CHAPTER - 3

WIRELESS LOCATIONS FOR OFDM BASED SYSTEMS

3.1 INTRODUCTION

Wireless networks are primarily designed and deployed for voice and data communications. The widespread availability of wireless nodes, however, makes it feasible to utilize these networks for wireless location purpose as an alternative to the GPS (Global Positioning Systems) location service. The commercially available location technology is implemented on cellular networks and WLAN, such as E911 (Enhanced 911) and indoor position with Wi-Fi (Wireless Fidelity). In this dissertation, we are investigating wireless location technology aimed at a different network, i.e., WiMax (Worldwide Interoperability for Microwave Access) system.

3.2. OVERVIEW AND ANALYSIS OF MIMO OFDM FOR WIRELESS LAN

The early OFDM schemes required banks of sinusoidal subcarrier generators and demodulators, which imposed a high implementation complexity. This drawback limited the application of OFDM to military systems until 1971, when Weinstein and Ebert suggested that the Discrete Fourier Transform (DFT) can be used for the OFDM modulation and demodulation processes, which significantly reduces the implementation complexity of OFDM. Exploitation reduced complexity algorithms for achieving a significantly lower computational complexity than that of classic single-carrier time-
domain Quadrature Amplitude Modulation (QAM) modems. OFDM has some key advantages over other widely-used wireless access techniques, such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). The main merit of OFDM is the fact that the radio channel is divided into many narrow-band, low-rate, frequency-nonselective subchannels or subcarriers, so that multiple symbols can be transmitted in parallel, while maintaining a high spectral efficiency. Each subcarrier may deliver information for a different user, resulting in a simple multiple access scheme known as Orthogonal Frequency Division Multiple Access (OFDMA). This enables different media such as video, graphics, speech, text, or other data to be transmitted within the same radio link, depending on the specific types of services and their Quality-of-Service (QoS) requirements. Furthermore, in OFDM systems different modulation schemes can be employed for different subcarriers or even for different users.

For example, the users close to the Base Station (BS) may have a relatively good channel quality, thus they can use high-order modulation schemes to increase their data rates. By contrast, for those users that are far from the BS or are serviced in highly-loaded urban areas, where the subcarriers’ quality is expected to be poor, low-order modulation schemes can be invoked.

Besides its implementation flexibility, the low complexity required in transmission and receptions as well as the attainable high performance render OFDM a highly attractive candidate for high data rate communications over time varying
frequency-selective radio channels. For example, in classic single-carrier systems, complex equalizers have to be employed at the receiver for the sake of mitigating the Inter-Symbol Interference (ISI) introduced by multipath propagation. By contrast, when using a cyclic prefix, OFDM exhibits a high resilience against the ISI. Incorporating channel coding techniques into OFDM systems, which results in Coded OFDM (COFDM), allows us to maintain robustness against frequency-selective fading channels, where busty errors are encountered at specific subcarriers in the FD.

However, besides its significant advantages, OFDM also has a few disadvantages. One problem is the associated increased Peak-to-Average Power Ratio (PAPR) in comparison to single-carrier systems, requiring a large linear range for the OFDM transmitter’s output amplifier. In addition, OFDM is sensitive to carrier frequency offset, resulting in Inter-Carrier Interference (ICI). As a summary of this section, we outline the milestones and the main contributions found in the OFDM literature in Table 3.1.

High data-rate wireless communications have attracted significant interest and constitute a substantial research challenge in the context of the emerging WLANs and other indoor multimedia networks. Specifically, the employment of multiple antennas at both the transmitter and the receiver, which is widely referred to as the Multiple-Input Multiple-Output (MIMO) technique, constitutes a cost-effective approach to high-throughput wireless communications. In 1996, Rayleigh and Foschini proposed new approaches for improving the efficiency of MIMO systems, which inspired numerous further contributions.
<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>Chang</td>
<td>Proposed the first OFDM scheme</td>
</tr>
<tr>
<td>1967</td>
<td>Saltzberg</td>
<td>Studied a multi carrier system employing O-QAM</td>
</tr>
<tr>
<td>1968</td>
<td>Chang and Gibby</td>
<td>Presented a theoretical analysis of the performance of an orthogonal multiplexing data transmission scheme</td>
</tr>
<tr>
<td>1970</td>
<td>Chang</td>
<td>U.S. patent on OFDM issued</td>
</tr>
<tr>
<td>1971</td>
<td>Weinstein and Ebert</td>
<td>Applied DFT to OFDM Modems</td>
</tr>
<tr>
<td>1980</td>
<td>Keasler</td>
<td>Invented an OFDM Modem for telephone networks</td>
</tr>
<tr>
<td>1981</td>
<td>Hirosaki</td>
<td>Suggested a DFT based implementation of OFDM systems</td>
</tr>
<tr>
<td>1985</td>
<td>Cimini</td>
<td>Investigated the feasibility of OFDM in mobile communication</td>
</tr>
<tr>
<td>1986</td>
<td>Hirosaki, Hasegawa and Sabato</td>
<td>Developed a Group band data modem using an Orthogonally multiplexed QAM technique</td>
</tr>
<tr>
<td>1987</td>
<td>Alard and Lasalle</td>
<td>Employed OFDM for digital broadcasting</td>
</tr>
<tr>
<td>1989</td>
<td>Kalet</td>
<td>Analyzed multitone QAM modems in Linear Channels</td>
</tr>
<tr>
<td>1990</td>
<td>Bingham</td>
<td>Discussed various aspects of OFDM techniques in depth</td>
</tr>
<tr>
<td>1991</td>
<td>Cioffi</td>
<td>Introduced the ANSI ADSI standard</td>
</tr>
<tr>
<td>1997</td>
<td>Li and Cimini</td>
<td>Revealed how clipping and filtering effect OFDM systems</td>
</tr>
<tr>
<td>1998</td>
<td>Li, Cimini and Sollenberger</td>
<td>Designed a robust Minimum Mean Square Error (MMSE) Based channel Estimator for OFDM Systems</td>
</tr>
<tr>
<td></td>
<td>May, Rohling and Engels</td>
<td>Carried out a performance analysis of Viterbi Decoding in the context of 64 - DAPSK and 64 - QAM modulated OFDM signals</td>
</tr>
<tr>
<td>1999</td>
<td>Li and Sollenberger</td>
<td>Focused on parameter estimation invoked by a MMSE diversity combiner designed for adaptive antenna array aided OFDM</td>
</tr>
<tr>
<td></td>
<td>Armour, Nix and Bull</td>
<td>Illustrated the combined OFDM Equalization aided receiver and the design of Pre - Fast Fourier Transform (FFT) equalizers</td>
</tr>
<tr>
<td></td>
<td>Wong</td>
<td>Advocated a subcarrier, bit and power allocation algorithm to minimize the total transmit power of multi - user OFDM</td>
</tr>
<tr>
<td>2000</td>
<td>Fazel and Fettvis</td>
<td>A collection of state - of - the - art works on OFDM</td>
</tr>
<tr>
<td></td>
<td>Van Nee and Prasad</td>
<td>OFDM for wireless Multimedia Communications</td>
</tr>
<tr>
<td></td>
<td>Lin, Cimini and Chuang</td>
<td>Invoked Turbo coding in an OFDM system using diversity</td>
</tr>
<tr>
<td>2002</td>
<td>Lu and Wang</td>
<td>Considered channel coded STC - assisted OFDM systems</td>
</tr>
<tr>
<td>2003</td>
<td>Hanzo, Munster, Choi and Keller</td>
<td>OFDM for broadband multi - user communications, WLANs and broadcasting</td>
</tr>
<tr>
<td>2004</td>
<td>Simeone, Bar- Ness and Spagnolini</td>
<td>Demonstrated a sub space tracking algorithm used for channel estimation in OFDM systems</td>
</tr>
<tr>
<td></td>
<td>J.Zhang, Rohling and P.Zhang</td>
<td>Adopted an Inter - Carrier Interference(ICI) cancellation scheme to combat the ICI in OFDM Systems</td>
</tr>
<tr>
<td></td>
<td>Necker and Stuber</td>
<td>Exploited a blind channel estimation scheme based on the Maximum Likelihood(ML) principle in OFDM system</td>
</tr>
<tr>
<td></td>
<td>Doufexi</td>
<td>Reflected the benefits of using sectorized antennas in WLANs</td>
</tr>
<tr>
<td></td>
<td>Alsusa, Lee and Mc Laughlin</td>
<td>Proposed packet based multi-user OFDM systems using adaptive subcarrier - user allocation</td>
</tr>
<tr>
<td>2005</td>
<td>Williams</td>
<td>Evaluated a Pre - FFT synchronization method for OFDM</td>
</tr>
<tr>
<td>2007</td>
<td>Fischer and Siegl</td>
<td>Multi-user MIMO-OFDM for next - generation wireless</td>
</tr>
<tr>
<td></td>
<td>Hanzo and Choi</td>
<td>Adaptive HSDPA - style OFDM and MC-CDMA Transceivers</td>
</tr>
<tr>
<td>2009</td>
<td>Fischer and Siegl</td>
<td>Peak - to - Average Power ratio reduction in single - and multi - antenna OFDM</td>
</tr>
<tr>
<td></td>
<td>Mileoumis</td>
<td>Blind identification of Hammerstein channels using QAM , PSK and OFDM inputs</td>
</tr>
<tr>
<td></td>
<td>Huang and H wang</td>
<td>Improvement of active interference cancellation: avoidance technique for OFDM cognitive radio</td>
</tr>
<tr>
<td></td>
<td>Chen</td>
<td>Spectrum sensing for OFDM systems employing pilot tones</td>
</tr>
<tr>
<td></td>
<td>Talbot and Farhiang - Boroujeny</td>
<td>Time - varying carrier offsets in mobile OFDM</td>
</tr>
</tbody>
</table>
As a key building block of next-generation wireless communication systems, MIMOs are capable of supporting significantly higher data rates than the Universal Mobile Telecommunications System (UMTS) and the High Speed Downlink Packet Access (HSDPA) based 3G networks. As indicated by the terminology, a MIMO system employs multiple transmitter and receiver antennas for delivering parallel data streams, as illustrated in Figure 3.1. Since the information is transmitted through different paths, a MIMO system is capable of exploiting transmitter and receiver diversity, hence maintaining reliable communications.

Figure 3.1 Schematic of the generic MIMO system employing $M$ transmitter antennas and $N$ receiver antennas
3.3. CHANNEL ESTIMATION FOR MULTICARRIER SYSTEMS

The ever-increasing demand for high data-rates in wireless networks requires the efficient utilization of the limited bandwidth available, while supporting a high grade of mobility in diverse propagation environments. Orthogonal Frequency Division Multiplexing (OFDM) and Multi-Carrier Code Division Multiple Access (MC-CDMA) techniques are capable of satisfying these requirements. This is a benefit of their ability to cope with highly time variant wireless channel characteristics. However, as pointed out in the capacity and the achievable integrity of communication systems are highly dependent on the system’s knowledge concerning the channel conditions encountered. Thus, the provision of an accurate and robust channel estimation strategy is a crucial factor in achieving a high performance. Well-documented approaches to the problem of channel estimation are constituted by pilot assisted, decision directed and blind channel estimation methods. The family of pilot assisted channel estimation methods was investigated, for example by Li, Morelli and Mengali, Yang et al. as well as Chang and Su, where the channel parameters are typically estimated by exploiting the channel-sounding signal. Standardized video frame dimensions and applications given in table 3.2 However, the bit rates are tremendous and hence the provision of DVB-H services to our mobiles seemed unthinkable until very recently. Yet, it has its commercial applications by now. Even a system with tiny little pictures, like a (176 x 144)-pixel system, would require nearly 1 Megabyte/sec transmission speed, if it is uncompressed, so compression is extremely important.
Table 3.2: Standardized video frame dimensions and their Typical Applications

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Dimension</th>
<th>Pixel/sec at 30f/s</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-QCIF</td>
<td>128x96</td>
<td>0.37M</td>
<td>Hand held Mobile video</td>
</tr>
<tr>
<td>QCIF</td>
<td>176x144</td>
<td>0.76M</td>
<td>Video Conference via Public Phone Network</td>
</tr>
<tr>
<td>CIF</td>
<td>352x288</td>
<td>3.04M</td>
<td>Consumer Tape Equivalent</td>
</tr>
<tr>
<td>CCIR601</td>
<td>720x480</td>
<td>10.40M</td>
<td>TV</td>
</tr>
<tr>
<td>HDTV1440</td>
<td>1440x960</td>
<td>47.0M</td>
<td>Consumer HDTV</td>
</tr>
<tr>
<td>HDTV</td>
<td>1920x1080</td>
<td>62.70M</td>
<td>Studio HDTV</td>
</tr>
</tbody>
</table>

3.4. MIMO – OFDM SYSTEM DESCRIPTION

The block diagram of a MIMO-OFDM system [40.45] is shown in figure 3.2. Basically the MIMO –OFDM transmitter has $N_t$ Parallel transmission paths which are very similar to the single antenna OFDM system, each branch preferring, serial to parallel conversion, $N$ point IFFT cyclic extension before the final Tx signals are up converted to RF and Transmitted. It is worth noting that the channel encoder and the digital modulation, in some spatial multiplexing systems [40, 46], can also be done per branch, not necessarily implemented jointly over all the $N_t$ branches.

The receiver first must estimate and correct the possible symbol timing error and frequency offsets, e.g., by using some training symbols in the preamble as standardized in
Subsequently, the CP is removed and N-point FFT is performed per receiver branch. In channel estimation algorithm we proposed is based on single carrier processing that implies MIMO detection that has to be done per OFDM subcarrier. Therefore, the received signals of subcarrier K are routed to the Kth MIMO detector to recover all the Nt data signals transmitted to that subcarrier.

Figure 3.2: N_t x N_r MIMO-OFDM System Model
3.4.1 Signal Model

There is $N_t$ transmit antennas and hence on each of the $N$ subscribers, $N_t$ modulated signals and transmitted simultaneously. Denote $S(m)$ and $S(mN+k)$ as the $m^{th}$ modulated OFDM symbol in frequency domain and the $k^{th}$ modulated subcarrier respectively as:

$$
\begin{align*}
\tilde{S}(m) &= \begin{bmatrix} 
\tilde{S}(mN) \\
\vdots \\
\tilde{S}(mN + N - 1) 
\end{bmatrix} \\
\tilde{S}(mN+k) &= \begin{bmatrix} 
S_1(mN+k) \\
\vdots \\
S_{N_t}(mN+k) 
\end{bmatrix}
\end{align*}
$$

(3.1)

Where $S_j(mN+k)$ represents the $k^{th}$ modulated subcarrier for the $m^{th}$ OFDM symbol transmitted by the $j^{th}$ antenna. And it is normalized by a normalization factor $K_{MOD}$ so that there is a unit normalized average power for all the mappings. Taking IFFT of $S(m)$ as a baseband modulation, the resulting time domain samples can be expressed as

$$
\begin{align*}
\tilde{S}(m) &= \begin{bmatrix} 
\tilde{S}(mN) \\
\vdots \\
\tilde{S}(mN + N - 1) 
\end{bmatrix} \\
\tilde{S}(mN+n) &= \begin{bmatrix} 
S_1(mN+n) \\
\vdots \\
S_{N_t}(mN+n) 
\end{bmatrix}
\end{align*}
$$

(3.2)

$$
\tilde{S}(m) = \frac{1}{N} \left( P_N^{ij} \otimes I_{N_t} \right) \tilde{S}(m)
$$

For MIMO OFDM channel estimation, we need, at least, $N_t$ disjoint sets of pilots-tones indexed by $\{p_1, p_2, \ldots, p_{N_t}\}$. It is assumed that $N= ML$ and hence there are totally $M=N/L$
different sets. It indicates a constraint imposed on the selection of FFT size $N$ for MIMO system i.e $N \geq N_t L$. This observation tallies with the result in[16]. In practice, the selection of $N$ determines the number of subscribers utilized in the system. For systems like WLAN and WiMax [47,48], $N$ is not very large because a larger $N$ means narrower subscriber spacing which may cause severe ICI. Furthermore, those systems often operate in a low SNR environment.

### 3.4.2. LS Channel Estimation

Assume that we have $N_t$ disjoint sets of pilot-tones. Then we have the following observation equations

$$
\tilde{Y}^{(P_1)}(m) = S^{(P_1)}_{diag,1}(m) F_{LNr} W_N^{(P_1)} h_m(:,1) + \ldots + S^{(P_1)}_{diag,N_t}(m) F_{LNr} W_N^{(P_1)} h_m(:,N_t) + \tilde{V}^{(P_1)}(m)
$$

$$
\vdots
$$

$$
\tilde{Y}^{(P_{N_t})}(m) = S^{(P_{N_t})}_{diag,1}(m) F_{LNr} W_N^{(P_{N_t})} h_m(:,1) + \ldots + S^{(P_{N_t})}_{diag,N_t}(m) F_{LNr} W_N^{(P_{N_t})} h_m(:,N_t) + \tilde{V}^{(P_{N_t})}(m)
$$

(3.3)

To use LS (Least square) method for channel estimation, we usually put those observation equations into a matrix form. LS is well known method and widely used for estimation. We choose LS rather than other methods like MMSE channel estimation for simplicity implementation. In a matrix form, it is described by

$$
\tilde{Y}^{(P)}(m) = S^{(P)}(m) \tilde{h}_C(m) + \tilde{V}^{(P)}(m)
$$

(3.4)
Where

\[
\tilde{\mathbf{Y}}^{(P)}(m) = \begin{bmatrix}
\tilde{\mathbf{Y}}^{(P_1)}(m) \\
\vdots \\
\vdots \\
\tilde{\mathbf{Y}}^{(P_{N_T})}(m)
\end{bmatrix};
\tilde{\mathbf{h}}_C(m) = \begin{bmatrix}
h_m(:,1) \\
\vdots \\
h_m(:,N_t)
\end{bmatrix};
\tilde{\mathbf{v}}^{(P)}(m) = \begin{bmatrix}
\tilde{\mathbf{v}}^{(P_1)}(m) \\
\vdots \\
\tilde{\mathbf{v}}^{(P_{N_T})}(m)
\end{bmatrix}
\]

and

\[
\mathbf{S}^{(P)}(m) = \begin{bmatrix}
S_{\text{diag}, 1}^{(P_1)}(m) F_{LN_r} W_N^{(P_1)} & \cdots & S_{\text{diag}, N_t}^{(P_1)}(m) F_{LN_r} W_N^{(P_1)} \\
\vdots & \ddots & \vdots \\
S_{\text{diag}, 1}^{(P_{N_t})}(m) F_{LN_r} W_N^{(P_{N_t})} & \cdots & S_{\text{diag}, N_t}^{(P_{N_t})}(m) F_{LN_r} W_N^{(P_{N_t})}
\end{bmatrix}
\]

In the above expression, \( \mathbf{S}^{(p)}(m) \) is an \( N_t N_t L \times N_t N_t L \) square matrix, composed of \( N_t^2 \) pilot-tone block matrices \( \{ \mathbf{S}_{\text{diag}, j}^{(p_i)}(m) \} \), \( j = 1 \). At each transmit antenna \( N_t \) sets of pilot tones are transmitted with the same index \( \{ p_1, p_2, \ldots, p_{N_t} \} \).

The standard solution to the LS channel estimates (49) is known as

\[
\tilde{\mathbf{h}}_{C, \text{LS}}(m) = \left[ (\mathbf{S}^{(P)}(m))^H \mathbf{S}^{(P)}(m) \right]^{-1} (\mathbf{S}^{(P)}(m))^H \tilde{\mathbf{Y}}^{(P)}(m)
\]

(3.5)

### 3.5. WI-FI

In 1999, the Wi-Fi Alliance was founded as a global, non-profit organization, aiming for developing a single globally accepted standard for high-speed WLANs. The mission of the Wi-Fi Alliance was to promote the Wi-Fi technology and the corresponding Wi-Fi product certification. The Wi-Fi Alliance has now more than 300 members from more than 20 countries and Wi-Fi have achieved a huge worldwide success. A study released in September 2008 by the Wi-Fi Alliance found that an increased number of consumers in the United States, the United Kingdom and Japan
value the Wi-Fi Certified brand. Developed in March 2000, the certification program has approved more than 4,800 products from various vendors worldwide.

3.6. WIMAX EVOLUTION

The rapidly growing demand for flexible, high-speed broadband services requires advanced communication technologies. The more conventional family of high-rate broadband access techniques has relied on wired access, such as Digital Subscriber Line (DSL), cable modems, Ethernet and optical fibers. However, the extension of the coverage area results in a significantly increased cost imposed by building and maintaining wired networks. This is particularly true for less densely populated zones, for example suburban and rural areas.

Hence, Broadband Wireless Access (BWA) techniques have emerged as potent competitors of their conventional wired counterparts, facilitating the provision of broadband services for subscribers that are far from the coverage area of the wired networks. Being flexible, efficient and cost-effective, BWA provides an excellent solution to overcome the above-mentioned coverage problem. During the past decade or so, a number of proprietary wireless access systems have been developed by the wireless industry. Naturally, these proprietary products were based on diverse specifications, which inevitably limited their applications and markets. As a matter of fact, the potential benefits of BWA services were not expected to be widely achieved due to the lack of a
common international standard, until the emergence of the Worldwide Interoperability for Microwave Access (WiMAX) standard.

WiMAX is one of the most popular BWA technologies available at the time of writing, aiming to provide high speed broadband wireless access for Wireless Metropolitan Area Networks (WMANs). As a standardized technology, WiMAX ensures the inter-operability of equipment certified by the WiMAX Forum, resulting in a significant cost reduction for service providers that would like to use products manufactured by diverse vendors. This distinct advantage has paved the way for global broadband wireless services. Another key benefit of WiMAX is that it has been optimized for offering excellent Non-Line-of-Sight (NLOS) coverage with the aid of advanced wireless transmission techniques, such as Multiple-Input Multiple-Output (MIMO) transmit/receive diversity and Automatic Re-transmission Request (ARQ), etc, combined with Orthogonal Frequency Division Multiplexing (OFDM) or Orthogonal Frequency Division Multiple Access (OFDMA).

### 3.6.1 Overview to Wireless Location System

Wireless location refers to determination of the geographic coordinates, or even the velocity and the heading in a more general sense, of a mobile user/device in a cellular, WLAN or GPS environments. Usually wireless location technologies fall into two main categories: handset-based and network-based. In handset-based location systems [50], the mobile station equipped with extra electronics determines its location from signals
received from the base stations or from the GPS satellites. In GPS-based estimations, the MS (mobile station) receives and measures the signal parameters from at least four satellites of a currently existing constellation of 24 GPS satellites. The parameter of which the MS measures is the time for each satellite signal to reach the MS. GPS systems have a relatively higher degree of accuracy and they also provide global location information. However, embedding a GPS receiver into mobile devices leads to increased cost, size and battery consumption. It also requires the replacement of millions of mobile handsets that are already in the market with new GPS-featured handsets. In addition, the accuracy of GPS measurements degrades in urban and indoor environments. For these reasons, some wireless carriers may be unwilling to embrace GPS fully as the only location technology.

On the other hand, network-based location technology relies on the ever existing network infrastructures to determine the position of a mobile user by measuring its signal parameters when received at the network BSs (base stations). This may require some hardware upgrade or installation at the BSs, but the cost can be shared by a huge number of mobile subscribers and it does not affect the users in using their mobile devices. In this technology, the BSs measure the signal transmitted from an MS and relay them to a central site for further processing and data fusion to provide an estimate of the MS location. Network-based technologies have the significant advantage that the MS is not involved in the location finding process; thus the technology does not require modifications to existing handsets. However, unlike GPS location systems, many aspects of network-based location are not yet fully studied. In Figure 3.3, network-based wireless
location technology is illustrated. Network-based wireless location technology gains more recognition with the increasing number of wireless subscribers and the demands for some location-oriented services such as E911. It is estimated [51, 52] that location based service will generate annual revenues in the order of $15B worldwide. In U.S. alone, about 170 million mobile subscribers are expected to become covered by the FCC mandated location accuracy for emergency services. The following is a partial list of applications that will be enhanced by using wireless location information [53].

- **E911.** Nowadays a high percentage of E911 calls are generated from mobile phones; the percentage is estimated [54, 55] to be at one third of all 911 calls (170,000 per day). These wireless 911 calls do not receive the same quality of emergency assistance as those fixed-network 911 calls enjoy. This is due to the unknown position of the wireless 911
caller. To fix this problem, FCC issued an order on July 12, 1996 [54], requiring all wireless service providers to report accurate MS location to the E911 operator at the PSAP (public safety answering point). In the FCC order, it was mandated that within five years from the effective date of the order, October 1, 1996, wireless service providers must convey to the PSAP the location of the MS within 100 meters of its actual position for at least 67 percent of all wireless E911 calls. This FCC order has motivated considerable research efforts towards developing accurate wireless location algorithms for cellular networks and has led to significant enhancement to the wireless location technology.

- **Mobile advertising**: Location specific advertising and marketing will benefit once the location information is available. For example, stores would be able to track customer locations and to attract them in by flashing customized coupons on their wireless devices [55]. In addition, a cellular phone or a PDA (personal digital assistant) could act as smart handy mobile yellow pages on demand.

- **Asset tracking (indoor/outdoor)**: Wireless location technology can also assist in advanced public safety applications such as locating and retrieving lost children, patient, or even pets. In addition, it can be used to track personnel/assets in a hospital or a manufacturing site to provide a more efficient management of assets and personnel. One could also consider application such as smart and interactive tour guides, smart shopping guides that lead shoppers based on their location in a store, smart traffic control in parking structures that guides cars to free parking slots. Department stores, enterprises,
hospitals, manufacturing sites, malls, museums, and campuses are some of the potential end-users to benefit from the technology.

- **Fleet management**: Many fleet operators, such as police force, emergency vehicles, and other services including shuttle and taxi companies, can make use of the wireless location technology to track and operate their vehicles in an efficient way in order to minimize the response time. In addition, a large number of drivers on roads and highways carry cellular phones while driving. The wireless location technology can help track these phones, thus transforming them into sources of real-time traffic information that can be used to enhance transportation safety.

- **Location-based wireless security**: New location-based wireless security schemes can be developed to add a level of security to wireless networks against being intercepted or hacked into. By using location information, only people at certain specific areas could access certain files or databases through a WLAN.

- **Location sensitive billing**: Using the location information of wireless users, wireless service providers can offer variable-rate call plans or services that are based on the caller location.

### 3.6.2. Review of Data Fusion Methods

We assume that the location is specified by \((x; y)\) for simplicity. As shown in Figure 3.3, data fusion center is to determine the mobile user location by exploring all the estimated signal parameters from BSs. The most common signal parameters are time, angle and amplitude of arrival of the MS signal. Therefore, different data fusion
algorithms are proposed accordingly. The materials in this section are mainly based on the survey paper in [56].

- **Time:** By combining the estimates of the TOA (time of arrival) of the MS signal when received at the BSs, the MS location can be determined in a wireless network with three or more BSs. It is illustrated in Figure 3.4.

![Figure 3.4: TOA/TDOA data fusion using three BSs](image)

Without loss of generality, the geometric coordinate of BS₁ is assumed to be (0; 0). The location of other BSs are denoted by \((x_k, y_k)\); \(k = 2; 3\). Obviously \(x_1 = y_1 = 0\). Since the radio signal travels at the speed of light \(c = 3 \times 10^8 m/s\), the distance between the MS and \(BS_k\) is given by
Where $t_0$ is the time instant when the MS starts transmitting signal and $t_k$ is the time of arrival of the MS signal at $BS_k$. The distances $\{R_{k,T}\}_{k=1}^3$ can be used to estimate the MS location $(x_T, y_T)$ by solving the following set of equations

$$
R_{1,T}^2 = x_T^2 + y_T^2 \\
R_{2,T}^2 = (x_2 - x_T)^2 + (y_2 - y_T)^2 \\
R_{3,T}^2 = (x_3 - x_T)^2 + (y_3 - y_T)^2
$$

(3.7)

To solve the above over determined nonlinear system of equations, we can reformulate (3.7) into an LS-type presentation by subtracting the first equation from the second and the third equations respectively. Hence the following equation is obtained

$$
R_{2,T}^2 - R_{1,T}^2 = x_2^2 + y_2^2 - 2(x_2x_T + y_2y_T) \\
R_{3,T}^2 - R_{1,T}^2 = x_3^2 + y_3^2 - 2(x_3x_T + y_3y_T)
$$

(3.8)

In a matrix form, it can be rewritten as

$$
\begin{bmatrix}
x_2 & y_2 \\
x_3 & y_3
\end{bmatrix}
\begin{bmatrix}
x_T \\
y_T
\end{bmatrix} = \frac{1}{2}
\begin{bmatrix}
R_{2,T}^2 - (R_{2,T}^2 - R_{1,T}^2) \\
R_{3,T}^2 - (R_{3,T}^2 - R_{1,T}^2)
\end{bmatrix}
$$

(3.9)

Where

$$
R_k = \sqrt{x_k^2 + y_k^2}
$$

is the distance of the base station $BS_k$ to the origin point in the coordinate, and clearly $R_1^2 = 0$. If we have more than three BSs, a compact form can be obtained in a similar way as

$$
\vec{b} = A\vec{\theta};
$$

(3.10)

Where

$$
\vec{b} = \frac{1}{2}
\begin{bmatrix}
R_{2,T}^2 - (R_{2,T}^2 - R_{1,T}^2) \\
R_{3,T}^2 - (R_{3,T}^2 - R_{1,T}^2) \\
R_{4,T}^2 - (R_{4,T}^2 - R_{1,T}^2) \\
\vdots
\end{bmatrix}; \\
A = \begin{bmatrix}
x_2 & y_2 \\
x_3 & y_3 \\
x_4 & y_4 \\
\vdots & \vdots
\end{bmatrix}; \\
\vec{\theta} = \begin{bmatrix}
x_T \\
y_T
\end{bmatrix}
$$
A standard LS estimation of $\theta$ is given by

$$\hat{\theta} = (A^T A)^{-1} A^T \hat{b}$$

(3.11)

Note that $R_{1,T}^2$ is a function of $x_T$ and $y_T$ as defined in eq. 3.7. Hence eq. 3.11 only provides an intermediate solution and the estimates $\hat{x}_T$ and $\hat{y}_T$ can be obtained by solving the resultant quadratic equation. And clearly the TOA data fusion method requires perfect timing between the MS and the BSs since a small offset of a few microseconds between the MS clock and the BS clock will reflect into hundreds of meters of errors in location estimate. But the current wireless network standards only mandate tight timing synchronization among BSs [57]. The accuracy of TOA method is heavily dependent on the timing between BS and MS. There is another alternative of using the TDOA (time difference of arrivals) which help avoid the MS clock synchronization problem. Define the TDOA associated with the base station $BS_k$ as $\Delta t_{k,1} = t_k - t_1$, i.e., the difference between the TOA of the MS signal at the BS $BS_k$ and BS$_1$. Then the difference between $R_{k,T}$ and $R_{1,T}$ can be related to $\Delta t_{k,1}$ as

$$\Delta R_{k,1} = R_{k,T} - R_{1,T}$$

$$= (t_k - t_0) c - (t_1 - t_0) c$$

$$= \Delta t_{k,1} c$$

(3.12)

Clearly it is seen that the possible timing error on the MS clock $t_o$ is canceled out. This insensitivity to $t_o$ gives TDOA method the advantage over TOA. By substituting $R_{k,T}^2 = (R_{1,T} + \Delta R_{k,1})^2$ in eq. 3.7 and rearranging some terms, we can obtain the following LS expression for any number of base stations as

$$R_{1,T} \hat{c} + \hat{d} = A \hat{\theta}$$

(3.13)
Where
\[
\tilde{c} = \begin{bmatrix} -\Delta R_{2,1} \\ -\Delta R_{3,1} \\ -\Delta R_{4,1} \\ \vdots \end{bmatrix} ; \quad \tilde{d} = \frac{1}{2} \begin{bmatrix} R_2^2 - \Delta R_{2,1}^2 \\ R_3^2 - \Delta R_{3,1}^2 \\ R_4^2 - \Delta R_{4,1}^2 \\ \vdots \end{bmatrix}
\]

Notice that \( R_{1,T} = x_T^2 + y_T^2 \) is not known and hence only \( n \) intermediate solution can be obtained from the above LS formulation

\[
\tilde{\theta} = (A^T A)^{-1} A^T ( R_{1,T} \tilde{c} + \tilde{d} )
\]

(3.14)

Since

\[
\|\tilde{\theta}\|^2 = R_{1,T}^2
\]

(3.15)

- **Angle:** The AOA (angle of arrival) can be obtained at a BS by using an antenna array. The direction of arrival of the MS signal can be calculated by measuring the phase difference between the antenna array elements or by measuring the power spectral density across the antenna array in what is known as beam forming [58]. Intuitively, the MS location can be estimated by combining the AOA estimates from two BSs as shown in Figure 3.5. Compared to TOA/TDOA methods, the number of BSs needed for location is relatively smaller and there is no need for timing synchronization between base stations and MS clocks.
However, one disadvantage is that antenna array used at the BS which is not available in 2G systems. It is planned for 3G cellular systems such as UMTS and CDMA2000 [59, 60]. As indicated in Figure 3.4, we have

$$\begin{bmatrix} x_T \\ y_T \end{bmatrix} = \begin{bmatrix} R_{1,T} \cos(\beta_1) \\ R_{1,T} \sin(\beta_1) \end{bmatrix}, \quad \begin{bmatrix} x_T \\ y_T \end{bmatrix} = \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} + \begin{bmatrix} \cos(\beta_2) \\ R_{2,T} \sin(\beta_2) \end{bmatrix}$$  \hspace{1cm} (3.16)

Where

$$R_{2,T} = \sqrt{R_{1,T}^2 + R_2^2 - 2R_{1,T}R_2\cos(\alpha_1 - \beta_1)} = f(\alpha_1, \beta_1, R_{1,T}, R_2)$$

If there are more than two BSs, an LS formulation can be obtained by collecting the relations in (3.16) into single equation as

$$\bar{b} = A\bar{\theta}$$  \hspace{1cm} (3.17)

The LS solution for $\bar{\theta}$ is then

$$\bar{\theta} = (A^T A)^{-1} A^T \bar{b}$$  \hspace{1cm} (3.18)
Since this intermediate solution involves the unknown $R_{1,T}$, we have to utilize the relation in (3.15) to get the positive root of the quadratic equation and then substitute $R_{1,T}$ back to (3.18) for a final solution of $\hat{\theta}$.

- **Amplitude**: Amplitude-based wireless location technology is mainly used in indoor environments where WLAN standards such as 802.11a and 802.11g have been widely adopted. The WLAN connectivity has also become a standard feature for laptop computers and PDAs. As such, there is an increasing interest in utilizing these networks for location purposes to help provide a good coverage for indoor scenario. In 802.11b and 802.11g MAC layer, the information about the signal strength and the signal-to-noise ratio is provided. Hence, a software level location technique could be developed for WLAN networks based on the amplitude of arrival of the MS signal at different access points [30, 31, 32]. Specifically, when an IEEE 802.11 networks operate in the infrastructure mode, there are several APs (access point) and many end users within the network. RF-based systems that use the signal strength for location purposes can monitor the received signal strength from different APs and use the obtained statistics to build a conditional probability distribution network in order to estimate the location of the mobile client. These schemes usually work in two stages. The first stage is the offline training and data gathering phase and the second stage is the location determination phase using the online signal strength measurements. In the training phase, signal strength measurements are used to build an a priori probability distribution of the received signal strength at the mobile user from all APs. Assume there are $Na$ APs in the system and the
radio map is created based on measurements from \( Nu \) user locations. It is illustrated in Figure 3.6.

![Figure 3.6: Magnitude based data fusion in WLAN networks](image)

### 3.7. SUMMARY

In this chapter, an introduction about WiMax networks and its IEEE standard evolution and applications in most aspects is given and the outdoor/indoor wireless location technologies based on measurements of TOA's, TDOA's, AOA's and amplitudes are reviewed. With measurements of TDOA and AOA available, we present a constrained LS type algorithm to estimate the target location. The proposed method is different from the commonly used ML algorithm, though the latter is heavily preferred in some applications for its superior performance. Because of the large number of observation data and the additive measurement noise, maximizing the likelihood function involves a great amount of computational load. Even it does not guarantee that the
optimal estimation can be obtained due to the existence of local minimum. Under the assumption of zero-mean additive Gaussian noise with a very small variance, the location estimation problem is formulated into a quasi-linear form, which is solvable by the LS algorithm. The assumption is usually validated as in [61]. Therefore, our method holds the preferable properties of the ML algorithm in the sense that it approaches the Cramer-Rao bound with a large sample of observation data. More importantly, the computational complexity is reduced by the LS algorithm. As shown in this chapter, the LS algorithm also involves a constraint that $||\hat{\theta}|| = ||R_{1,1}||$. The target location can only be obtained by substituting the intermediate LS solution into the constraint and solving the resultant quadratic equation. It brings complexity back to the solution. Hence the Lagrange multiplier is explored to solve the above constrained LS optimization problem. The simulation results show that our scheme is effective in location estimation.