Time of Arrival Estimation for WLAN Indoor Positioning Systems using Matrix Pencil Super Resolution Algorithm

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Abstract - The accuracy of prediction of time of arrival (TOA) in wireless local area networks (WLAN) is the most important parameter for indoor positioning systems. This paper presents the application of super resolution matrix pencil (MP) algorithm for TOA estimation for indoor positioning application. Also it presents the results of frequency sweep measurements of indoor channel for the WLAN IEEE 801.11 standards (a, b, and g). The simulation and experimental results show that MP can accurately estimate TOA and has superior performance over the Fourier transform technique. Also the computational complexity of the proposed technique is compared with the ESPRIT and root-MUSIC algorithms.

1 Introduction

The positioning systems that are used to track and determine the users have gained increasing interest. A Global Positioning System (GPS) is a typical example which depends on the received signal from multiple satellites. In indoor location systems GPS is not efficient due to obstruction and shielding of satellite signals. Also there are cellular networks base wide area location systems, which are limited by the cell size. In indoor environment, there are many positioning systems based on different technologies such as ultrasound [1], Infrared [2], video surveillance and the systems that depend on received signal strength [3].

For indoor environment indoor Wireless Positioning Systems (WPS) based on WLAN infrastructure have gained great attention in recent years [4][5][6]. A WLAN-based positioning system has advantages over all other indoor positioning systems because it is a part of the existing communication structure and can cover many buildings. The characteristics of radio signal in mobile environments are utilized to predict the location of the mobile unit. The basic characteristics are Received Signal Strength (RSS), Angle of Arrival (AOA) estimation and time of arrival TOA estimation. The disadvantage of the RSS method is the random deviation from mean received signal strength caused by shadowing and small scale channel effect [7]. The AOA requires antenna arrays at each node which increase the complexity of the existing system, as well as, performing worse in multipath environment.

The most important parameter for accurate indoor positioning systems is the time of arrival TOA of the Direct Line of Sight DLOS path [8]. In this case accurate estimation of TOA from received communication signals are required. Indoor multipath interference is the main factor that limits deploying indoor positioning systems, the multipath is sever and complex which leads to inaccurate estimate of the TOA using conventional techniques. Also in systems that have fixed bandwidth it is important to find alternative TOA estimation techniques. Different super resolution techniques such as Estimation of Signal Parameters via Rotational Invariance

Techniques (ESPRIT) and Multiple Signal Classification (MUSIC) have been used for spectral estimation applications. Super resolution techniques are studied in the field of TOA estimation in indoor positioning systems such as multiple signal classification MUSIC [8] and Root-MUSIC [9]. Super resolution techniques can increase time domain resolution but in this case, the complexity of the system implementation also increases. For example MUSIC have a limitation which includes the computational complexity of covariance matrix estimation. The goal of this paper is to efficiently estimate TOA of a direct ray with lower complexity using super resolution matrix pencil MP algorithm [10] based on frequency domain measurements of indoor channel. This paper is organized as follows: Section 2 presents the indoor channel model and the application of the MP algorithm for TOA estimation. Section 3 demonstrates the simulation results. Section 4 demonstrates the experimental measurement system and the prediction results and Section 5 concludes the paper.

2 Multipath Indoor Radio Channel

The complicated indoor radio propagation can be characterized using the baseband complex impulse response which can be expressed as:

$$h(t)=\sum_{k=1}^{L} a_k \delta(t-\tau_k) \tag{1}$$

where L is the total number of the delayed paths, $a_k=|a_k|\, e^{j\theta_k}$ is the complex amplitude, τ_k is the propagation delay, and δ is the Dirac delta function. The parametric model of discrete complex frequency domain indoor wireless channel can be expressed as:

$$H(f_n)=\sum_{k=1}^{L} a_k e^{-j(2\pi f_n \tau_k)} \quad for \quad n=0,1,2,.....N-1 \tag{2}$$

where $f_n = fo + n f_s$, fo is the starting frequency in Hz, f_s is the frequency spacing and N is the number of measured points. The frequency domain transfer function can be written as:

$$H(n)=\sum_{k=1}^{L} A_k z_k^{\,n} \tag{3}$$

Where $A_k=a_k e^{-j2\pi f_o \tau_k}$, and $z_k=e^{-j2\pi f_s \tau_k}$ are the poles in the Z plan. For the prediction problem, it is reasonable to assume that within a time frame the scattering geometry and multipath parameters are time invariant [11]. The problem of finding multipath parameters and TOA can be reduced in a form that can be solved using the MP algorithm. Fig. 1 shows the flowchart of the algorithm. At first the matrix $H_{(N-M)x(M+1)}$ is formed using the complex data sequence $H(n)$ as follows:

$$H=\begin{bmatrix} H(0) & H(1) & \cdots & H(M) \\ H(1) & H(2) & \cdots & H(M+1) \\ \vdots & \vdots & \vdots & \vdots \\ H(N-M-1) & H(N-M) & \cdots & H(N-1) \end{bmatrix} \tag{4}$$

where M is called the pencil parameter. With large value of M the computation of high resolution MP algorithm increases. The value of M is to be selected as a compromised between resolution and computation complexity. M is chosen empirically between $N/3$ and $2N/3$ to get a good performance[10]. Afterward the two $(N-M)\times M$ matrices H_1 and H_2 are defined as:

$$H_1 = \begin{bmatrix} H(0) & H(1) & \cdots & H(M-1) \\ H(1) & H(2) & \cdots & H(M) \\ \vdots & \vdots & \vdots & \vdots \\ H(N-M-1) & H(N-M) & \cdots & H(N-2) \end{bmatrix} \quad (5)$$

and

$$H_2 = \begin{bmatrix} H(1) & H(2) & \cdots & H(M) \\ H(2) & H(3) & \cdots & H(M+1) \\ \vdots & \vdots & \vdots & \vdots \\ H(N-M) & H(N-M+1) & \cdots & H(N-1) \end{bmatrix} \quad (6)$$

By considering the following pencil matrix :

$$H_1 - \lambda H_2 \quad (7)$$

Which represent a generalized eigenvalue problem, the poles z_k can be calculated from the principle eigenvalues of (7). The time delays can be estimated as:

$$\tau_k = \frac{Im(z_k)}{2\pi f_s} \quad (8)$$

The complex amplitudes a_k of the impulse response can be obtained by solving the linear system of (2) which can be formulated as a matrix equation:

$$\overline{H} = S\overline{A} \quad (9)$$

Where

$$S = \begin{bmatrix} e^{-j\omega_o\tau_1} & e^{-j\omega_o\tau_2} & \cdots & e^{-j\omega_o\tau_L} \\ e^{-j\omega_1\tau_1} & e^{-j\omega_1\tau_2} & \cdots & e^{-j\omega_1\tau_L} \\ \vdots & \vdots & \vdots & \vdots \\ e^{-j\omega_{N-1}\tau_1} & e^{-j\omega_{N-1}\tau_2} & \cdots & e^{-j\omega_{N-1}\tau_L} \end{bmatrix}$$

$$\overline{H} = \left[H(\omega_o) \quad H(\omega_1) \quad \cdots \quad H(\omega_{N-1}) \right]^T$$

$$\overline{A} = \left[a_1 \quad a_2 \quad \cdots \quad a_L \right]^T$$

Where ω=$2\pi f_n$. Eq.(9) is an over determined system which can be solved to find complex amplitudes a_i using linear least squares and pseudoiverse approach as follow :

$$\overline{A} = (S^* S)^{-1} S^* \overline{H} \tag{10}$$

where * is the complex Hermitian transpose.

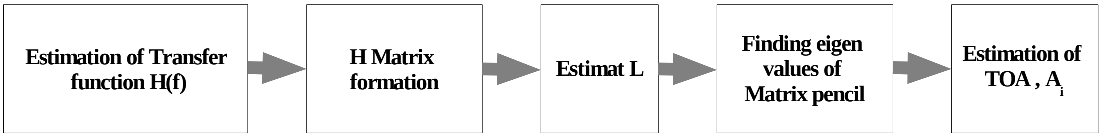

Fig.1 Receiver of Super resolution MP TOA estimation system

MP algorithm needs to identify and estimate the number of multipath components L to work correctly. There are number of methods based on statistical classification criteria, which can be used to estimate L. In this paper, the Minimum Descriptive Length (MDL) and Akiake Information Criteria (AIC) are used[12] as follow:

$$MDL(k) = -log(f(\Theta)) + \frac{1}{2} k(2N-k) log M \tag{11}$$

and

$$AIC(k) = -log(f(\Theta)) + 2k(2N-k)M \tag{12}$$

where $f(\Theta)$ is the likelihood function and it becomes the ratio of the geometric mean to arithmetic mean of a number of the eigenvalues. In the above equations the value of k that minimizes the MDL and AIC represents the number of multipath components L.

3 Simulation Results

To demonstrate the performance of MP algorithm in TOA estimation for WLAN indoor positioning application, extensive simulations were performed. Comparison of the proposed algorithm with the conventional inverse Fourier transform (IFT) is presented. The complex frequency response was calculated by simulating the indoor WLAN channel. Fig.2 shows the normalized time domain channel impulse responses obtained from frequency swept data in the range 2.4 to 2.48 GHz (IEEE801.11b WLAN standard). In this situation which appear in limited bandwidth systems makes it impossible to distinguish the DLOS path using the conventional IFT technique. It shows the ability of MP for detecting DLOS path, which correspond to the TOA.

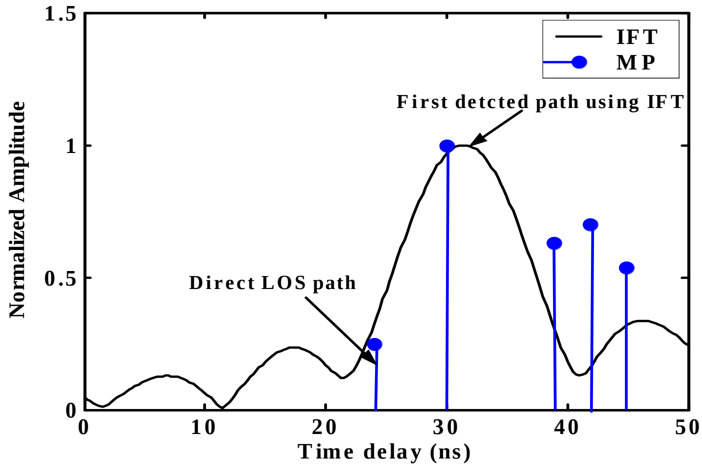

Fig.2 Normalized impulse response

Fig.2 presents the error prediction performance as a function of the number of points of the complex frequency response. We can observe that the error decreases as the number of points increase (high sampling frequency). In conventional techniques in order to separate two components of τ_1 and τ_2 with $\tau_2 > \tau_1$ it is necessary to have a frequency response with a bandwidth of 1/(τ_1- τ_2).

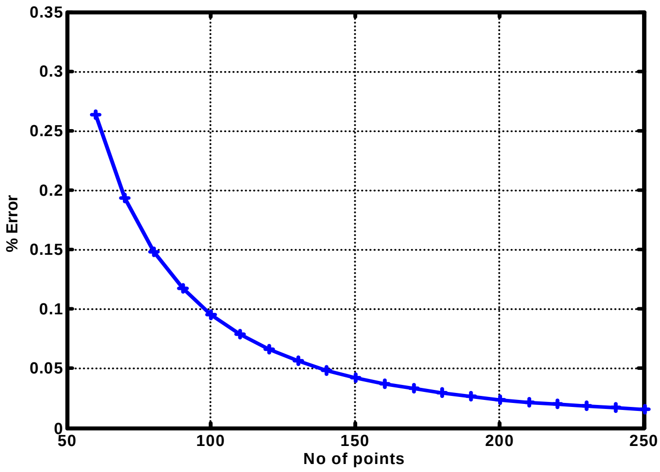

Fig. 3 TOA estimation error performance

Fig. 4 demonstrates the computational time performance of the MP algorithm as compared to ESPRIT and root-MUSIC. It illustrates the advantage of using MP for TOA estimation as compared with root-MUSIC, and also shows that MP have computation advantage compared with ESPRIT which make MP algorithm more attractive for real time applications.

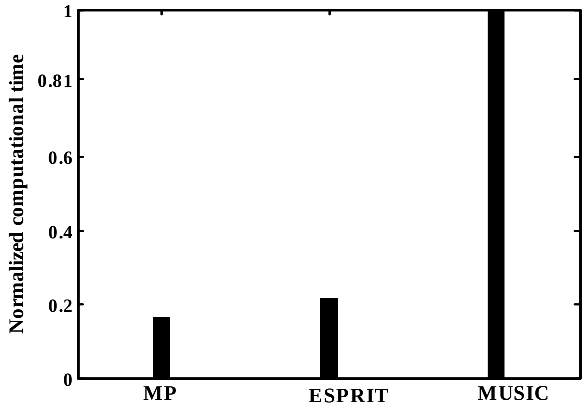

Fig.4 Computational time performance comparison

4 Measurement System and Experimental Results

One of the most popular techniques to experimentally calculate the TOA is through the use of a frequency domain measurement system using Vector Network Analyzer (VNA). The main component of the measurement system used is an Anritsu-Wiltron 37347A network analyzer. The complex frequency channel response can be obtained by sweeping the channel at uniformly spaced frequencies. The forward transmission scattering coefficient S_{21} (the complex channel frequency response) is measured. The system is depicted in the block diagram of Fig.5.

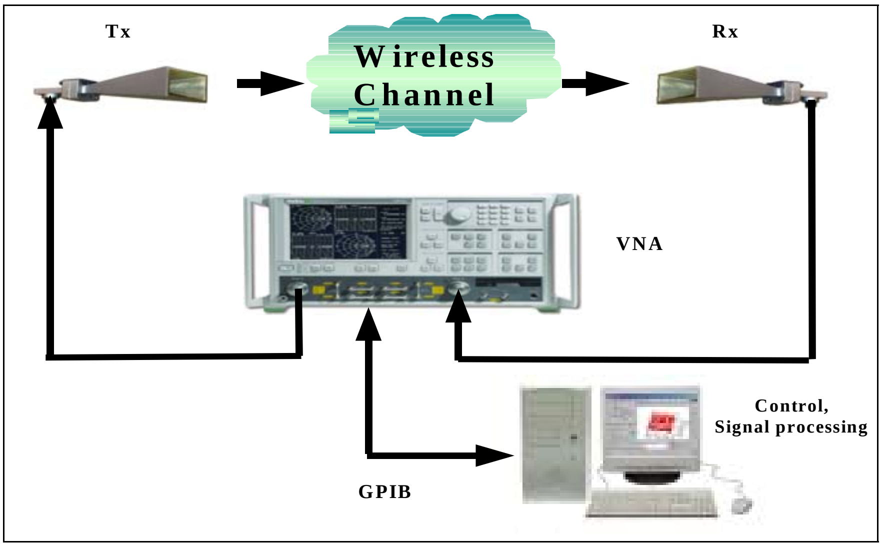

Fig. 5 Block diagram of VNA frequency response measurement system

The magnitude and phase of the measured frequency response were stored for each measurement and later used for further processing. The measurement system was calibrated to reduce the effects of the measuring equipment. Also, the self vector error correction facility in the VNA allows the tracking errors of the entire measurement system to be removed. All measurements are automated using PC with control through a Hewlett Packard's version of a General-Purpose Instrumentation Bus (GPIB). The frequency responses are collected at 3 frequency bands 2 -2.5 GHz, 5-5.5 GHZ, and 5.5-6 GHz. There are 1601 complex data points for each response. The measurements are performed in the 3rd floor of the building of institute of electronics, signal processing and communication, University of Magdeburg. The layout of the measurement hall is shown in Fig.6.

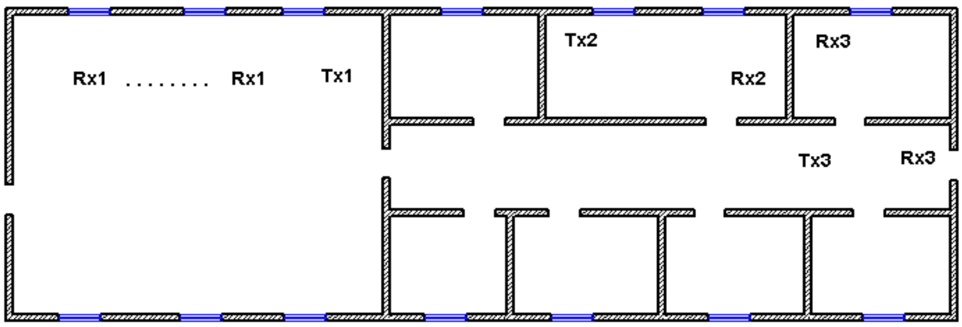

Fig. 6 Floor plan of the measurements location

The time synchronization between transmitter and receiver for TOA estimation is very important for positioning system. The VNA system operates with a transmitted reference (Tx-Rx synchronization) and allows the phase to be stable. Using VNA for measurements will solve the problem of synchronization between Tx and Rx. The calibration procedure sets the time reference points from the analyzer ports to the calibration points which, in our study, are at the end of the cables. When the time reference is shifted to the end of the cables (to the antenna connectors), the resulting delay profiles include only the propagation delays that are coming from the radio channel. Schematic diagram of the synchronization process of the VNA is shown in Fig. 7.

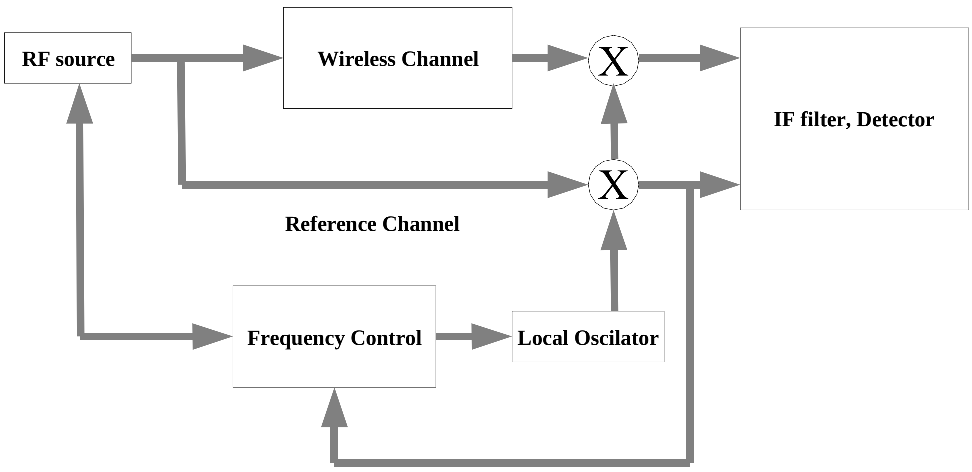

Fig. 7 Schematic diagram of the transmitted reference VNA

The measurements in the three frequency bands were done with separation distance from 5 to 12 m between the transmitter Tx and the receiver Rx in 1m step for each measurement. The

Tx and Rx antennas were two identical TEM horn antennas. To relate the estimation results of TOA to indoor positioning applications, time delays are converted to distance *d* between Tx and Rx as follow:

$$d=c.\ min\{\ \tau_i\ i=1..L\} \tag{13}$$

where *c* is the speed of light in free space, $3x10^8$ m/sec. A part from measurements, which corresponds to frequency ranges of WLAN standards as shown in Table.1 are used for the estimation of TOA and then distances between Tx and Rx.

Standard Approved	IEEE 802.11a	IEEE 802.11b	IEEE 802.11g
Frequencies of Operation	5.15 - 5.35 GHz, 5.725 - 5.825GHz	2.4 - 2.4835 GHz	2.4 - 2.4835 GHz

Tab.1 WLAN standards.

The MP applied to the frequency channel responses then the TOA and the distance between Tx and Rx are estimated. Sample from the measurements are shown in Fig.8.

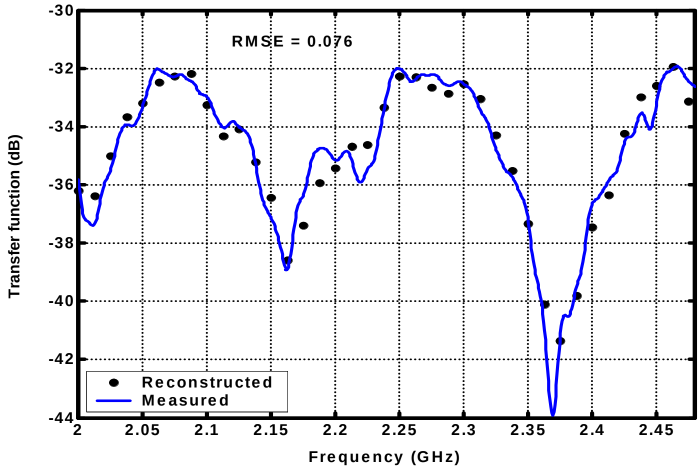

Fig.8 Measured and reconstructed frequency response magnitude

The results of estimated distances between Tx and Rx (i.e. TOA of direct ray) are shown in Fig.9. To measure the accuracy of the obtained results the response is reconstructed from the estimated parameters and the root mean square error RMSE were also calculated. Results of reconstructions are shown in Fig.8.

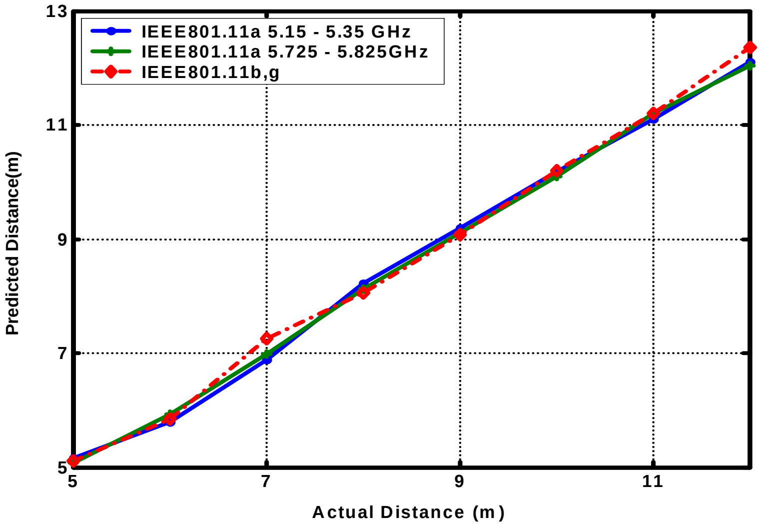

Fig.9 Range prediction performance

Fig. 10 shows the values of MDL and AKI as a function of the number of multipath components of measurements of Fig.8. The minimum of MDL and AKI can be considered as an estimate to the number of multipath components *L*.

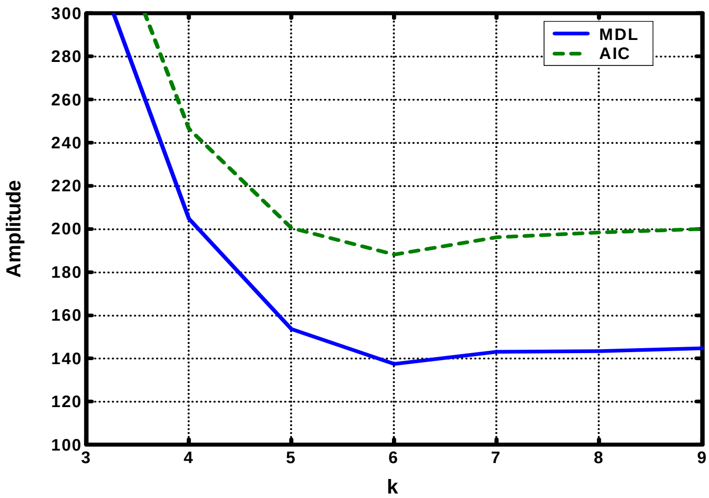

Fig.10 MDL and AIC criterions as a function of the number of multipath components.

5 Conclusions

In this paper, MP algorithm has been applied to complex frequency response to perform TOA estimation for indoor positioning application. Extensive measurements of frequency responses for IEEE801.11 WLAN standards (a,b and g) have been done. The simulation and experimental results outperform the high resolution of the algorithm. The results show that MP have better performance than conventional IFT techniques. Also the computation performance of MP is found to be better than that of ESPRIT and MUSIC super resolution algorithms.

6 References

[1] M. Hazas, A. Ward "A Novel Broadband Ultrasonic Location System, ". *In: Proc. Int. Conf. on Ubiquitous Computing*. (2002) 264-280.

[2] RoyWant, Andy Hopper, Veronica Falcao and Jon Gibbons "The Active Badge Location System," *ACM Trans. Information Systems*, Jan. 1992, pp. 91-102.

[3] Y. Wang, X. Jia, H.K. Lee, and G.Y Li, "An indoor wireless positioning system based on WLAN infrastructure," *6th Int. Symp. on Satellite Navigation Technology Including Mobile Positioning & Location Services*, Melbourne, Australia, 22-25 July , 2003.

[4] E. Elnahrawy, X. Li, and R. P. Martin, "The Limits of Localization Using Signal Strength: A Comparative Study," *Proceedings of the First IEEE International Conference on Sensor and Ad hoc Communications and Networks*, Santa Clara, CA, October, 2004.

[5] K. Pahlavan, X. Li and J. Makela, "Indoor geolocation science and technology," *IEEE Commun. Mag*., vol. 40, pp. 112-118, Feb. 2002 .

[6] Z. Xiang, S. Song, J. Chen, H. Wang ,J. Huang, and X. Gao, "A wireless LAN based indoor positioning technology," *IBM J. Res. and Dev*. Vol. 48, No. 5/6 ,pp 617-626, 2004.

[7] Geo_rey G. Messier, Michel Fattouche and Brent R. Petersen, "Locating an IS-95 Mobile Using Its Signal," *The Tenth International Conference on Wireless Communications (Wireless 98*), vol. II, (Calgary, AB, Canada), July , 1998, pp. 562-574.

[8] Xinrong Li, Kaveh Pahlavan, "Super-Resolution TOA Estimation With Diversity for Indoor Geolocation," *IEEE Transactions on Wireless Communications* vol.3 No.1.,pp 224-234, 2004.

[9] L. Dumont, M. Fattouche and G. Morrison, "Super-resolution of multipath channels in a spread spectrum location system," *Electron. Lett*., vol. 30, pp. 1583-1584, Sept. 1994.

[10] Sarkar, T.K. Pereira, O. , "Using the matrix pencil method to estimate the parameters by a sum of complex exponentials," *IEEE Antennas Propagat,* vol. 37, No.2, pp. 48–55, Feb. 1995.

[11] J. Hwang and J. Winters, "Sinusoidal modeling and prediction of fast fading processes," in *Proc. IEEE GLOBECOM*, Sydney, NSW , Australia ,Nov. 1998, pp. 892–897.

[12] M. Wax and T. Kailath, "Detection of signals by information theoretic criteria," *IEEE Trans. Acoust. Speech Signal Processing*, vol. ASSP-33, no. 2, pp. 387–392, Apr. 1985.