to be solved is \( f(x) \) which is given by,
\[ f(x) = P_R(x) - P_L(x) = 0 \]  
\[ (A_R - A_L)x^2 + (B_R - B_L)x + (C_R - C_L) = 0 \]

Solution to the Equation (3.6) is given by

\[ x = \frac{-(B_R - B_L) \pm \sqrt{(B_R - B_L)^2 - 4(A_R - A_L)(C_R - C_L)}}{2(A_R - A_L)} \]

where \( x \) is the solution for the quadratic polynomial given in Equation (3.7). There are ‘n’ possible roots for a polynomial of degree ‘n’, thereby a quadratic polynomial has two roots. To choose the right value of \( x \), the value of \( x \) which lies between the maximum sample and the immediate next samples is considered as the measured TOA. Since the curves intersect at only one point near the peak, the measured TOA is always a unique value. Thus by using curve fitting, TOA of the received signal can be detected in between samples which reduces the error considerably.

![Polynomial Curve Fit on Correlation Peak to find Exact TOA](image)

**Figure 3.5** Zoomed view of the correlation peak with two curves fit on both sides.

Since the correlation peak is asymmetric, there are two polynomial curve fits used as mentioned in Section 3.2.1. Peak of a typical correlation curve of the magnitude of the AM signal zoomed is
shown in Figure 3.5. To prove that the curve fitting provides better accuracy in TOA acquisition, the AM signal is delayed by a known and fractional delay for simulation. Two polynomial curves are used to fit the data points of the correlation. Data points are separately chosen for the curve fitting for both the right and left side of the plot. By trial and error method we choose an optimum amount of data points to help in extrapolation of the curve, thereby help in a better fit. After simulation, it was found that the optimum number of data points chosen must be more than twice the number of unknown constants to be found in the equation. The optimum amount of data points differ with change in sampling frequency. The maximum peak value of the correlation plot is omitted for the curve fitting. The intersection point of both the right and left curve is the point of the TOA.

![Image of curve fitting near the correlation peak](image1)

![Image of curve fitting accuracy compared to sample accuracy](image2)

**Figure 3.6 Accuracy of Curve fitting Vs the Accuracy due to Sampling Interval**
Figure 3.6 shows the curve fitting for the correlation of a received signal and local signal sampled at 10 MHz. The maximum error due to sampling interval would be $T_{\text{samp}}/2$, where $T_{\text{samp}}$ is the sampling time interval and is the inverse of the sampling frequency $f_s$. For $f_s=10\text{MHz}$, $T_{\text{samp}}=1\times10^{-7}\text{second}$. Therefore, error due to sampling interval will be $5\times10^{-8}\text{second}$. This is the TOA error between one transmitter and one receiver and this will translate into a distance error of 15 m and localization error of a few kilometers as mentioned before. From Figure 3.6 it can be inferred that the intersection point which is taken as the measured TOA is much closer to the actual delay. Simulations were run for different delay values, with different Signal to Noise ratio and each time curves were fit and solved to find TOA. The big advantage of using Digital AM is that it is robust, less susceptible to interference and noise has little effect on the signal. From [25] a noise level of -65 dBC per 300 Hz bandwidth was chosen as a suitable noise level and the corresponding signal to noise ratio was calculated to be 52 dB.

![Figure 3.7 TOA Estimation Error Vs different SNR in the received signal](image)

However, in case of adverse channel noise, the SNR can be degraded greatly. Hence, lower SNR levels of 10 dB and 32 dB are also considered for simulation. Noise added in the channel is
additive white Gaussian Noise. Figure 3.7 shows the accuracy of curve fitting at different delays for different SNR values simulated in a particular received signal waveform.

Even though the TOA estimation error is more chaotic for a SNR value of 10 dB, it is observed that even for this SNR value of 10 dB, the TOA estimation errors are well within the limits. To make sure the TOA estimation error for the 10 dB SNR case can be used for the purpose of localization, a Monte Carlo simulation was done. Twenty one different random signals were simulated and the TOA measurement errors after curve fitting were recorded at different delays. The ensemble average of these TOA estimation errors are shown in Figure 3.8.

![Figure 3.8 Ensemble Average of a 10 dB signal with 21 different delays over 21 runs](image)

Results confirm that a 10 dB SNR signal can be very well used for localizing. Thus, a SNR of 10 dB is used for all the simulations in this thesis.

Since the final localization error of a few hundred meters after curve fitting is also undesirable for accurate positioning, a concept called time averaging is introduced in Section 4.3.1. A complete analysis of the effects of sampling frequency, time averaging and curve fitting on the localization error is discussed in Section 5.4.
Chapter 4 Principle of differential Time Difference of Arrival (dTDOA) for Localization

Once all the TOAs from different transmitters are obtained, they are sent to a processing station. At the processing station the TOAs of all the transmitters with respect to the receivers are used to formulate the differential Time Difference of Arrival (dTDOA) distance equations which are used to determine locations. The dTDOA formulation forms the crux of the thesis and is explained in the following description. Consider a case where there are two transmitters A and B and two receivers C and D as shown in Figure 4.1

![Figure 4.1 Principle of differential Time Difference of Arrival](image)
When the transmitter A is transmitting its signal, it is received at different time instances by receivers C and D. This is due to the different propagation delays and the receivers may be spaced kilometers apart. The internal clock of each receiver records the correlation peak with respect to its local time at the corresponding receivers [17]. TOAs of the signal from transmitter A at both receivers C and D are noted. The Equations for the TOA are given by (4.1) and (4.2)

The TOA of the signal from A received by C and D are given by

\[ \tau^A_C = \tau_A + \frac{d_{AC}}{c} + \Delta\tau_C \]  
(4.1)

\[ \tau^A_D = \tau_A + \frac{d_{AD}}{c} + \Delta\tau_D \]  
(4.2)

where \( \tau_A \) is the unknown transmission time of A, \( d_{AC} \) and \( d_{AD} \) are the distances between transmitter A and receivers C and D respectively. \( \Delta\tau_C \) and \( \Delta\tau_D \) are the unknown internal clock offsets with respect to each receiver and \( c \) is the RF propagation speed, the velocity of light. Since transmitter locations are known a priori, if the unknown distances between the transmitter and the receivers can be found, then the receiver locations could be computed. However, there is the unknown transmission time \( \tau_A \) and unknown clock offset at each of the receivers. To eliminate the unknown transmission time, we subtract Equation (4.1) and (4.2). The difference in the TOAs with respect to A gives the TDOA as given in Equation (4.3)

\[ \tau^A_C - \tau^A_D = \frac{1}{c} \left( d_{AC} - d_{AD} \right) + \Delta\tau_C - \Delta\tau_D \]  
(4.3)

However, Equation (4.3) still contains unknown clock offsets of both the receivers and hence it is still not useful to us to calculate distances. To eliminate the clock offsets, we repeat the same
procedure as done with transmitter A with a new transmitter B and two receivers C and D. Hence the TOA of signal from B with respect to receivers C and D is given by Equations (4.4) and (4.5)

\[
\tau_C^B = \tau_B + \frac{d_{BC}}{c} + \Delta \tau_c \tag{4.4}
\]

\[
\tau_D^B = \tau_B + \frac{d_{BD}}{c} + \Delta \tau_D \tag{4.5}
\]

Now, to eliminate the unknown transmission time of B and to calculate the TDOA of the signal from B, Equations (4.4) and (4.5) can be subtracted as

\[
\tau_C^B - \tau_D^B = \frac{1}{c} (d_{BC} - d_{BD}) + \Delta \tau_c - \Delta \tau_D \tag{4.6}
\]

To eliminate the unknown clock offsets we find the difference between these TDOAs as given in Equation (4.3) and (4.6). This gives a differential TDOA equation as given in Equation (4.7).

\[
dTDOA = \tau_{CD}^{AB} = (\tau_C^B - \tau_D^B) - (\tau_C^A - \tau_D^A)
\]

\[
= \frac{d_{AC} - d_{AD} - d_{BC} + d_{BD}}{c}
\]

Thus, by using a minimum of two transmitters and two receivers, a dTDOA cancels receiver clock offsets and unknown transmission time, thus avoiding the need of precise clock synchronization. But for dTDOA to be applicable we need a minimum of at least two receivers in the working range. As stated before, the location of all transmitters are fixed and known \textit{a priori} and when a sufficient number of transmitters and receivers are used, dTDOA can be used to calculate the unknown locations using distance equations [17]. The methodology to solve for the distances, thereby calculating locations is explained in the following section.
4.1 Location Estimation

The TOA values obtained using the correlation techniques for individual AM signals are transferred to a processing station and the dTDOA values are calculated there as explained in Section 4.

In this thesis, localization is done only for a 2-Dimensional navigation system. For a 2-Dimensional system, there are two unknown ‘x’ and ‘y’ coordinates for each receiver. For a set of ‘m’ transmitters and ‘n’ receivers, there are only (m-1) (n-1) independent dTDOA equations [27]. In order to estimate the location of the two receivers, four unknown coordinates (assuming all transmitter locations are known), two for each receiver needs to be determined. In a 2-Dimensional system, considering a five transmitter and two receiver system, it would result in an exact set of four independent equations in four unknown variables. For a six transmitter and two receiver system, we could obtain an over-determined system of five independent equations. By using an over determined system, instead of an exact system the error in the localization can be reduced. This also increases the robustness of the system even though the localization requires more computational resources.

Therefore at any point, in a 2-Dimensional navigational system, five to six transmitters are required to determine the location of two receivers with respect to each other. The Section 4.1.1 explains the dTDOA equations and the methodology to solve them to obtain the receiver locations.
4.1.1 Non Linear System of Equations

Considering a six transmitter and two receiver system, we can form five independent dTDOA equations. These dTDOA equations are linear in terms of the twelve unknown distances between the transmitter and the receiver as shown in Figure 4.2.

\[
(dt_{T_1,T_2} = \frac{(d_1 - d_2) - (d_7 - d_8)}{c})
\]

\[
(dt_{T_2,T_3} = \frac{(d_2 - d_3) - (d_8 - d_9)}{c})
\]

Figure 4.2 A Six Transmitter and two Receiver network - distances between the transmitters and receivers.
\[ dt_{T_3,T_4} = \frac{(d_3 - d_4) - (d_9 - d_{10})}{c} \]  \hfill (4.10)

\[ dt_{T_4,T_5} = \frac{(d_4 - d_5) - (d_{10} - d_{11})}{c} \]  \hfill (4.11)

\[ dt_{T_5,T_6} = \frac{(d_5 - d_6) - (d_{11} - d_{12})}{c} \]  \hfill (4.12)

These 12 unknown variables \( d_i \), \( i = 1, \ldots, 12 \), form an under-determined system of 5 linear equations. It is impossible to estimate the 12 distances from these 5 linear equations using simple algebraic techniques. Therefore, the individual distances \( d_i \) are rewritten in terms of the locations of the receivers and transmitters in Cartesian coordinates using the simple distance formula. For the distance \( d_1 \), the distance formula is given as follows,

\[ d_1 = \sqrt{(x_{R_1} - x_{T_1})^2 + (y_{R_1} - y_{T_1})^2} \]  \hfill (4.13)

where \((x_R, y_R)\) are the coordinates of the receiver and \((x_T, y_T)\) are the coordinates of the transmitter. The transmitter locations are known \textit{a priori}. Therefore the number of unknown parameters is reduced to just four coordinates of the two receivers. Substituting the distance equation as written in Equation (4.13) in the linear system of dTDOA equations, the Equations (4.8) to (4.12) would become simultaneous nonlinear system of equations as given below.

\[ dt_{T_1,T_2} \times c = \left\{ \begin{array}{l}
\sqrt{(x_{R_1} - x_{T_1})^2 + (y_{R_1} - y_{T_1})^2} - \sqrt{(x_{R_1} - x_{T_2})^2 + (y_{R_1} - y_{T_2})^2} \\
- \sqrt{(x_{R_2} - x_{T_1})^2 + (y_{R_2} - y_{T_1})^2} + \sqrt{(x_{R_2} - x_{T_2})^2 + (y_{R_2} - y_{T_2})^2}
\end{array} \right\} \]  \hfill (4.14)

\[ dt_{T_2,T_3} \times c = \left\{ \begin{array}{l}
\sqrt{(x_{R_1} - x_{T_2})^2 + (y_{R_1} - y_{T_2})^2} - \sqrt{(x_{R_1} - x_{T_3})^2 + (y_{R_1} - y_{T_3})^2} \\
- \sqrt{(x_{R_2} - x_{T_2})^2 + (y_{R_2} - y_{T_2})^2} + \sqrt{(x_{R_2} - x_{T_3})^2 + (y_{R_2} - y_{T_3})^2}
\end{array} \right\} \]  \hfill (4.15)
\[ dt_{T3,T4} \times c = \left( \sqrt{(x_{R1} - x_{T3})^2 + (y_{R1} - y_{T3})^2} - \sqrt{(x_{R1} - x_{T4})^2 + (y_{R1} - y_{T4})^2} \right) \]
\[ - \left( \sqrt{(x_{R2} - x_{T3})^2 + (y_{R2} - y_{T3})^2} + \sqrt{(x_{R2} - x_{T4})^2 + (y_{R2} - y_{T4})^2} \right) \]  
\[ (4.16) \]

\[ dt_{T4,T5} \times c = \left( \sqrt{(x_{R1} - x_{T4})^2 + (y_{R1} - y_{T4})^2} - \sqrt{(x_{R1} - x_{T5})^2 + (y_{R1} - y_{T5})^2} \right) \]
\[ - \left( \sqrt{(x_{R2} - x_{T4})^2 + (y_{R2} - y_{T4})^2} + \sqrt{(x_{R2} - x_{T5})^2 + (y_{R2} - y_{T5})^2} \right) \]  
\[ (4.17) \]

\[ dt_{T5,T6} \times c = \left( \sqrt{(x_{R1} - x_{T5})^2 + (y_{R1} - y_{T5})^2} - \sqrt{(x_{R1} - x_{T6})^2 + (y_{R1} - y_{T6})^2} \right) \]
\[ - \left( \sqrt{(x_{R2} - x_{T5})^2 + (y_{R2} - y_{T5})^2} + \sqrt{(x_{R2} - x_{T6})^2 + (y_{R2} - y_{T6})^2} \right) \]  
\[ (4.18) \]

The transmitter locations T1 to T6 are known. These non-linear dTDOA equations in four unknown variables form the basis of the localization of the receivers. The solution set of four receiver coordinates from this simultaneous non-linear system of equations is the desired output.

### 4.1.2 Solution of the Non-Linear System of Equations

The non-linear over determined or exact system of equations as discussed above can be solved using many iterative procedures. Iterative techniques like the Gauss-Newton method were also used to solve the non-linear system of equations, but it was found that the solution is mostly driven to the local minimum instead of the global minimum. Hence, over a number of iterations, the solution is stuck and so will never converge to the right solution. In this thesis, the method of least squares using Levenberg-Marquardt technique is used to iteratively solve the simultaneous non-linear equations. Simulations were run and it was found that the Levenberg-Marquardt method was more robust than the Gauss-Newton method as it was capable of converging to the solution in the global minimum even if the initial guess was relatively far away. Levenberg-
Marquardt (LM) method is used in this thesis for finding the solution to the non-linear system of equations.

Rewriting Equation (4.14) we get

\[
f_1(x_{R_1}, x_{R_2}, y_{R_1}, y_{R_2}) = dt_{T_1,T_2} \times c - \left( \sqrt{(x_{R_1} - x_{T_1})^2 + (y_{R_1} - y_{T_1})^2} - \sqrt{(x_{R_1} - x_{T_2})^2 + (y_{R_1} - y_{T_2})^2} \right) = 0
\]

Equation (4.19) shows only one dTDOA equation as a function. We can get equations like \(f_1, f_2, f_3, f_4, f_5\) and so on. The iterative non-linear least square technique minimizes \(f_1, f_2, f_3, f_4, f_5\) simultaneously using the LM technique. Since it is computationally impossible to achieve zero value using iterative techniques; a tolerable minimum least square error value of the system of equations was set.

**4.2 Initialization of the System**

The iterative non-linear least square technique works well, when it was provided with a reasonable initial estimate of the solution. If the initial estimate is not good enough, the solution often converges to a local minimum instead of the global minimum. Therefore, it is crucial that before using the iterative non-linear least square technique an initial estimate of the solution must be obtained. There are several ways in which an approximate initial estimate can be calculated. The possible methods which were used, their functions and shortcomings are discussed in detail below.
4.2.1 Multi-Dimensional Scaling

Multi-dimensional scaling computes locations of all participating nodes from their known pairwise distances. Such computation could be done in various ways, e.g., by finding eigenvectors of the distance matrix or by optimizing a cost function which usually reduces to solving non-linear equations. In order for the MDS to work, we need to obtain pair-wise distances between all nodes [30]. In our case nodes are the transmitters and receivers. From Section 4.1.1 it is clear that there are more unknown distances than the independent dTDOA equations. Therefore not all pair-wise distances are known. Attempting to solve all distances from the independent dTDOA equations would result in an underdetermined set of equations. Hence the MDS method could not be applied for our case.

4.2.2 Taylor’s Series

Taylor’s series is one of the simplest initialization techniques available. Taylor’s series of the first order was used to linearize the system of non-linear equations. The Taylor series on the dTDOA equations were calculated around the midpoint of the two transmitters. The error in the first order Taylor’s series expansion was too large, that it often leads the solution to a local minimum. Including the second order terms of the Taylor’s series, involves a lot of non-linear terms that complicates the procedure.

4.2.3 Annealing Techniques

Annealing techniques like Genetic Algorithms can be useful in finding out the global minimums in a rugged non-linear system like this. But such annealing techniques are known to require
heavy computational burdens. Even though this technique seems to work fine, it takes a lot of time and computational resources to find the global minimum. It is impractical to apply the annealing techniques on a real time application.

4.2.4 Artificial Neural Network

ANN gives a functional relation (using weights and bias values) between the dTDOA values and the 4 unknown receiver locations [31]. Therefore, it is a good substitute for the Taylor’s Series expansion. Once a simple well-trained network for a specific set of transmitter positions is available, it can be used to find an approximate value of the receiver locations corresponding to the dTDOA values given as inputs. Disadvantage of using a simpler ANN is that, every ANN network is very specific to a set of transmitters. Therefore, it can be very well used in and around a city where, the transmitter locations are known and fixed. But in order to achieve coverage over an entire state or a region, many trained networks specific to every transmitter set is required. Thus a database of networks should be maintained or a complex ANN must be developed for a general prediction using transmitter locations as inputs.

4.2.5 Look Up Table

For a given set of transmitter locations, using the dTDOA Equations (4.14) to (4.18) and for a selected set of the receiver locations, corresponding dTDOA values can be calculated. The receiver locations are chosen to be equally spaced points like a mesh throughout the working range of the transmitter set. This mesh size can be varied depending on the computational resources available and the desired accuracy. By a trial and error process, a mesh of 11x11 points was found to be working well. Once the dTDOA values are obtained for these different receiver
locations, a look up table was made. This look up table of 4 location variables corresponding to different dTDOA values is used to estimate the approximate initial locations of the receivers directly. When a set of new dTDOA values are obtained, the closest dTDOA combination matching was found and the corresponding receiver locations are used as the initial value. The look up table size depends on the system resource and required accuracy. This technique is very similar to ANN, but it requires more computational resources compared to ANN.

Figure 4.3 Estimation of the Receiver locations using Look up Table technique. Axes are not to scale. o—transmitters, .—predetermined locations on the look up table, *—Initial estimate of the receivers, *—Actual and predicted locations (overwritten) of the two receivers.
The look up table has to search through a database of 121 x120 x5 values to calculate the minimum RMS error between the obtained dTDOA and the dTDOA in the table. In contrast, for ANN, for a given dTDOA value, less than hundreds of weights and bias calculations are required. But, this technique is also more reliable, repeatable and can be incorporated online directly depending on the transmitter set, trading-off some initial estimation time. Disadvantage of doing this offline is that, a huge database is required to be stored if the estimation is done over a state or a big region.

Figure 4.3 shows six transmitters depicted by circles and their operating range. The receiver is localized in the region of intersection of all the transmitter ranges.

4.2.6 Error Feedback Mechanism

In this thesis, we have used a simple error feedback mechanism to initialize the non-linear system of equations. Once all the transmitter locations and their ranges are mapped, Levenberg-Marquardt method with an error response is used to initialize the system to find the receiver locations. The region of common intersection of all the transmitters is only considered as the working range for both the receivers. It is in this region that two locations must be chosen and fed into the dTDOA equations as a good initial guess. Similar to the look-up table method, the working range of all transmitters is divided into five points as shown in Figure 4.4. For the first iteration, any two points of the five points are chosen as the initial guess and fed into the Levenberg-Marquardt method of least squares to solve the dTDOA equations as given in Equation (4.14) to (4.18). The initial guess converges to a solution which estimates the initial location of the receivers. The converged solution may get stuck in a local minimum instead of the global minimum. So in order to check if the solution provided by the Levenberg-Marquardt
The method of least squares provides the right initial location; we back substitute the converged locations into the dTDOA equations to calculate dTDOA values. If the root mean square error between the obtained dTDOA from the processing station and the calculated dTDOA as a result of substitution of the converged location is less than a predetermined threshold, that location is taken as the initial location of the receivers. If the error is high, it implies that the chosen two initial locations drive the system to be stuck in a local minimum. This means that the actual location of the receivers are too far from the chosen set and so another set of two locations is to be considered to solve for the initial location. This method is similar to the look up table, but a great advantage of this method is that it can be used online and does not require a large look-up table, and the Levenberg-Marquardt method is very fast.

Figure 4.4 Error Feedback Mechanism – Axes are not to scale and are only a representation of the transmitter ranges.
4.3 Tracking

Once the initial location is found out, the next step is to track the location of the receivers when they are moving. To find the next location, the previous location is fed into the LM method to find the next location. The LM method for the tracking phase has a faster convergence than for the initialization phase and the next location is predicted quickly. This greatly helps to track moving receivers which move at higher speeds as well. This is the procedure which is continued, to track the moving receivers. However, due to error in tracking the predicted location is not exact and is usually around the actual location. A number of factors affect the performance of tracking. The number of independent dTDOA equations required to solve for the location of receivers depends on the number of transmitters. The number of independent equations is given by \((m-1)(n-1)\) where \(m\) is the number of transmitters, and \(n\) is the number of receivers. Since at any point we will require two receivers to solve for dTDOA equations, the two receivers map to two locations or four unknowns in a two dimensional plane. Considering an over-determined system will make the system robust and the extra equation will validate for the location. So, if six transmitters are considered, we have five independent equations to solve for four coordinates. But in the event that only five transmitters are available, the system will be exact to solve for four coordinates.

Once the ranges of all the transmitters are mapped, the working range of all the transmitters is considered for the tracking of both receivers. The receivers choose transmitters based on the signal strength of each transmitter in the working range. Since a six transmitter system is found to be more stable than five transmitters, the receivers try to receive signals from six transmitters whenever available. In the event that only five transmitters are available, the receivers use the
five transmitters as a minimum for localization. Several real time conditions which can affect the performance of tracking are considered. In the event that a receiver goes out of range of a particular transmitter, it tries to receive signal from the next best transmitter available, thereby a new working range will be formed. This can be due to loss of signal, reflection due to buildings or other obstruction in the path. During this zone change, the processing station may choose another transmitter or a new receiver to recalculate dTDOA and solve for new locations. During this zone change, the processing station may choose another receiver to recalculate dTDOA and solve for new locations. Whenever a zone change occurs, the receivers are reinitialized from the initial location for simplicity of programming. In reality such re-initialization should start from the previously known locations. Whenever a zone change occurs, the receivers are reinitialized from the initial location. Simulations have been run to ensure smooth transition among different transmitters and cases where one receiver is switched off and another receiver is used. More information on this can be found in Section 5.3.1

4.3.1 Time Averaging

As the TOA error magnifies to a localization error when many transmitters and receivers are used, the error increases from the order of tens of meters to kilometers. Although curve fitting reduces TOA estimation distance error from tens of meters to a few meters, this error again magnifies to the order of a few hundred meters of localization error when fed into the dTDOA equations. Since such a tracking result will not be of any use in navigation, there is a need to improve tracking results by reducing the error. Figure 4.5 shows the method of averaging all the tracked locations for a stationary receiver.
As shown in the Figure 4.5 the tracked locations of any stationary receiver always form an error ellipsoid due to the noise and computation error. This ellipsoid pattern of tracked locations is also noted in simulations done by [27]. The tracked points are depicted by black points in the image. The yellow circle corresponds to the actual location. By simulation it was found that, averaging all the possible predicted locations produced a location much closer to the actual location. The red cross is the averaged location.

This is averaging for the case of a stationary receiver. Hence for a moving receiver, we plan to time average all the predicted locations to find a location closer to the actual location. At the same time, there is a trade off in choosing the number of tracked locations to time average. If more number of predicted points are considered for time averaging, the location predicted may much lag the actual location in time. If the predicted location lags from the actual location, the
receiver may have moved a considerable distance during that time. Thus we can say that tracking is affected by how frequent we update the locations. We call this update rate. Update rate is constant and hence periodic updating of the location occurs only at the updating frequency. Doppler Effect also alters this update rate depending on the direction of travel of the receiver and its velocity.

A new parameter called time averaging window is introduced which is a predefined time span over which all the tracked locations are averaged. Apart from the time averaging window there are other factors which contribute to the lag in position, like signal processing time, data processing time, circuit delays, transmission delay between processing station and receiver etc. But the delay caused by time averaging window is of several orders of magnitude more than any other minor delays and so it dominates the position lag.

The number points for averaging inside this time averaging window depends on the velocity of the receiver and Doppler Effect. Simulations on the effects of time averaging are presented in the next chapter.
Chapter 5 Simulations and Results

To test the techniques and ideas explained in the previous chapters, it is necessary to provide results to validate and evaluate digital AM’s performance. The primary aim is to prove that the accuracy of digital AM has been improved using methods explained in the previous sections, thereby making AM suitable for navigation. A number of factors affect the performance of digital AM used for navigation. To name a few, they are sampling frequency used to sample the signal, noise in the system, time averaging window, location update frequency, smooth transition among zones etc. All these factors influence the error in the system thereby affect the final accuracy. Simulations have been run to study all the above mentioned cases and are presented in the following sections.

5.1 Digital AM Transmitter Environment

To begin the process of localization, it is necessary to first map the locations of transmitters used in the system. As mentioned in Section 4.0, transmitter locations are known a priori and are mostly located in the heart of a city and downtown areas to ensure maximum reception and coverage. We make use of the information provided by iBiquity Corporation, with the latitude and longitude locations of all the transmitters used [32]. In order to simulate all possible cases as in a real world environment we would need at least seven to eight transmitters in a region, with the minimum requirement being five transmitters. A requirement of using seven to eight transmitters would be justified to simulate smooth zone change, loss of transmission due to obstructions, choosing a new transmitter and to compare the tracking performance in a five transmitter and six transmitter zone. Apart from that, simulations of receivers which are
stationary or moving in a curved path have also been simulated and the results are presented. To simulate all the above mentioned conditions, the working range of both the receivers should be vast so that results can be comprehended better. Each transmitter has an approximate range of 50-150 kilometers. The working range of each transmitter is assumed to be circular for simplicity and we are interested in finding the region of common intersection of all the transmitters for our receivers to be functional. If the range of each transmitter is too small a span, it is difficult to get common working ranges for the receivers.

Table 5.1 Various locations and ranges of Digital AM Radio [32] in Chicago

<table>
<thead>
<tr>
<th>STATION</th>
<th>Frequency (Hz)</th>
<th>POWER (Watt)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Range (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSCR</td>
<td>670 AM</td>
<td>50000</td>
<td>41° 56' 01&quot; N</td>
<td>88° 04' 23&quot; W</td>
<td>169.847</td>
</tr>
<tr>
<td>WMVP</td>
<td>1000 AM</td>
<td>50000</td>
<td>41° 49' 05&quot; N</td>
<td>87° 59' 18&quot; W</td>
<td>96.112</td>
</tr>
<tr>
<td>WBBM</td>
<td>780 AM</td>
<td>50000</td>
<td>41° 59' 26&quot; N</td>
<td>88° 01' 39&quot; W</td>
<td>147.62</td>
</tr>
<tr>
<td>WLS</td>
<td>890 AM</td>
<td>50000</td>
<td>41° 33' 21&quot; N</td>
<td>87° 50' 54&quot; W</td>
<td>119.62</td>
</tr>
<tr>
<td>WTMJ</td>
<td>620 AM</td>
<td>50000</td>
<td>42° 42' 28&quot; N</td>
<td>88° 03' 57&quot; W</td>
<td>91.5783</td>
</tr>
<tr>
<td>WVON</td>
<td>1690 AM</td>
<td>10000</td>
<td>41° 44' 14&quot; N</td>
<td>87° 42' 04&quot; W</td>
<td>42.339</td>
</tr>
<tr>
<td>WMBI</td>
<td>1110 AM</td>
<td>4200</td>
<td>41° 55' 41&quot; N</td>
<td>88° 00' 25&quot; W</td>
<td>62.429</td>
</tr>
</tbody>
</table>

To simulate this environment, a city which has seven transmitters was to be chosen. Cities like Cincinnati, Columbus and Indianapolis have sufficient transmitters for the localization simulation, but a dynamic system including all the different cases couldn’t have been created in
these cities due to insufficient number of transmitters. The best option was to choose Chicago where there are many transmitters transmitting digital AM providing coverage to the city. We chose six best transmitters in Chicago based on power of the signal and location and another transmitter from Milwaukee which reaches Chicago [32]. The working range of the receivers is large enough to perform detailed study of all the navigation techniques. The details of the radio stations chosen in and around Chicago are tabulated in Table 5.1 and the locations of the radio station transmitters are shown Figure 5.1

![Transmitter Mapping and Different Zones](image)

**Figure 5.1** Location of all the Transmitters and their Ranges [32] (Axes are in kilometers).

### 5.1.1 Transmitter Mapping

Once the latitudes and longitudes of the transmitters are obtained, to simulate them we need to convert them to two dimensional X-Y Cartesian coordinates. The earth is assumed to be flat over a region of 200 square kilometers. The objective is to simulate the tracking environment on
different routes on the map of Chicago. To do this we fix an origin around the center of the city and mark its latitude and longitude. We consider four reference points on the Chicago map around the chosen center and form a square with the chosen four points. The latitude and longitudes of the four points are also marked. Since we know the distance between these reference points, we can convert the latitude and longitude of all the transmitters to coordinates in terms of kilometers with respect to the chosen origin. Once we determine the coordinate system we can convert these quantities to image pixels in the Chicago map image in order to explain the results of simulation.

5.2 Routes and Zones for Simulation

After the four reference points and the origin are marked, the routes for the receivers are to be considered for simulation. Figure 5.1 shows the location of transmitters in the city of Chicago. The areas covered by each transmitter are depicted by circles in Figure 5.1 and the center of each circle is the location of the transmitter. Each transmitter is depicted by a specific color as can be inferred from the figure. There are six transmitters shown in the city of Chicago and the range of the one in Milwaukee is also shown in Figure 5.1

Once the transmitter and its ranges are marked, the next stage is to find the common working range of all the transmitters. Ideally, the working range is the area of intersection of all the transmitter ranges. As mentioned in Section 4.2.6, the receivers have to be inside the working range to implement the method of dTDOA. However, in reality it is very difficult to obtain the intersection of all the transmitters. Hence relaxing the constraint, to implement the method of dTDOA in practice, the receivers must be in the intersection range of at least five transmitters to
solve for four locations. The more the number of transmitters’ ranges intersecting; the better the solution to the localization problem.

However, after running simulations on the working range of a seven transmitter zone, it was found that the accuracy of a seven transmitter system was equivalent to the accuracy of a six transmitter system. The advantage of a seven transmitter zone is that even if the receiver loses its reception of any transmitter, the remaining six transmitters will be able to localize both the receivers well. However, a seven transmitter system consumes more computational resources and it is very difficult to find an intersection of a seven transmitter zone.

The results of the tracking performance of a five transmitter zone and a six transmitter zone will be presented and their tracking accuracy will be discussed. To illustrate tracking, two routes are considered. We assume that a receiver travels from Rockford, Illinois to downtown Chicago. This path is chosen especially to simulate various cases and provide tracking results of five transmitter and six transmitter zone, loss of signal due to reflection and zone changes. To illustrate all the above mentioned cases clearly, we divide this path into two routes.

Route One: Receiver moving from Rockford as shown in Figure 5.2

Route Two: Receiver moving to Chicago as shown in Figure 5.2

We eliminate the region in between as nothing special or different worth simulating occurs there. Route one contains the working region of five transmitters and this route will focus on the tracking performance of a five transmitter region. This route is away from city limits and is 28.16 kilometers long. This can be better depicted in Figure 5.2. Route two is more interesting as it contains most number of cases to be studied. The primary focus of this region is to explain
tracking results of a six transmitter zone. This route is in the downtown region of Chicago and is 46.18 kilometers long. Since the receiver will be travelling through this route, it may be subjected to poor reception or signal attenuation due to buildings and obstructions. Such conditions have been considered, modeled and the transition from one transmitter to another transmitter has also been simulated. This is the path for receiver one. Since we focus on providing tracking results of receiver one during its travel, diverse kinds of conditions for receiver two are considered.

![Different Routes considered for Simulation](image)

**Figure 5.2 Different Routes considered for Simulation with Two Receivers. All axes are in kilometers**

Receiver two is considered both on land as well as in water (Lake Michigan). Also even if one receiver goes out of range, we discard that receiver and choose another random receiver in the working range. Whenever a new receiver is considered or when the working range of the receivers is altered like a zone change from five transmitter to a six transmitter occurs, then both the receivers are re-initialized by the method described in Section 4.2.6. This re-initialization is
done each time when a zone change occurs to make the algorithm robust and to make the program simpler. This will account for re-starting the localization procedure in a different processing station if required. Processing stations may be specific to a particular region. In reality re-initialization would not be needed for the tracked receiver since its previous location is known. Tracking results of a stationary and moving receiver are presented in Section 5.3. The speeds of the moving receivers considered for simulation varies from 15 to 115 kilometers per hour and of course the stationary receiver is immobile but is receiving signals.

5.3 Introduction to Simulation

Once the receiver routes are pre-determined, we simulate the receivers moving along those routes. The simulation includes the entire navigation technique. There was no hardware built to test the navigation strategy. The entire simulation was done only using programming codes in MATLAB. Therefore these programs were used to carefully include and simulate only few of the many real world factors that affect the localization.

The time domain AM received signal was modeled according to the specifications given in Section 2.2.4. Various delays were given to this signal and the performance of curve fitting in TOA measurement were studied carefully. The TOA measurement error in curve fitting is the most important factor for localization and it directly affects the localization of the two receivers. As the noise level in the signal increases the signal becomes more corrupt and there is a chance that the correlation peak is altered. Therefore a detailed evaluation of the correlation peak detection using curve fitting technique was done in Section 3.2.1 for different fixed levels of SNR. During the simulation, for modeling simplicity the noise variance at any location is assumed to be constant and same for all transmitter signals. Three different constant SNR values
of 52 dB, 30 dB and 10 dB were used for the simulation. The results in Section 3.2.1 show that curve fitting error almost remains the same for higher SNR signals. As the noise increases further, the SNR decreases and for signals with lower SNR of around 10 dB, the TOA error measurement showed a little chaotic pattern and the variation was very small. To conclude, the noise in the signal had little effect on the TOA error measurement and the navigation system is insensitive to SNR greater or equal to an SNR of 10 dB.

The localization error due to curve fitting technique for different sampling intervals will be explained later in Section 5.4. The signal was sampled at different sampling frequencies to study the effect of sampling frequency on the localization error. Simulations were repeated with different time averaging windows to study the time averaging technique. The effectiveness of the dTDOA technique and navigation process for different routes with special cases as shown in results of the simulation are discussed in the following sections.

5.3.1 Simulation of Route One

Route one was studied to understand the capability and performance of the dTDOA technique in a five transmitter network. Here, the receiver starts from Rockford where there are only four transmitters and moves towards Chicago. The route is shown in Figure 5.2. As soon as it picks up the AM signal from the WSCR radio station, the navigation procedure starts. The receiver will start the TOA acquisition process, once it receives all five signals. Since, two receivers are required for the dTDOA calculations, processing station collects TOA measurements from a different receiver that receives the same set of five signals. In this case, the processing station pairs the first receiver with a second receiver which is already being tracked. The processing station has no prior information on the location of the first receiver. After the dTDOA
calculation, the processing station runs the initialization algorithm as described in Section 4.2.6. These coordinates are then transmitted back to the receivers for tracking or is used by the processing station for other applications. The processing station continues to receive TOA measurements from both the receivers to calculate their subsequent locations. In the processing station, after every subsequent location was found, a time averaging algorithm as described in Section 4.3.1 averages the locations obtained over the last ‘n’ seconds. This averaged location is taken as the final locations of the receiver. These ‘n’ seconds are predetermined for a receiver by the time averaging window or could be variable based on the speed of the receiver.

The system continues to track the receiver when the receiver is in the five transmitter zone. Although route one is dedicated to provide tracking results in a five transmitter zone, we simulate only the zone change from a five transmitter to a six transmitter region. During this transition, receiver one picks up a new AM radio signal from the radio station WMBI. The processing station pairs the first receiver with a new second receiver in the six transmitter zone. The six transmitter system is studied in detail in the next Section 5.3.2. Table 5.2 shows the tracking results of a five transmitter system in route one. A maximum error of 10.23 m is obtained in the five transmitter zone for Route One. This exceptional result for a five transmitter system was unexpected. It is compared and discussed later in Section 5.4.1.

Table 5.2 Simulation Parameters and Results of Route One

<table>
<thead>
<tr>
<th>Route</th>
<th>Route One (Five Transmitter zone only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>24.41 km</td>
</tr>
<tr>
<td>Receiver Velocity</td>
<td>112.65 km/h</td>
</tr>
<tr>
<td>Sampling freq</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Update Rate</td>
<td>Approx 5.8x10^-3 s</td>
</tr>
<tr>
<td>Time Averaging Window</td>
<td>1 s</td>
</tr>
<tr>
<td>Maximum Error</td>
<td>10.2311 m</td>
</tr>
<tr>
<td>RMS Error</td>
<td>1.9419 m</td>
</tr>
</tbody>
</table>
5.3.2 Simulation of Route Two

In route two, several unique cases are studied. The simulation is studied in a much detailed manner than route one. Different cases studied in route two are tabulated in Table 5.3.

<table>
<thead>
<tr>
<th>Case</th>
<th>Receiver 1 (R1) Zone</th>
<th>Number of Transmitters Used, Missing Radio Station and Reason</th>
<th>Receiver 2 (R2) Status</th>
<th>Reason for Ending Case</th>
<th>Distance (km)</th>
<th>RMS Error (m)</th>
<th>Maximum Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 Transmitter /Same</td>
<td>6 Transmitters WVON - out of range</td>
<td>Stationary</td>
<td>R1 picks up WVON</td>
<td>3.29</td>
<td>0.222</td>
<td>0.6818</td>
</tr>
<tr>
<td>2</td>
<td>7 Transmitter /Same</td>
<td>6 Transmitters WTMJ -weakest</td>
<td>Moving</td>
<td>R2 goes out of range of WVON</td>
<td>8.70</td>
<td>0.4386</td>
<td>1.9003</td>
</tr>
<tr>
<td>3</td>
<td>7 Transmitter /Same</td>
<td>6 Transmitters WTMJ -weakest</td>
<td>Moving</td>
<td>WVON signal gets interrupted</td>
<td>4.55</td>
<td>0.7008</td>
<td>3.3702</td>
</tr>
<tr>
<td>4</td>
<td>7 Transmitter /Same</td>
<td>6 Transmitters WVON - lost</td>
<td>Moving</td>
<td>R1 picks up WVON</td>
<td>6.07</td>
<td>0.4439</td>
<td>2.5951</td>
</tr>
<tr>
<td>5</td>
<td>7 Transmitter /6 Transmitter</td>
<td>6 Transmitters WTMJ -weakest</td>
<td>Stationary in Downtown</td>
<td>R2 shutdown</td>
<td>6.82</td>
<td>1.0549</td>
<td>5.4139</td>
</tr>
<tr>
<td>6</td>
<td>7 Transmitter /6 Transmitter</td>
<td>6 Transmitters WTMJ -weakest</td>
<td>Moving Circular Arc</td>
<td>R1 loses WTMJ completely</td>
<td>0.67</td>
<td>0.5766</td>
<td>2.2096</td>
</tr>
<tr>
<td>7</td>
<td>6 Transmitter /Same</td>
<td>6 Transmitters WTMJ - out of range</td>
<td>Moving Circular Arc</td>
<td>R1 loses WMBI due to signal Blockage</td>
<td>8.55</td>
<td>1.0768</td>
<td>6.2432</td>
</tr>
<tr>
<td>8</td>
<td>6 Transmitter /Same</td>
<td>5 Transmitters WTMJ - out of range WMBI lost</td>
<td>Moving Circular Arc</td>
<td>R1 picks up WMBI again</td>
<td>0.62</td>
<td>6.1271</td>
<td>20.0462</td>
</tr>
<tr>
<td>9</td>
<td>6 Transmitter /Same</td>
<td>6 Transmitters WTMJ - out of range</td>
<td>Moving Circular Arc</td>
<td>R1 shutdown</td>
<td>6.98</td>
<td>1.8465</td>
<td>12.9431</td>
</tr>
</tbody>
</table>
The first receiver starts in a six transmitter zone. So, a second stationary receiver in the same zone is paired with the first receiver. The receiver showed tracking results with a maximum error under one meter. This can be accounted for the fact that the distant transmitter WTMJ is included for localization and the fact that the two receivers are set apart from each other. The localization result of the stationary receiver is studied later. Once the first receiver picks up the signal from WVON station, it enters a new zone of seven transmitters. Here, the receiver sorts the radio signals based on their received power at that location and chooses the six best transmitters for correlation. If the six best transmitters are the same as the previous zone, no change occurs. In the simulation, at this point a condition that the best six transmitters are different from the previous set is considered.

![Typical 6-Transmitter Localization Result](image)

Figure 5.3 Six Transmitter Localization Result (All axes are in kilometers)

In case two, the signal from station WTMJ which was used for localization so far is assumed to be the weakest now and hence discarded. Therefore the first receiver undergoes a zone change and is paired with a new moving second receiver which receives the same set of transmitter
signals. Since the farthest WTMJ signal is discarded, the localization error increases compared to case one. A typical six transmitter localization result is shown in Figure 5.3

The localization result shows precise tracking results with accuracy within the lane. In Figure 5.3 we also notice that, since time averaging is mathematically a smoothing operation, the sharp corners are smoothened as a result of this. This causes increased errors around corners.

Now consider a case when the second moving receiver goes out of range of the station WVON. Hence, the processing station detects one less TOA from receiver two. The processing station decides and changes the zone for the second receiver to a five transmitter zone and is discarded for our study. Another new second moving receiver is picked up to be paired with the first receiver in the six transmitter zone for case three. Therefore due to changes in second receiver, the initialization algorithm is run again as a precaution to find their initial locations even though the first receiver did not undergo any changes and the tracking is continued using those initial values. After reaching a certain point, both the receivers lose signal from the station WVON due to station interruption or other miscellaneous reasons. At this point, even though the signal from WTMJ is weaker, the receivers switch back to WTMJ station in order to sustain six transmitter tracking (case four). In this case due to the effect of the farther transmitter WTMJ, the errors are found to be relatively lower. Once the signal from WVON is received properly again, the receivers switch back to the best six transmitters (case five). In order to study a stationary receiver close to the city, a stationary receiver located in Chicago downtown region is paired with the first receiver. Here, the first receiver is in the seven transmitter zone, whereas second receiver is in a six transmitter zone, but they receive the same set of transmitter signals. After obtaining localization results on a stationary receiver for sufficient time, the second receiver
which is stationary is shut down. Once the stationary receiver is shut down, a circular arc is chosen as the route for a second receiver in Lake Michigan (case six).

![Figure 5.4](image1)

**Figure 5.4 Localization Result of Receiver two on a Circular Track (All axes are in kilometer)**

The tracking result of receiver two in a circular arc is shown in Figure 5.4. The figure shows quite accurate tracking results even for a curvier track.

![Figure 5.5](image2)

**Figure 5.5 Five Transmitter Localization Result (All axes are in kilometers.)**
The first receiver loses WTMJ completely and hence travels out of the seven transmitter zone into the six transmitter zone. Since the transmitter set is the same for both the zones, no significant changes take place.

While tracking continues in case seven, the first receiver loses the weakest WMBI signal due to blockage from tall buildings in downtown region. At this point, the localization is forced to happen in a five transmitter system in both the receivers to study the effect clearly (case eight). Figure 5.4 also shows the difference in tracking for the second receiver when there are only five transmitters. Figure 5.5 shows tracking result of the first receiver in a five transmitter system.

Once the first receiver receives the previously lost WMBI radio signal again, the system goes back to a six transmitter network (case nine).

The errors seem to be the largest in this case. The large error could be related to the smaller distances between the two receivers and also to the geometry of the transmitters and receivers. Both first and second receivers are tracked till the first receiver comes to a stop and stays stationary for a while. The tracking results of route two using six transmitter system generally shows an accurate prediction and tracks the receivers within a lane.

<table>
<thead>
<tr>
<th>Table 5.4 Simulation Parameters and Results of Route Two</th>
<th>Route two (Six Transmitter zones only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route</td>
<td>Route two (Six Transmitter zones only)</td>
</tr>
<tr>
<td>Distance</td>
<td>45.56 km</td>
</tr>
<tr>
<td>Receiver Velocity</td>
<td>0-96.56 km/h</td>
</tr>
<tr>
<td>Sampling Freq</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Update Rate</td>
<td>Approx 5.8x10^{-3} s</td>
</tr>
<tr>
<td>Time Averaging Window</td>
<td>1 s</td>
</tr>
<tr>
<td>Maximum Error</td>
<td>12.9431 m</td>
</tr>
<tr>
<td>RMS Error</td>
<td>1.0435 m</td>
</tr>
</tbody>
</table>
Table 5.4 shows that the RMS error for route two is only 1.04 m, which indicates a very good prediction. But the maximum error of 12.94 m also represents that the localization can vary randomly based on changes in dTDOA which depend on the transmitter-receiver geometry.

![One of the worst situation in 6-Transmitter Localization](image)

**Figure 5.6 One of the worst Situations in a Six Transmitter Tracking (All axes are in kilometers)**

Under the worst case of dTDOA errors, the system deviates around 13 m as shown in Figure 5.6. In Figure 5.6, it is not clear how much the final tracked location lags the actual location. To make that clear, a video was simulated for tracking and the snapshots of the path are given in Figure 5.7. The video was made for a high velocity receiver traveling at 112.6 km/h to understand the lagging effect due to time averaging. To see the lagging effect clearly, the update rate was reduced by 50 times. Figure 5.7 clearly shows a lag of around 15 m at this velocity for a time averaging window of 1 second. This lag is not a measure of error in the system. It can be inferred to as reaction distance or reaction time of the user. The tracking error of the receiver should not be calculated with the tracked position and the current or latest actual position. Since,
averaging is done over the time averaging window, the actual position corresponding to the time averaged location is at the midpoint of the time averaging window.

Figure 5.7 Video snapshots of Tracking results showing position lag at 50 times reduced update rate. (Axes are in kilometers). ‘o’ is actual location, ‘*’ is final tracked location.
Both RMS errors and maximum errors are calculated between the final time averaged location and the actual position corresponding to the midpoint of the time averaging window. This lag is directly proportional to the velocity of the receiver. In real world conditions, in case of sharp turns, since the velocity of the receiver will be considerably reduced, the lag will also be reduced by the same amount. This lag can be decreased by reducing the velocity of the receiver, reducing the time averaging window or by predicting the receiver position using its previous locations or by Doppler Effect integration.

### 5.4 Analysis of Results

Sampling frequency and time averaging window are the parameters that are in our control. Therefore the effect of sampling frequency and time averaging window are studied in detail here. This will help in choosing the most optimized value for a particular application. Sampling frequency affects both time averaging and curve fitting techniques. Time averaging window affects only the time averaging technique.

The received time domain signal after initial analog processing can be sampled at different rates according to the application and resources available. An increase in sampling rate than required is usually not preferred, since higher sampling rates mean larger correlators, larger and faster data processors and larger shift registers. Thus, it is vital to choose a sampling frequency as small as we can.

Figure 5.8 shows the localization error results for different sampling rates under different circumstances. The effects on both curve fitting and time averaging can be studied from this single plot. Simulations were run for different sampling rates on routes one and two and the maximum of the localization error between route one five transmitter network and route two six
transmitter network is plotted in this figure. Four different circumstances were considered.
Simulation with no curve fitting and without time averaging shows the error from the raw localization data. Here, the TOA error is half of the sampling interval. The dTDOA localization method clearly seems to amplify the TOA error many times to give a huge error of more than one kilometer for sampling frequencies lesser than 10MHz. When these raw data are time averaged, the localization error decreases from approximately three times at 1.1MHz to ten times at 90 MHz. Under this situation, by just using time averaging technique, we would need a sampling frequency at least 90MHz to achieve a localization error below 25m.

![Figure 5.8 Effect of Curve Fitting and Time Averaging on Localization Error at different Sampling Frequencies on a Logarithmic Scale.](image)

Curve fitting technique eliminates the need for such high sampling frequencies. TOA error due to sampling interval is large and is quite regular, whereas TOA error due to curve fitting is very chaotic or random. Thus it is difficult to compare the pattern of localization error with curve
fitting and without curve fitting data. But, the plot clearly shows that effect of curve fitting (dark blue) on the localization accuracy is more than the effect of time averaging (brown).

When the curve fitting and time averaging techniques were combined (red), we noticed a dramatic increase in accuracy compared to the raw localization result (light blue). Comparing the data shown in the plot, the error in the combined navigation system is 200 times lesser than the raw prediction data. Thus by utilizing the effects of curve fitting and time averaging we have managed to achieve 13m accuracy at a sampling rate of 10MHz. All the simulations on different sampling intervals are done with a time averaging window of 1 second. So to achieve reasonable localization accuracy, a sampling frequency of at least 10 MHz is required. Time averaging window is the most important factor that controls the accuracy of the time averaging technique. We expect that the accuracy would increase as we keep increasing the time averaging window, but this would result in a decrease in the reaction time of the user. Velocity of the receiver is one of the limiting factors in the choice of time averaging window. A faster receiver would have lesser distance to react than a slower moving receiver. To realize the real world conditions, we calculate that for a receiver traveling at a maximum speed of 145 km/h, a time averaging window of 1 second can be converted to 20.14 meters of tracking lag. For a user travelling at 145 km/h, 20 meters is a reasonable tracking lag to react. Thus, the time averaging window also determines the velocity restriction on the application.

Simulations on routes one and two are run with different time averaging windows to understand the accuracy of the system. Simulation results of one of the stationary receivers in route two is shown in Figure 5.9
The tracked locations shown in the Figure 5.9 are the localization results before time averaging and it shows a large error of around ±100 m. These tracked locations are not fit to be used for navigation. Therefore we try to reduce the error using the time averaging technique. Figure 5.9 shows that time averaging technique increases the accuracy tremendously. As the time averaging window is increased, the time averaging error clearly decreases. Therefore by choosing higher time averaging window the error in localization can definitely be reduced. We also notice that the time averaging result does not increase much after a time averaging window of 1 second (red) in Figure 5.9. Simulation results of route one for different time averaging windows of a moving receiver are shown in Figure 5.10.
Figure 5.10 Route One Localization Error for Different Time Averaging Window

Figure 5.10 shows that both maximum localization error and the RMS localization error decreases as the time averaging window increases. But, the functional relation is clearly not linear. The required time averaging window seems to exponentially increase as the error requirement decreases. For navigation purpose any time averaging window above 0.25s seems to be good, since the maximum error is only around 20m. We also notice that the RMS error is lesser than 4m even for 0.25s time averaging window which is quite exceptional for a five transmitter system.

Simulation results of route two for different time averaging windows of a moving receiver are shown in the Figure 5.11 which shows a very similar pattern compared to route one. Figure 5.11 shows that for five transmitter and six transmitter systems, the time averaging window has the same effect as route one. As the time averaging window is increased both the maximum and RMS errors decrease, but it saturates for higher time averaging windows.
Therefore, according to the application requirement, we may choose the desired time averaging window. Considering the reaction time, for any real-time applications like navigation, a time averaging window of around 1 second is recommended.

As discussed in Section 4.3.1, the disadvantage of a higher time averaging window is that the user’s reaction time to the guidance of the navigation system decreases. It is possible to reduce this reaction by predicting the movement of the receiver using velocity measurements. Velocity of the receivers can be measured using Doppler shifts or simply using the previously tracked positions. The number of points for averaging within a time averaging window depends on the Doppler Effect as well. If the receiver moves towards a transmitter, the receiver receives the signal at a faster rate and if the receiver moves away from a transmitter, it will receive the signal at a relatively slower rate. Since we need TOAs from all the transmitters, we take the slowest rate among different transmitters as the update frequency for that instant. Update rate of the system is ideally the same as the correlation frequency. Doppler Effect has very little effect on the update rate since the receiver velocities are not very large. However prediction based on
previous location estimates will have a much more significant effect on improving the accuracy of a moving receiver.

5.4.1 Five Transmitter vs. Six Transmitter

Figure 5.11 for route two, clearly shows that as expected six transmitter system localizes the receivers with much more precision than a five transmitter system. This is well in accordance with the theory of non-linear simultaneous equations.

Even though a six transmitter over-determined system is more robust and is expected to perform better than five transmitters, results show a decrease in maximum error in the five transmitter system in route one compared to six transmitter system. Table 5.5 compares the results of routes one and two for a time averaging window of 1 second and sampling frequency of 10 MHz.

| Table 5.5 Comparison of the Localization Error Performance of a Five Transmitter and Six Transmitter Systems |
|-------------------------------------------------|-----------------|-----------------|-----------------|
| Error for different routes                      | Route one       | Route two       | Route two       |
|                                                | Five Transmitter| Six Transmitter | Five Transmitter|
| Route Length                                   | 24507 m         | 45634 m         | 622.6 m         |
| Maximum Error                                  | 10.2311 m       | 12.9431 m       | 20.0462 m       |
| RMS Error                                      | 1.9419 m        | 1.0435 m        | 6.1271 m        |

Interesting observation made here is that the maximum error for a five transmitter system in route one is lesser than the six transmitter system in route two. But, when the RMS errors are compared, the six transmitter still seems to work better than a five transmitter system. Also, compared to the five transmitter system from route two, six transmitter system clearly has a huge
advantage. The reason for lesser error in route one of five transmitter system is explained as follows.

The smaller five transmitter travel zone in route one is far away from the transmitters in the city, whereas the six transmitter zone in route two is very close to the transmitters in the city. In addition, the second receiver in route one is far apart from the tracked receiver compared with that of route two. Therefore, in the dTDOA equations, the distances in route two are much smaller than those in route one. Since the TOA measurement errors are the same, we can reasonably assume that this same amount of measurement errors in dTDOA equations would result in the same relative errors in their solutions. But the same relative errors in location solutions with larger distances would result in smaller location errors, and vice versa. This is also manifested in the fact that the routes near the transmitters in the city show more chaotic behavior as shown in Figure 5.5 and Figure 5.6 whereas the routes that are far away from the transmitters outside the city show a very smooth and regular localization result. This effect can also be noticed in the simulation of two stationary receivers. Figure 4.5 shows tracked locations of a stationary receiver that is away from the city with a location error of ± 20m. Figure 5.9 shows tracked locations of a stationary receiver that is in the city with a location error of ± 100m. This tells us that we should set the two receivers apart as much as possible, and that we should use transmitters as far away as possible to improve accuracy. Despite this, the lesser route length and higher RMS error for route one compared to the six transmitter system in route two is the indication that a six transmitter system is still better than a five transmitter system.
Chapter 6 Conclusion and Scope for Future Work

This chapter summarizes the methods, information and results provided in the previous chapters to justify that digital AM radio can be used for navigation.

6.1 Conclusion

The signal format of the digital AM radio, its configuration, and its transmission was explained in Chapter 1. Sampling the received signal at higher sampling rates does not help much in improving the system accuracy due to the inherent nature of the digital AM signal of longer symbol duration. The maximum error obtained after signal matching using correlation was found to be half of the sampling interval. Since this kind of accuracy is undesirable, there was a need to resort to a method which can improve the accuracy of digital AM despite of its narrow bandwidth nature. The technique of curve fitting was used to fit curves near the correlation peak samples and it was found that the TOA error due to curve fitting was at least ten times lesser than the error due to sampling interval. The TOA of the signal was simulated and simulations were run for different levels of SNR in the received signal. However, it was found that even for a low level of SNR of 10dB, the estimation error of TOA varied only slightly. The method of dTDOA is applied to find the location of receivers. A set of nonlinear equations in terms of locations are formed. The locations were solved using the Levenberg-Marquardt algorithm. However, the initialization of the system of nonlinear equations posed a problem. After analyzing various methods, a new technique called error feedback mechanism using Levenberg-Marquardt...
algorithm was devised which solved the initialization problem accurately within a few iterations. After initialization, the problem of localization was addressed. Many cases were considered for the purpose of simulation like zone change, lost signal reception, simulating stationary & moving receivers etc. It was found that the localization error amplified when the TOA error was fed into the system of nonlinear equations using dTDOA method. To reduce the localization error, time averaging was performed on all the predicted locations. It was found from simulations that a time averaged location was much closer to the actual location. Thus the requirement of sampling the received signal at nearly 100MHz was brought down to 10MHz using curve fitting and time averaging.

The accuracy of a six transmitter system was better than a five transmitter system. However, tracking in a five transmitter system was found, and it is believed true in general, to be better if the receivers were found to be located far away from the transmitters and if the two receivers are set apart far away. The effects of time averaging window were also discussed. The localization accuracy obtained finally was sufficient enough for domestic navigation.

6.2 Future Work

While tracking of a receiver in the five transmitter zone, loss of signal reception by a receiver receiving from any transmitter will result in only four transmitters. This will prevent the receiver in determining its own location, as the dTDOA requires a minimum of five transmitters to localize two receivers. In this case, the receiver would have to move a considerable distance until it starts receiving signal from another transmitter. This is a significant drawback of the dTDOA method. If three receivers are tracked simultaneously, their locations can be found with four transmitters.
We can also alleviate this problem by extending the idea of using reference receivers in GPS to the concept of dTDOA. Of the two receivers required for dTDOA to function, if one of the receiver’s locations is known, the location of the other receiver can be obtained with just three transmitters. This situation can be carried out in any city as there is a ready availability of at least three digital AM transmitters almost everywhere.

Also, by using a reference receiver, the localization can be extended to the third dimension. In a 3-Dimensional localization system, the dTDOA equations need to be solved for an extra variable (height) for the ‘z’ coordinate. Therefore by employing a minimum of four transmitters, the dTDOA equations can be solved for the unknown three variables of an unknown receiver using a known reference receiver. The application for a 3-Dimensional localization system includes local aerial navigation, tall building guidance systems, predicting projectile trajectories, etc. The ability of the digital AM signals to penetrate through buildings can be most utilized in the 3-D system.

One of the major issues dealt with this thesis is the unavailability of transmitters. Since it is a relatively newer technology, very few transmitters are in operation at present. Once this technology gains popularity we can hope that more transmitters and radio stations will come into existence thereby there will be no problem of exploring more transmitters.

Simple threshold detection for multipath signals can be used to record time of arrival. For moving receivers, Doppler shift should also be accounted for while updating locations during tracking. There is a change in the update frequency of the receiver, when it is moving either towards or away from the transmitter. This will affect the time averaging method in our case. However, extensive studies on both multipath and Doppler Effect integration of the system were not conducted and can be a good scope for future work.
The accuracy of the final localization result can still be improved in two ways. Firstly, by predicting the location of the receivers using the receiver velocity and direction of travel of the receiver calculated using the previously known positions or using Doppler Effect integration for higher velocities. Secondly, in a real world application it is not rare for a single receiver to be paired with two or more receivers. In that case, averaging the location results obtained using different pairs of receivers would help further improve the accuracy.

As mentioned in the conclusion, the real world environment may be different from the cases considered here for simulation. An attempt was made to model most of the simulations in this thesis and the number of Floating Point Operations per second (FLOPS) was approximately calculated for 10MHz sampling frequency. This FLOPS is given in Table 6.1. The challenge would be implementing this setup on hardware and put it into practice.

<table>
<thead>
<tr>
<th>Receiver Operations</th>
<th>FLOPS per Transmitter</th>
<th>Update (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polynomial Fit Left</td>
<td>597</td>
<td>5.8</td>
</tr>
<tr>
<td>Polynomial Fit Right</td>
<td>597</td>
<td>5.8</td>
</tr>
<tr>
<td>Solving the two polynomials</td>
<td>252</td>
<td>5.8</td>
</tr>
<tr>
<td>Coarse correlation peak search</td>
<td>4</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Correlation</td>
<td>&lt; 2 million</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td><strong>Processing station</strong></td>
<td><strong>FLOPS</strong></td>
<td>Update (ms)</td>
</tr>
<tr>
<td>dTDOA</td>
<td>15</td>
<td>5.8</td>
</tr>
<tr>
<td>Initial estimate</td>
<td>approx 62632 to 187896</td>
<td>only for initial estimate</td>
</tr>
<tr>
<td>Localization</td>
<td>&lt; 40000</td>
<td>5.8</td>
</tr>
<tr>
<td>Time averaging</td>
<td>&lt; 2000</td>
<td>5.8</td>
</tr>
</tbody>
</table>
References


