Detection of Fading Overlapping Multipath Components for Mobile-Positioning Systems

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Abstract— **The Federal Communications Commission (FCC) mandate for locating the position of wireless 911 callers is fueling research in the area of mobile-positioning technologies. Overlapping multipath propagation is one of the main sources of mobile-positioning errors, especially in fast channel fading situations. In this paper we develop a technique for detecting and providing an estimate of the number of overlapping fading multipath components. Such information is vital for accurate resolving of overlapping multipath components as well as avoiding unnecessary computations and errors in single-path propagation cases. The proposed technique exploits the fact that multipath components fade independently as well as the pulse shape symmetry. The paper also presents supporting simulation results.**

I. Introduction

Mobile-positioning is an essential feature of future cellular systems; it enables the positioning of cellular users in emergency 911 (E-911) situations. A recent government mandate for such services, given in [1], has led to the development of numerous mobile-positioning systems (see, e.g., [2] and the many references therein). Such systems have many other applications, besides E-911 public safety, such as location sensitive billing, fraud protection, mobile yellow pages, and fleet management.

In infrastructure-based mobile-positioning systems, the accurate estimation of the time and amplitude of arrival of the first arriving ray at the receiver(s) is vital (see [2], [3]). Such estimates are used to obtain an estimate of the distance between the transmitter and the receiver(s). However, wireless propagation usually suffers from severe multipath conditions. In many of these cases, the prompt ray is succeeded by a multipath component that arrives at the receiver(s) within a short delay. If this delay is smaller than the duration of the pulse-shape used in the wireless system (the chip duration T_c in CDMA systems), then the two rays will overlap causing significant errors in the prompt ray time and amplitude of arrival estimation (see, e.g., [3]).

Fig. 1 shows the combined impulse response of a two ray channel and a conventional pulse-shape, for a CDMA IS-95 system, in two cases (a,b). In case (a), the delay between the two channel rays is equal to twice the chip duration ($2T_c$). It is clear that the peaks of both rays are resolvable, thus allowing relatively accurate estimation of the prompt ray time and amplitude of arrival. However, in case (b), both multipath components overlap and are *nonresolvable* by means of a peak-picking procedure. This can lead to significant errors in the prompt ray time and amplitude of arrival estimation.

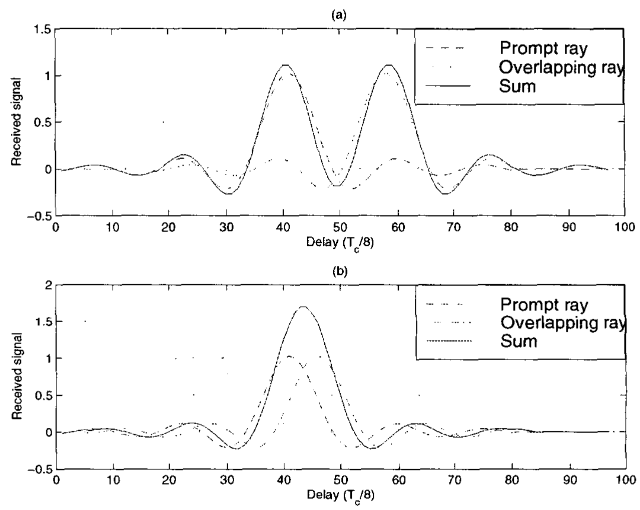

Fig. 1. *Overlapping rays. (a) Delay=$2T_c$. (b) Delay=$T_c/2$.*

Several works in the literature have addressed the problem of resolving overlapped multipath components by using constrained least-squares methods, which exploit the known pulse-shape (see, e.g., [4], [5], [6]). However, these least-squares methods introduce additional errors due to noise enhancement that arises from the ill-conditioning of the matrices involved in the least-squares operation, especially in fading conditions that prohibit long averaging intervals (see [6] for more details). Furthermore, applying least-squares methods can produce unnecessary errors in the case of single-path propagation.

Now, having *a-priori* information about the *existence and number* of multipath components can be useful in overcoming many of the challenges facing overlapping multipath resolving in the following aspects. First, if no overlapping multipath components are detected within a pulse-shape period from the prompt ray, a peak-picking operation is sufficient and no least-squares operation is needed. This avoids noise enhancement and saves unnecessary calculations. In these cases, the single path searcher of [7],

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[8] achieves a high accuracy for the time and amplitude of arrival estimates of the first arriving ray. Second, if overlapping multipath components are detected, an adaptive searcher, which avoids the matrix ill-conditioning problem associated with the least-squares design, can be designed [12]. Third, having information about the existence of overlapping multipath components could serve to provide a measure of the *degree of confidence* in the location estimation in general. Providing such level of confidence in the location process is recommended by the FCC [1].

The main contribution of this paper is to describe a technique for detecting overlapping fading multipath components for mobile-positioning systems. The technique is based on exploiting the fact that overlapping multipath components *fade independently* (see, e.g., [9]) as well as the pulse shape symmetry. The method is based on introducing and comparing two cost functions. The two functions coincide for single-path propagation, while a difference is detected under multipath conditions.

II. Problem Formulation

Consider a received sequence $\{r(n)\}$ that arises from a model of the form

$$r(n) = c(n) \star p(n) \star h(n) + v(n), \quad (1)$$

where $\{c(n)\}$ is a known binary sequence, $\{p(n)\}$ is a known pulse-shape waveform sequence, $v(n)$ is zero-mean additive white Gaussian noise of variance σ_v^2, and $h(n)$ denotes the impulse response of a multipath channel with taps

$$h(n) = \sum_{l=1}^{L} \alpha_l x_l(n) \delta(n - \tau_l^o), \quad (2)$$

where α_l, $\{x_l(n)\}$, and τ_l^o are respectively the unknown gain, the normalized amplitude sequence, and the time of arrival of the l^{th} multipath component (ray).

A common structure for CDMA channel estimation is to correlate the received signal, $r(n)$, with delayed replica of the known pulse-shaped code sequence, say $s(n-\tau) = c(n-\tau) \star p(n)$, over a dense grid of possible values of τ. This correlation is done over a period of N samples of the received sequence, to obtain the following function of τ:

$$\frac{1}{N} \sum_{n=1}^{N} r(n) s(n-\tau).$$

If the channel has only one ray, it is well known that this function attains a maximum at a specific value of the delay, τ_p, which agrees with the time of arrival of this single ray [10].

For the case of fading channels, the correlation operation, described above, cannot be extended for the whole length of the received sequence, $r(n)$, as this would cause the correlation output to degrade due to the random variations of the fading channel phase. In this case, the correlation is obtained over a period of N samples of the received sequence, during which the fading channel does not vary much. The phase of the correlation over these N samples is removed by squaring and the squared value is stored. The same procedure is repeated over the next N samples of the received sequence and the resulting value is averaged with the stored value and so on, to obtain the following cost function

$$J(\tau) = \frac{1}{M} \sum_{m=1}^{M} \left| \frac{1}{N} \sum_{n=n_o}^{mN} r(n) s(n-\tau) \right|^2, \quad (3)$$

where $n_o = (m-1)N + 1$, and the length of the received sequence, $\{r(n)\}$, is equal to NM. This procedure is known as coherent/noncoherent averaging [10].

It is shown in [7], [8] that the time of arrival of the first arriving ray, τ_1^o, is obtained by estimating the index of the earliest peak of the cost function, $J(\tau)$. This algorithm was shown to be successful in estimating the time of arrival of the prompt ray *only* if the difference between the prompt ray delay, τ_1^o, and the delay of the succeeding ray, τ_2^o, is larger than the pulse-shape waveform main lobe duration, T_p. If this condition is not satisfied, picking the first peak of $J(\tau)$ could lead to significant errors in estimating the prompt ray time and amplitude of arrival as indicated in Figure 1. This problem was also noticed in the field trial results given in [11].

III. The Proposed Technique

We now describe a method for multipath detection in wireless environments. Here, we use the term "*detection*" to refer to determining if the number of multipath components within the vicinity of the first arriving peak is *equal to* or *more than* one. For example, if more than one ray exists, then overlapping multipath components are *detected*. The method exploits the fact that different multipath rays fade independently, i.e., it exploits the following property [9]:

$$\begin{aligned} \mathrm{E}\left[x_i(n) x_j(n)\right] &= 1, \quad i = j\,, \\ &= 0, \quad i \neq j\,. \end{aligned} \quad (4)$$

We first explain the intuition behind the proposed algorithm. Consider the case of a noiseless single path channel that consists of a single delay τ_p. Notice that, in this case, the cost function, $J(\tau)$ of (3) will satisfy the symmetry property $J(\tau_p + \delta\tau) = J(\tau_p - \delta\tau)$ so that

$$\begin{aligned} & \frac{1}{M} \sum_{m=1}^{M} \left| \frac{1}{N} \sum_{n=n_o}^{mN} r(n) s(n - \tau_p - \delta\tau) \right|^2 \\ = & \frac{1}{M} \sum_{m=1}^{M} \left| \frac{1}{N} \sum_{n=n_o}^{mN} r(n) s(n - \tau_p + \delta\tau) \right|^2 \\ = & \frac{1}{M} \sum_{m=1}^{M} \left(\left[\frac{1}{N} \sum_{n=n_o}^{mN} r(n) s(n - \tau_p + \delta\tau) \right] \right. \\ & \left. \cdot \left[\frac{1}{N} \sum_{n=n_o}^{mN} r(n) s(n - \tau_p - \delta\tau) \right]^* \right), \end{aligned} \quad (5)$$

where '*' denotes complex conjugation. In other words, we can see that due to the symmetry of the pulse-shape waveform, $p(n)$, the cost function, $J(\tau)$, is also symmetrical around the delay τ_p. Thus, the value of $J(\tau_p + \delta\tau)$ can be obtained by any of three different operations: (i) by averaging the squared partial correlations of N samples of the received sequence, $r(n)$, with $s(n - \tau_p - \delta\tau)$, (ii) by averaging similar squared partial correlations with $s(n - \tau_p + \delta\tau)$, (iii) or by averaging the product of the partial correlations with $s(n - \tau_p - \delta\tau)$ and the complex conjugate of similar partial correlations with $s(n - \tau_p + \delta\tau)$. Let $J_{product}$ denote the value obtained using the third operation. Thus, in the case of noiseless single path propagation, we have

$$J(\tau_p + \delta\tau) = J(\tau_p - \delta\tau) = J_{product}.$$

In the case of overlapping fading multipath propagation, the previous equality does not hold as the three functions, $J(\tau_p+\delta\tau)$, $J(\tau_p-\delta\tau)$, and $J_{product}$, will contain cross terms of *different* multipath components, as well as other squared terms of the same rays. Since, different rays fade *independently*, we expect the averaged cross terms to vanish leaving only same ray squared terms. Thus, we would expect a difference to exist between $J_{product}$ and each of $J(\tau_p + \delta\tau)$ and $J(\tau_p - \delta\tau)$, in the multipath propagation case. We will base our proposed algorithm on detecting this difference and using it as an index of the existence of overlapping fading rays. Moreover, we will use a special form of this difference; namely $J(\tau_p+\delta\tau)+J(\tau_p-\delta\tau)-2J_{product}$. It can be shown that this difference will generally be positive.[1]

After explaining the intuition behind the proposed method, we now present the proposed detection algorithm. The steps of this algorithm are summarized as follows:

1. A power delay profile (PDP), $J(\tau)$, of the received sequence, $\{r(n)\}$, is computed according to (3).

2. Resolvable rays are separated from the prompt ray by keeping values of $J(\tau)$ within a window of twice the chip duration ($2T_c$) around the first arriving peak and discarding values of $J(\tau)$ outside this window range. That is we consider only the range of delays given by

$$\tau_p - T_c < \tau < \tau_p + T_c \tag{6}$$

where τ_p is the index of the first arriving peak, which is given by

$$\tau_p = \max_{\tau} J(\tau). \tag{7}$$

Here we note that rays separated by more than T_c are resolvable by peak-picking techniques since the width of the main lobe of a CDMA pulse-shaping waveform is conventionally chosen to be equal to the chip duration (T_c). Note also that the number of delays inside the search window defined by (6) is equal to $2T_c/T_s+1$, where T_s is the sampling period of the received sequence, $\{r(n)\}$.

3. Two cost functions (C_s and C_m) are then computed and compared. These two cost functions are designed such that their values are different if multiple rays exist within the vicinity of the first arriving peak. On the other hand, the two cost functions coincide for single path propagation implying that the time of arrival of the prompt ray is equal to τ_p.

In order to define C_s and C_m, we first define the two functions $J_s(\delta\tau)$ and $J_m(\delta\tau)$:

$$\begin{aligned} J_s(\delta\tau) &\triangleq \frac{1}{M}\sum_{m=1}^{M}\left|\frac{1}{N}\sum_{n=n_o}^{mN} r(n)s(n-\tau_p+\delta\tau)\right|^2 \\ &+\frac{1}{M}\sum_{m=1}^{M}\left|\frac{1}{N}\sum_{n=n_o}^{mN} r(n)s(n-\tau_p-\delta\tau)\right|^2 \\ &= J(\tau_p+\delta\tau)+J(\tau_p-\delta\tau)\ , \end{aligned} \tag{8}$$

and

$$\begin{aligned} J_m(\delta\tau) &= \frac{2}{M}\sum_{m=1}^{M}\left(\left[\frac{1}{N}\sum_{n=n_o}^{mN} r(n)s(n-\tau_p+\delta\tau)\right]\right. \\ &\quad \cdot\left.\left[\frac{1}{N}\sum_{n=n_o}^{mN} r(n)s(n-\tau_p-\delta\tau)\right]^*\right) \\ &= 2\ J_{product}\ . \end{aligned} \tag{9}$$

The two cost functions, C_s and C_m, are then calculated from

$$C_s \triangleq \frac{T_s}{T_c}\sum_{\delta\tau=T_s}^{T_c} J_s(\delta\tau) - \frac{2\widehat{\sigma_v^2}}{N}\ , \tag{10}$$

$$C_m \triangleq \frac{T_s}{T_c}\sum_{\delta\tau=T_s}^{T_c} J_m(\delta\tau)\ , \tag{11}$$

where the quantity $\widehat{\sigma_v^2}$ is an estimate of the noise variance σ_v^2, which can be estimated using many conventional techniques (see, e.g., [7], [8] for a CDMA example). As the previous equations show, C_s and C_m are averaged values of the two functions $J_s(\delta\tau)$ and $J_m(\delta\tau)$, for all possible values of $\delta\tau$.[2] Thus, we would expect the difference between C_s and C_m to represent an average of the difference $J_s(\delta\tau) - J_m(\delta\tau)$ over all values $\delta\tau$. As we discussed in the beginning of this section, this average difference resembles an average of the difference $J(\tau_p+\delta\tau)+J(\tau_p-\delta\tau)-2J_{product}$ over all values $\delta\tau$, which we would expect to be an index of the existence of overlapping multipath components.

4. The multipath existence decision criterion is thus based on comparing the difference between both functions with a threshold value, β: if $C_s - C_m < \beta$, we declare that only one ray exists in the vicinity of the first arriving peak. However, if $C_s - C_m > \beta$, we declare that multipath propagation exists. Figure 2 shows an implementation scheme of the proposed algorithm.

If only one ray is detected, no least-squares operations are needed and the prompt ray time of arrival is set to

[1]This proof is omitted for brevity.

[2]The need for subtracting the noise variance term $2\widehat{\sigma_v^2}/N$ is to remove a noise bias that occurs in the functions $J(\tau_p+\delta\tau)$ and $J(\tau_p-\delta\tau)$ [7], [8].

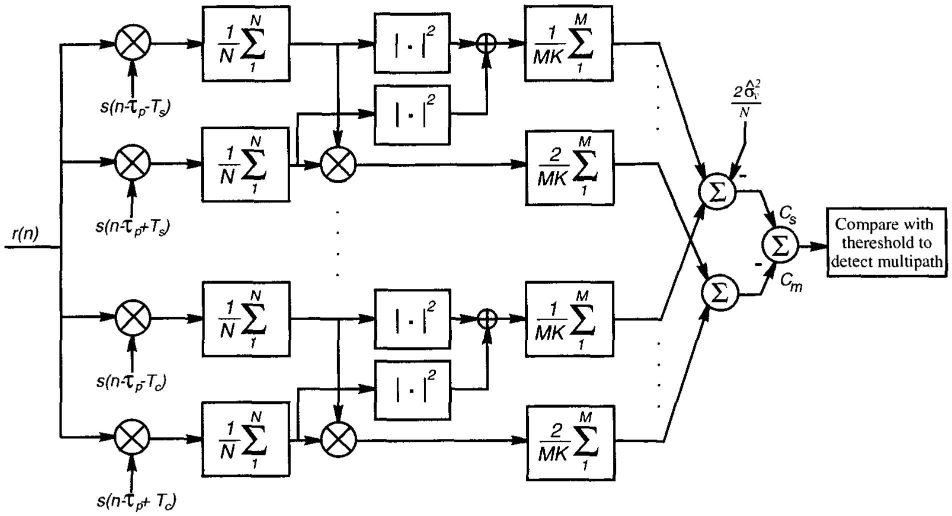

Fig. 2. *Block diagram of the proposed multipath detection technique.*

τ_p. On the other hand, if multiple rays are detected, a constrained least-squares operation is performed with the number of rays set to two. The index τ_p is then set to the time of arrival of the first arriving ray estimated from the least-squares operation and the steps of the algorithm are repeated to detect more than two overlapping rays. This procedure is repeated until no further rays are detected. For simplicity, we do not expand on this issue and focus on the case of only two overlapping rays in the vicinity of the first arriving peak and leave the case of $L > 2$ for future work.

We now finalize the proposed method by selecting the parameters N and β. The coherent averaging interval N should be continuously adapted according to an estimate of the maximum Doppler frequency as in [7], [8], [6]. On the other hand, the threshold value β is fixed to a value that corresponds to half the minimum expected difference between the two cost functions C_m and C_s. Arriving at expressions for the selection of these parameters is omitted from the current article for brevity and will be published elsewhere.

IV. Simulation results

The performance of the proposed technique is evaluated by computer simulations. In the simulations, a typical IS-95 signal is generated, pulse-shaped, and transmitted through a multipath Rayleigh fading channel. The total power gain of the channel components is normalized to unity. The delay between the two multipath components is chosen to be multiples of $T_c/8$. Both multipath components fade independently at a maximum Doppler frequency of $f_D = 80$ Hz. Additive white Gaussian noise is added at the output of the channel to account for both multiple access interference and thermal noise. The received chip energy-to-noise ratio (E_c/N_o) of the input sequence, $r(n)$, is varied in the range of -10 to -20 dB.

A. Effect of R on P_d

Figure 3 shows the probability of multipath detection (P_d) versus E_c/N_o for four different values of the ratio between the prompt ray power and the overlapping ray power ($R(dB) = 20\log_{10}(\alpha_1/\alpha_2)$). In these simulations, the delay between the two rays is equal to $T_c/8$, β=0.001, and P_d is calculated as the average of 100 runs. For R=0 dB (equal rays), P_d is approximately equal to unity for the chosen range of E_c/N_o. On the other hand, P_d is approximately equal to zero for $R = \infty$ (single-path propagation). Thus the proposed technique can successfully distinguish between single-path and multipath propagation, even for low values of E_c/N_o.

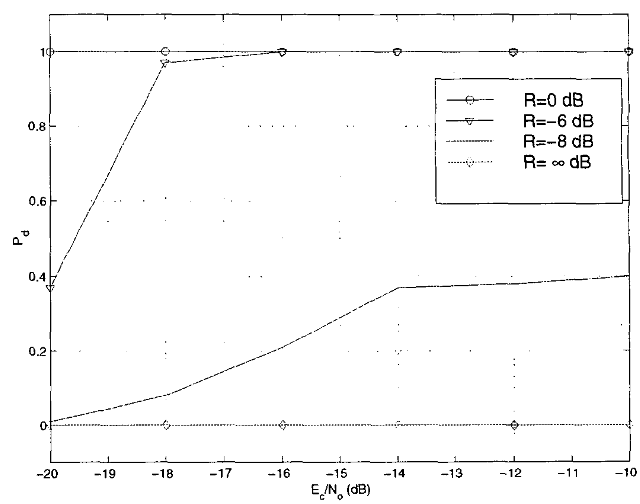

Fig. 3. *Probability of multipath detection versus* E_c/N_o.

B. Effect of $\Delta\tau$ on P_d

Figure 4 shows the probability of multipath detection (P_d) versus E_c/N_o for four different values of the delay between the two rays, $\Delta\tau$. In this simulation, R, is set to -5 dB for the multipath case and ∞ for the single-path case, β=0.0042, and P_d is calculated as the average of 100 runs. We can see from these results that the proposed algorithm has perfect detection probability except at very low values of E_c/N_o and relatively small values of $\Delta\tau$ ($T_c/8$).

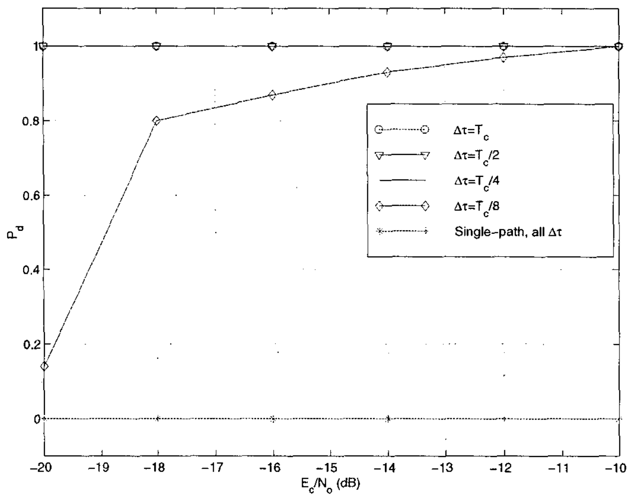

Fig. 4. *P_d versus E_c/N_o for different values of $\Delta\tau$.*

C. Effect of M on P_d

We now check the performance of the proposed detection technique for finite length received sequences, i.e., for practical values of M. Figure 5 shows the effect of varying M on the probability of multipath detection, P_d, for multipath ($R = 0$dB) and single-path ($R = \infty$dB) cases, respectively. Here we can see that the precision of the detection process increases with M. This is expected as the assumption that the channel multipath components fade independently is not feasible unless a long enough received sequence is used, i.e., for long enough M. Note also that the results reflect that for the conditions described above, a very high probability of detection can be achieved for M larger than 64, which is a reasonable value in practice. Notice that for $R = \infty$dB, the probability of detection is zero for all considered values of M, i.e., no false alarm was ever noticed in these simulations. Thus, a relatively smaller value of M can guarantee that no false alarm occurs. This is in fact a useful property of the proposed detection method as a false alarm could be more damaging to the estimation process than not detecting existing overlapping multipath components.

D. Mobile-positioning application

With a priori channel information provided by the proposed method in hand, an adaptive overlapping multipath resolving algorithm was developed in [12]. It was shown that this adaptive algorithm possesses a superior performance over conventional algorithms (see [12] for more details and simulation results).

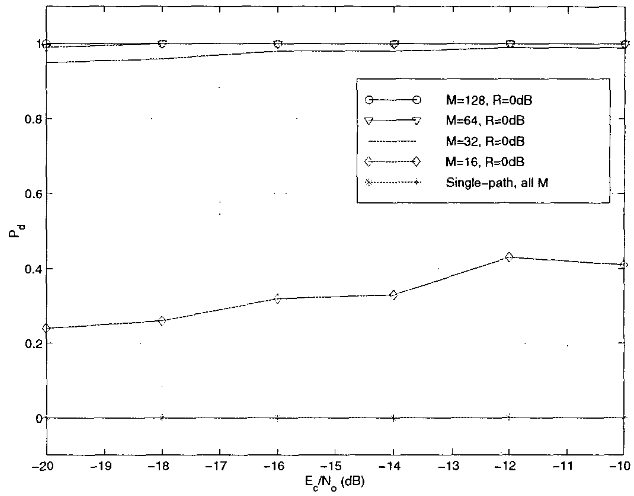

Fig. 5. *P_d versus E_c/N_o for different values of M.*

V. Acknowledgement

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