Improved Wireless Location Accuracy Using Antenna Arrays and Interference Cancellation

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ABSTRACT

Location finding for CDMA subscribers using an antenna array at the base station is studied in this paper. Two methods are considered for radio location that are based on time of arrival (TOA) and angle of arrival (AOA) measurements. For TOA estimates, a maximum likelihood algorithm and a practical structure are proposed when an antenna array is available. For AOA estimates, a least-squares (LS) algorithm is used. The LS module is combined with a multiple access interference (MAI) cancellation technique to improve the AOA estimation accuracy in multiuser multipath scenarios.

1. INTRODUCTION

The U.S. Federal Communications Commission (FCC) has made E911 a mandatary requirement for wireless communications services [1]. E911 requires all 911 calls from mobile telephones in the U.S. to be located with some accuracy in order to route the calls to the appropriate emergency service providers. Besides emergency assistance, E911 will trigger many location-based services within the mobile phone or wireless network.

There are several approaches for implementing a radio location system including those based on TOA, AOA, Time Difference Of Arrival (TDOA) and signal-strength [2]. The performance of these location techniques depends on a number of factors, such as multipath propagation, temporal and spatial variations of the channel and the distribution of scatterers. For instance, in urban areas, TOA based techniques outperform the AOA based methods and vice-versa for rural environments. The performance of a TOA only system can be improved by utilizing the AOA measurements [3]. Using an antenna array at the base station can further improve the location estimation by providing both the TOA and AOA information. This paper presents algorithms for estimating TOA and AOA in a multiuser CDMA system and the use of interference cancellation techniques for accuracy improvement.

The paper is organized as follows. In the next section, the joint maximum likelihood estimation of TOA and AOA in a single-user single-path case is derived, followed by a practical sub-optimal architecture. In Sec. 3, the LS estimator for AOA is presented, and a joint LS estimator and interference cancellation technique is proposed to improve the estimation accuracy in the presence of a large number of active users. Sec. 4 includes the simulation parameters and the results for both the TOA and AOA estimates. Conclusions of the paper are given in Sec. 5.

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2. MAXIMUM LIKELIHOOD ESTIMATION OF TOA

In this section we derive the maximum likelihood estimator of TOA and AOA for a single-user single-path scenario. The most general scenario is addressed in the next section. We assume that the base station uses an M-element antenna array. Using an array response model at the base station [4], the received signal at time n is an $M \times 1$ vector:

$$\mathbf{r}(n) = \mathbf{A}_\theta c(n) s(n-\tau) + \mathbf{v}(n) \tag{1}$$

where $c(n)$ and τ are respectively the unknown channel gain and delay, $s(n)$ is a known sequence transmitted by the user for training purposes, and $\mathbf{v}(n)$ is additive white Gaussian noise. Moreover, $\mathbf{A}_\theta$ is the array response defined by:

$$\mathbf{A}_\theta = \text{col}\left\{ \begin{array}{cccc} 1 & e^{j2\pi \frac{d}{\lambda} cos\theta} & \dots & e^{j2\pi \frac{(M-1)d}{\lambda} cos\theta} \end{array} \right\} \tag{2}$$

where θ is the AOA measured with respect to the array, d is the antenna spacing and λ is the wavelength corresponding to the carrier frequency.

The maximum likelihood estimates of τ and θ are defined by:

$$\{\hat{\tau}, \hat{\theta}\} = \arg\max_{\tau,\theta} [P(\mathbf{r}(1) \cdots \mathbf{r}(K)) | \{\tau, \theta\}] \tag{3}$$

where the likelihood function $P(\mathbf{r}|\{\tau,\theta\})$ is given by

$$\begin{aligned} P(\mathbf{r}|\{\tau,\theta\}) &= C_1 \exp\{-C_2 \frac{1}{K} \sum_{n=1}^{K} \|\mathbf{r}(n) - \\ &\quad \mathbf{A}_\theta c(n) s(n-\tau)\|^2\} \end{aligned} \tag{4}$$

where C_1 and C_2 are positive constants and $\|.\|$ is the Euclidean norm of the vector. Therefore, the ML estimates of $\{\tau, \theta\}$ can be found by solving

$$\{\hat{\tau}, \hat{\theta}\} = \arg\max_{\tau,\theta} [J_{ML}(\tau,\theta)] \tag{5}$$

where

$$J_{ML} = \frac{1}{K} \sum_{n=1}^{K} \|\mathbf{r}(n) - \mathbf{A}_\theta c(n) s(n-\tau)\|^2$$

This cost function can be simplified by using the fact that $\|\mathbf{A}_\theta\|^2 = M$ and $|A_\theta(i)| = 1$ for $i = 1, \cdots, M$,so that

$$J_{ML} = \frac{1}{K} \sum_{n=1}^{K} (\mathbf{A}_\theta^* \mathbf{r}(n) - c(n) s(n-\tau))^2 \tag{6}$$

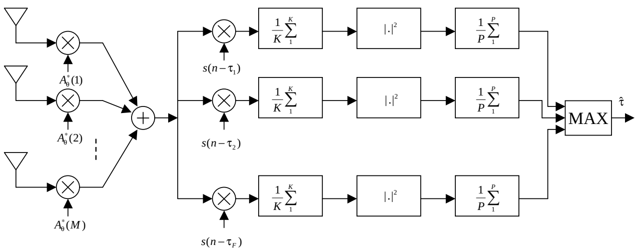

Fig. 1. A TOA estimation scheme using an antenna array.

The ML estimator (5) should, in principle, create all possible replicas $\{s(n-\tau)\}$, correlate them with $\mathbf{A}_\theta^*\mathbf{r}(n)$ for all possible values of θ, and pick the values for τ and θ leading to the largest value of the correlation. Obviously this type of search is not feasible in practice, although it is the optimum solution. An efficient sub-optimal estimator for τ using an antenna array can be derived using the results in [5]. Rather than performing a two dimensional search, this estimator performs the search for τ and θ separately. The estimate for θ is derived in the next section, and the process to estimate τ is explained here. The term $\mathbf{A}_\theta^*\mathbf{r}(n)$ in (6) can be interpreted as the output of a beamformer (antenna combiner) steered to direction θ, as shown in Fig. 1. Thus, the optimization problem for τ, given θ, can be simplified to the single-antenna case by using a beamformer at direction θ. Optimizing a cost function of the form J_{ML} in (6) for τ has already been studied in [5], [6] and the algorithms proposed there can be used in the multiple-antenna case as well. For instance, using the results in [5], the optimization problem (5) can be reduced to maximizing a function of the form

$$J(\tau|\theta) = \frac{1}{P}\sum_{m=1}^{P}\left|\frac{1}{K}\sum_{n=n_0}^{mK}\mathbf{A}_\theta^*\mathbf{r}(n)s(n-\tau)\right|^2 \quad (7)$$

with the resulting receiver structure shown in Fig. 1. Here K and P are respectively the coherent and non-coherent correlation lengths. Note that using the antenna array will increase the SNR by the beamformer gain and result in higher accuracy in τ compared to a single-antenna receiver.

3. MULTI-USER LEAST-SQUARES AOA ESTIMATION

Now we modify the channel model (1) to accommodate a multi-user multi-path system. The receiver observes a linear combination of all transmitted data sequences by all active users, each distorted by ISI, under white Gaussian noise. Assuming the maximum number of channel taps to be L, and the number of active users to be N, the received signal $\mathbf{r}(n)$ of size $M\times 1$ at time n is

$$\mathbf{r}(n) = \sum_{i=1}^{N}\sum_{k=1}^{L}\mathbf{h}_{i,k}(n)s_i(n-k) + \mathbf{v}(n) \quad (8)$$

where $s_i(n)$ is the transmitted sequence by the ith user and $\mathbf{v}(n)$ is a vector modelling the additive white Gaussian noise. Moreover, $\mathbf{h}_{i,k}(n)$ contains the kth channel tap from user i to the base station and it can be written as

$$\mathbf{h}_{i,k}(n) = \mathbf{A}_{\theta_{i,k}}c_{i,k}(n) \quad (9)$$

where $c_{i,k}(n)$ is the kth tap of the channel from the ith user to the base station and $\mathbf{A}_{\theta_{i,k}}$ is the array response as a function of the AOA of the kth multipath of the ith user given by (2).

The received SNR at the base station is generally low due to multiuser interference, which makes the channel estimates directly derived from the received samples not accurate. In CDMA systems, the training sequences $s_i(n)$ for different users are designed to have good orthogonality properties. This property can be used to increase the SNR at the receiver by correlating $\mathbf{r}(n)$ with the known sequence transmitted by each user. The correlations are performed over different delays for each known sequence, corresponding to the delays of the channel. The correlation results for each specific user and multipath are then used to estimate the AOA for that user and multipath. The correlation process for user i and multipath k is

$$\mathbf{x}_{i,k} = \frac{1}{K}\sum_{k}^{k+K}\mathbf{r}(m)s_i^*(m-k) \quad (10)$$

where K is the correlation length. Assuming constant channel taps during the estimation period, the correlation results $\mathbf{x}_{i,k}$ can be written in vector form:

$$\begin{aligned}\mathbf{x}_{i,k} &= \mathbf{G}_i\mathbf{h}_{i,k} + \mathbf{i}_{i,k} + \mathbf{v}' \\ \mathbf{i}_{i,k} &= \sum_{m=1}^{N}\sum_{\substack{l=1\\ m\neq i, l\neq k}}^{L}\rho_{i,m,k,l}\mathbf{G}_m\mathbf{h}_{m,l}\end{aligned} \quad (11)$$

where $\rho_{i,m,k,l}$ is the normalized cross-correlation between the known training sequences of users i and m, received on multipaths k and l, respectively, $\mathbf{G}_i$ is the identity matrix of size $M\times M$ scaled by the power of the signal s_i. In practice, the training signal s_i has a constant magnitude over time. Therefore, $\mathbf{G}_i$ can be replaced by $|s_i|^2 I_{M\times M}$. Equation (11) is used to form a least-squares estimator for $\mathbf{h}_{i,k}$ and consequently the AOA for user i and multipath k, i.e., $\theta_{i,k}$. Collecting R realizations of the correlation results $\mathbf{x}_{i,k}$ into a vector $\mathbf{d}_{i,k}$, the block LS problem can be written as:

$$\mathbf{d}_{i,k} \triangleq \begin{bmatrix}\mathbf{x}_{i,k}(1)\\ \mathbf{x}_{i,k}(2)\\ \vdots \\ \mathbf{x}_{i,k}(R)\end{bmatrix}, \qquad \mathbf{H}_i \triangleq \begin{bmatrix}\mathbf{G}_i\\ \mathbf{G}_i\\ \vdots\\ \mathbf{G}_i\end{bmatrix}$$

$$\begin{aligned}\hat{\mathbf{h}}_{LS_{i,k}} &= \arg\min_{\mathbf{h}_{i,k}}\|\mathbf{d}_{i,k} - \mathbf{H}_i\mathbf{h}_{i,k}\|^2 \\ &= (\mathbf{H}_i^*\mathbf{H}_i)^{-1}\mathbf{H}_i^*\mathbf{d}_{i,k} \\ &= \frac{1}{R|s_i|^2}\mathbf{H}_i^*\mathbf{d}_{i,k}\end{aligned} \quad (12)$$

AOA information can be extracted from the estimated channel taps $\hat{\mathbf{h}}_{LS_{i,k}}$ according to equation (2). The above LS estimation is repeated for all users and multipaths, $i = 1\dots N$, $k = 1\dots L$.

As the number of users and multipaths increases, Multiple Access Interference (MAI) and Inter Symbol Interference (ISI) in equation (11) become stronger. In practical scenarios with a large number of active users in a cell, the accuracy of the LS estimation of AOA is limited by MAI and ISI. One solution for reducing the effect of MAI in (11) is to increase the coherent correlation length K, as well as the LS estimation length R. This is due to the fact that the cross correlation terms ρ in equation (11) are in the order of $\frac{1}{K}$ for well designed training sequences. However, the correlation or estimation length cannot be increased indefinitely in order to achieve a higher estimation accuracy. The limit on the correlation length is set by the *Channel Coherence Time* (T_c). The correlation length should be short enough such that the channel taps can be assumed constant during the estimation process. In other words, the correlation length has to be smaller than the channel coherence time. The channel coherence time is limited by the maximum Doppler frequency in the channel.

We propose a joint least-squares estimation followed by a multiuser interference cancellation technique to provide an accurate AOA estimation even in the presence of a large number of interfering users. This joint technique takes advantage of the following two facts:

- A base station (in normal operation mode) detects and decodes the signals from all users simultaneously. Therefore, the base station knows the training sequences used by the users, i.e., $s_i(n), i = 1 \dots N$.
- The base station performs the LS estimation for all users and multipaths. Therefore, the LS estimation of the channel taps ($\hat{\mathbf{h}}_{LS_{i,k}}, i = 1 \dots N, k = 1 \dots L$) are available at the base station.

The above information is used in a secondary stage to further increase the accuracy of the estimation by cancelling the MAI in (11). The interfering signal is regenerated using the known $s_i(n)$ and estimated channel taps $\hat{\mathbf{h}}_{LS_{i,k}}$, subtracted from the previous correlation results $\mathbf{x}_{i,k}$ and a new LS estimation is obtained. Note that the new estimation uses less-corrupted signals compared to the first estimation. Following are the steps performed in the proposed architecture:

1. Use equations (11) and (12) to calculate the LS estimation of the channel taps for all users and multipaths.
2. Use the estimated channel taps to regenerate (estimate) the MAI in equation (11), i.e.,

$$\hat{\mathbf{i}}_{i,k} = \sum_{m=1}^{N} \sum_{\substack{l=1 \\ m \neq i, l \neq k}}^{L} \rho_{i,k,m,l} \mathbf{G}_m \hat{\mathbf{h}}_{LS_{m,l}} \qquad (13)$$

3. Subtract the estimated interference in step (2) from the correlation results in equation (11). The new $\mathbf{x}_{i,k}$ is

$$\mathbf{G}_i \mathbf{h}_{i,k} + \sum_{m=1}^{N} \sum_{\substack{l=1 \\ m \neq i, l \neq k}}^{L} \rho_{i,k,m,l} \mathbf{G}_m (\mathbf{h}_{m,l} - \hat{\mathbf{h}}_{LS_{m,l}}) + \mathbf{v}'$$

4. Use the new $\mathbf{x}_{i,k}$ in the LS estimation to calculate a new estimate for channel taps. The new channel estimation is referred to as MU-LS estimation.
5. Repeat steps 2-4 for all users and multipaths.

The new MU-LS channel estimates result in more accurate AOA estimates. The above procedure can be repeated until an AOA estimation within the desirable range is achieved, however the simulation results show that one iteration is enough to meet the location accuracy requirements.

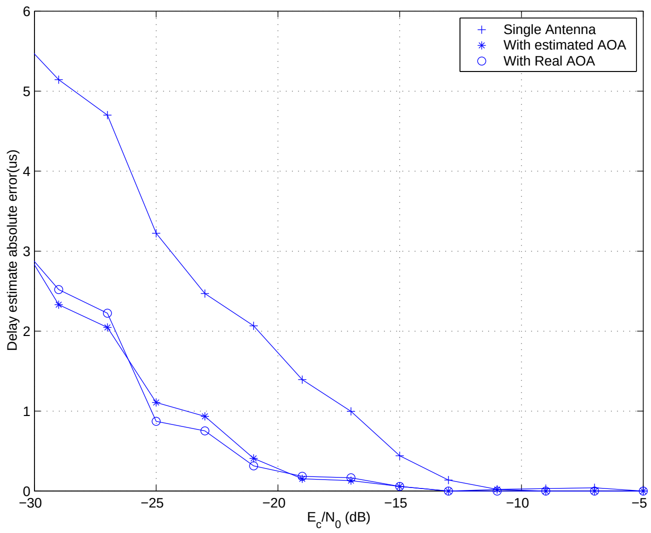

Fig. 2. Standard deviation of TOA estimation error versus E_c/N_0.

4. SIMULATION RESULTS

An uplink DS-CDMA system is used to evaluate the performance of the algorithms presented in the paper. We use the cdma2000 standard [7] to model the users within the cell and simulate the link (any DS-CDMA standard can be used). For simplicity of the simulation, we assume a processing gain of 64 for all the users. The known pilot sequence transmitted by each user is used for training purposes at the base station. The CDMA chip-rate in the simulation is 4MHz, and a 4-element antenna array is employed at the base station. The antenna spacing is assumed to be half a wavelength. The mobile users are uniformly distributed in a 120 degrees sector. This is due to the fact that in current cell designs, the cell is divided into 3 sectors of each 120 degrees. We choose the coherent correlation length (K) to be equal to the processing gain.

4.1. Maximum Likelihood Estimation of TOA

In this subsection we evaluate the performance of the TOA estimation technique presented in Sec. 2. Therefore, in this part we assume a single path channel with Rayleigh distribution and Doppler frequency of 100Hz. This Doppler frequency corresponds to a velocity of about 40mph at the carrier frequency of 1.8GHz. The error in TOA estimation versus the chip energy-to-noise ratio (E_c/N_0) is shown in Figure 2 for single antenna and multiple antenna scenarios. As shown in the figure, using antenna arrays at the base station improves the TOA estimation significantly. In the multiple antenna case, two different beamformers are simulated. One is the ideal beamformer using the real value for AOA, and the other is using the LS estimation of AOA to form the beam. As shown in Figure 2, the degradation in performance due to AOA estimation error is very small. This also validates the accuracy of the AOA estimation algorithm for chip energy-to-noise ratios as low as -30dB.

In addition to the variance of the TOA estimation error, there is another criterion to evaluate the performance of location estimation algorithms, called *Failure Rate*. Failure rate is defined as

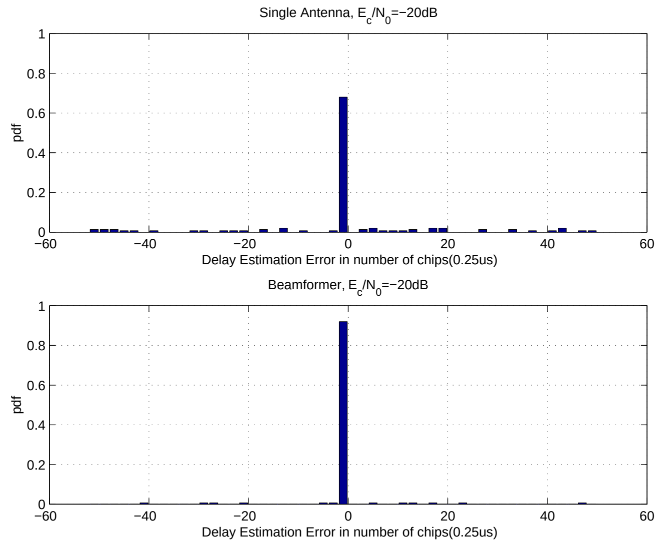

Fig. 3. Distribution of the error in TOA estimation at E_c/N_0 of -20dB.

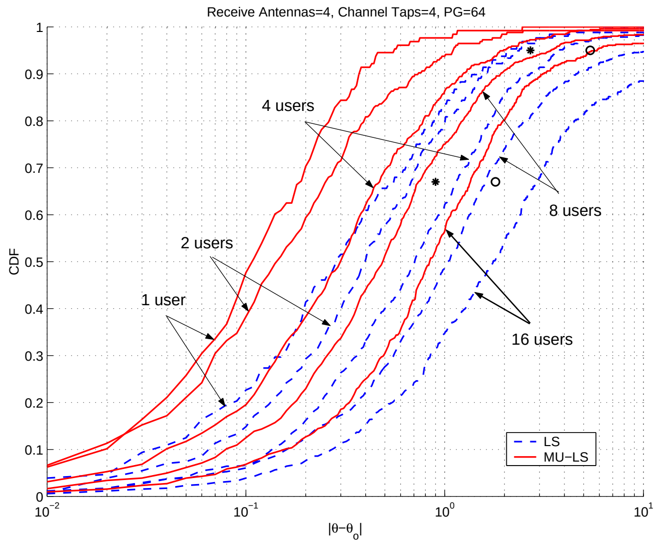

Fig. 4. Outage curves vs. error in AOA for 1,2,4,8 and 16 active users. The *circle* and *star* markers are respectively the Network-Based and Handset-Based requirements mandated by the FCC for 67% and 95% outage.

the probability at which the algorithm fails to estimate the location with an acceptable accuracy. The simulation results for single antenna and multiple antenna receivers are shown in Figure 3. In the plot, an accuracy of 1 CDMA chip duration (0.25us) in TOA estimation is assumed as an acceptable estimation. This amount of TOA estimation error translates into 75 meters error in location estimation. As shown in the figure, using an antenna array decreases the failure rate in TOA estimation significantly. At $E_c/N_0 = -20$dB, using an antenna array improves the failure rate from 32 percent down to 7 percent. The improvement in lower SNR is more significant. At $E_c/N_0 = -30$dB, using the antenna array lowers the failure rate from 82 percent down to 41 percent. Note that lowering the failure rate means increasing the reliability and availability of the location estimation in practical applications.

4.2. MU-LS Estimation of AOA

In this subsection, we simulate the performance of the proposed AOA estimator in a multiuser multipath scenario. The propagation model used for each user is a 4-multipath channel with independent taps and random AOA. The Outage (or Cumulative Distribution Function) as a function of the error in AOA estimation is plotted in Figure 4 for LS and MU-LS techniques. The figure depicts the simulation results for a cell with 1,2,4,8 and 16 active users. The FCC mandatory requirements of location accuracy (using AOA estimation) are also shown in Figure 4, for 67% and 95% outage. A cell size of 2 miles has been considered to translate the location accuracy in meters to AOA accuracy in degrees. The *circle* and *star* markers are the Network-Based and Handset-Based requirements respectively.

5. CONCLUSIONS

The Maximum Likelihood TOA estimator proposed in previous works for single-antenna receivers has been generalized to multiple-antenna receivers. For AOA estimation, a least-squares estimator has been developed for a multi-user multi-path scenario. The LS estimator of AOA was combined with a Multiuser Interference Cancellation technique to further increase the accuracy of the AOA estimation in the presence of large number of users. The performance of the combined architecture meets the location accuracy requirements on AOA estimation.

6. REFERENCES

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