Adaptive Multipath Resolving for Wireless Location Systems [*]

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Abstract

In this paper we develop an adaptive technique for resolving overlapping multipath components. The technique relies on replacing the least-squares operation needed for resolving overlapping components by a gradient-based adaptive filter with projections. The projections are designed to incorporate a-priori channel information and improve the algorithm robustness against data ill-conditioning and high noise levels, which are common in wireless location applications.

1 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 government mandate for such services, given in [1], has led to the development of numerous mobile-positioning systems (e.g., [2]). Such systems have many other applications, besides E-911 public safety, such as location sensitive billing, fraud protection, mobile yellow pages, and fleet management (see, e.g., [3, 4]).

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 [2, 5]. 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., [5]).

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., [6, 7, 8]). 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 [8] for more details).

The goal of this paper is to develop an alternative to the least-squares operation, which is relatively *robust* to noise enhancement that results from matrix ill-conditioning. The method relies on replacing the least-squares operation needed for resolving overlapping multipath components by a gradient-based adaptive filter with projections. The projections are designed to incorporate a-priori channel information and improve the algorithm robustness to data ill-conditioning and high noise levels, which are common in wireless location applications.

2 Extracting A-priori Channel Information

In this section we illustrate how to extract useful a-priori channel information from the received signal. Such information will be used later in resolving overlapping multipath components via adaptive techniques. We study three different cases and show how to extract a-priori channel information in each case. Namely, we study the static, fading, and hybrid channel cases.

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

$$r(n) = c(n) \star p(n) \star h(n) + v(n) \tag{1}$$

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

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

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).

The first channel parameter to be extracted from the received signal is the *fading nature* of the first arriving ray. This prompt

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ray could either be static (non-fading), Rayleigh fading, or Rician fading (a combination of static and Rayleigh fading components). Furthermore, the prompt ray could be succeeded by an overlapping ray of a different fading nature. For example, a static prompt ray could be followed by an overlapping Rayleigh fading ray or vice versa. Knowing the fading nature of the multipath channel can be very valuable in the way the overlapping multipath components are resolved.

We now propose a technique for identifying the fading nature of the multipath channel, which is summarized as follows.

1. Two power delay profiles (PDPs) are evaluated to distinguish between static and fading multipath components. The two PDPs are given by

$$\begin{aligned} J_{st}(\tau) &\triangleq \left| \frac{1}{K} \sum_{n=1}^{K} r(n)s(n-\tau) \right|^2 \\ J(\tau) &\triangleq \frac{1}{M} \sum_{m=1}^{M} \left| \frac{1}{N} \sum_{n=n_o}^{mN} r(n)s(n-\tau) \right|^2 \end{aligned} \quad (3)$$

   where $K = NM$ is the received sequence length and

$$n_o \triangleq (m-1)N + 1, \quad s(n-\tau) \triangleq c(n-\tau) \star p(n) .$$

   Here, the coherent averaging interval, N, can be adapted according to an estimate of the maximum Doppler frequency, f_D, as done in [9, 10]. Note that the PDP, $J_{st}(\tau)$, will only include the contribution of the static multipath components as the length of the received sequence approaches infinity. The contribution of the fading ray in $J_{st}(\tau)$ would be minimal due to the long coherent averaging integration period used in building this PDP and which is extended to the total sequence length, K, in this case. On the other hand, $J(\tau)$ will reflect the existence of both static and fading multipath components due to the shorter length of the coherent averaging period N.

2. The *region of support* of both power delay profiles, R_s and R_f, respectively, are determined by comparing each PDP with a corresponding threshold, β_s and β_f, respectively. The region of support refers to the region of the delay (τ) that might contain significant multipath components. In other words, delay values outside this region are not likely to correspond to multipath components. Thus, the two regions of support are defined by

$$\begin{aligned} \tau \in R_s \quad iff \quad J_{st}(\tau) > \beta_s \\ \tau \in R_f \quad iff \quad J(\tau) > \beta_f . \end{aligned} \quad (4)$$

   We then restrict each R_s and R_f to the first continuous region of delays. In other words, R_s starts from the earliest delay that is higher than the threshold until the value of τ at which the PDP falls below the threshold. Likewise for R_f.

3. The peak of each PDP is determined along with the delays that correspond to the two peaks. Let τ_s and τ_f denote the delays of the peaks of $J_{st}(\tau)$ and $J(\tau)$, respectively

$$\begin{aligned} \tau_s &\triangleq \arg\max_{\tau} J_{st}(\tau), \quad \tau \in R_s \\ \tau_f &\triangleq \arg\max_{\tau} J(\tau), \quad \tau \in R_f . \end{aligned} \quad (5)$$

   Moreover, let m_s and m_f denote the values of the peaks of $J_{st}(\tau)$ and $J(\tau)$, respectively

$$\begin{aligned} m_s &\triangleq \max_{\tau} J_{st}(\tau), \quad \tau \in R_s \\ m_f &\triangleq \max_{\tau} J(\tau), \quad \tau \in R_f . \end{aligned} \quad (6)$$

4. The number of fading overlapping multipath components, L, that exist in the region of support, R_f is determined by using the multipath detection algorithm of [11].

5. Based on the values for τ_s, τ_f, R_s, R_f, and L we decide on the channel type to be one of three distinct categories from a wireless location point of view. We will denote the three channel categories to be *static*, *fading*, and *hybrid* channels. We will now define each channel type and the a priori channel information that could be extracted in each case.

2.1 Static Channels

We use the term *static channel* to refer to channels whose earliest arriving ray is a *static* or *non-fading* ray. In such cases, we need not consider the channel fading rays as their contribution can be significantly diminished by coherently averaging the received sequence for a relatively long interval. We may also add that these channels may include channels whose prompt ray is Rician fading with a relatively large portion of its power concentrated in the non-fading component of the ray, while a smaller portion of the ray power is designated to the fading component.

A channel is considered static for wireless location purposes if all the following conditions are satisfied:

1. The regions of support of R_s and R_f, defined in (4), overlap.
2. Not more than one fading multipath component exists in R_f, i.e., $L = 1$.
3. The peak of $J_{st}(\tau)$ precedes that of $J(\tau)$, i.e., $\tau_s \leq \tau_f$.

If the previous conditions are satisfied simultaneously, then we say that the prompt ray is a static or non-fading ray.

To understand why the above conditions lead to the conclusion that the channel is static from a wireless location point of view, we explain in the sequel what each condition means. First, we note that the region of support of $J_{st}(\tau)$ only contains the contribution of static rays, while that of $J(\tau)$ contains the contribution of both static and fading rays. Thus, if these regions overlap, this means that there *must* be at least one static ray in this overlapped region of τ. Second, if only one fading ray exists in this region (L=1), and the peak of $J_{st}(\tau)$ precedes that of $J(\tau)$, then this fading ray succeeds the existing static ray/rays. Thus, the first arriving ray (prompt ray) of the channel under consideration is a static ray. This prompt static ray can be separated from the overlapping fading ray by using a relatively long coherent integration interval. Fortunately, this interval can be extended to the total received sequence length as no fading ray have to be considered in this case. Still, we do not know in this case whether one or more static rays exist in the region of support of $J_{st}(\tau)$. Thus, a multipath resolving technique has to be applied to resolve any existing static rays. This technique will be described in the next section.

In conclusion, if the above conditions are satisfied simultaneously, we need only resolve static rays. Furthermore, the following a priori information can be used in the multipath resolving stage:

1. The delay of the ray to be resolved is confined to R_s.
2. The maximum of the amplitude of any ray in this region is less than or equal to the square root of the maximum value of $J_{st}(\tau)$. This value is equal to $\sqrt{m_s}$. This can be explained as follows. Since $J_{st}(\tau)$ is the contribution of the sum of one or more static rays, then the maximum of the sum must be larger than or equal to any of the existing rays. The equality occurs if only one static ray exists in R_s.

2.2 Fading Channels

We will consider a channel to be a *fading channel* for wireless location purposes if the prompt ray is a *fading* ray, which does not overlap with any static ray. In fact, identifying such a channel is relatively easy and is done as follows. A channel is considered a fading channel if the regions of support R_s and R_f, defined in (4), *do not overlap.* We note that if R_s and R_f *do not overlap* then it follows that the channel under consideration has a at least one fading ray whose contribution to $J(\tau)$ was detected, while its contribution to $J_{st}(\tau)$ was diminished due to the relatively long coherent averaging period used in building $J_{st}(\tau)$.

In this case, the following a priori information can be used in the multipath resolving stage:

1. The delay of the ray to be resolved is confined to R_f.
2. The number of fading overlapping multipath components that exist in R_f is equal to L.
3. The maximum of the amplitude of any ray in this region is less than or equal to the square root of the maximum value of $J(\tau)$ after equalizing for the noise and fading biases that may arise in this value. This value is equal to $\sqrt{C_f\ (m_f - B_n)}$, where B_n are C_f are two noise and fading biases that can be calculated as described in [9, 10].

2.3 Hybrid Channels

A channel is considered a *hybrid channel* for wireless location purposes if we are not able to decide whether the prompt ray is of static or fading nature, i.e., we suspect that there exist overlapping static and fading rays in the vicinity of the first arriving ray. Furthermore, a channel is considered a hybrid channel if both static and fading rays have to be resolved.

A channel is hybrid channel if all the following conditions are satisfied:

1. The regions of support R_s and R_f, defined in (4), overlap.
2. More than one fading multipath component exists in R_f, i.e., $L > 1$, or the peak of $J(\tau)$ precedes that of $J_{st}(\tau)$, i.e., $\tau_f < \tau_s$.

We note that in the case of hybrid channels, static rays can be separately resolved first, using the following a priori channel information.

1. The delay of the static rays are confined to R_s.
2. The maximum of the amplitude of any of the static rays is less than or equal to $\sqrt{m_s}$.

After resolving static rays, the following a priori channel information can be used in the second stage of multipath resolving for hybrid channels:

1. The channel contains the static rays obtained from the first multipath resolving stage.
2. The delays of the fading rays are confined to R_f.
3. The number of fading overlapping multipath components that exist in R_f is equal to L.
4. The maximum of the amplitude of any ray in this region is less than or equal to $\sqrt{C_f\ (m_f - B_n)}$.

The flow diagram, shown in Figure 1, summarizes the procedure used to determine the type of the channel for wireless location purposes based on the measured parameters τ_s, τ_f, R_s, R_f, and L.

2.4 Simulation Results

We now simulate the proposed channel identification algorithm for various types of channels. In the simulations, a typical IS-95 signal is generated, pulse-shaped, and transmitted through a multipath various channels. The total power gain of the channel components is normalized to unity. Four different channel types are considered in the simulations. Fading rays are independently Rayleigh fading rays of a maximum Doppler frequency f_D. 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, which is common for CDMA IS-95 systems.

To examine the performance of the channel type identification algorithm, 4000 channels are generated. The type of each channel is randomly chosen to be one of the four types; 2 ray static, 2 ray fading, 2 ray hybrid, and single ray fading channels. The channel type identification algorithm is run for each channel for various values of the maximum Doppler frequency f_D and the estimation period $T = KT_c$. The performance measure that we consider for the the proposed algorithm is the probability of detection of each channel type, which we denote by P_d.

Figure 2 show the probability of detecting each channel type for T 0.5 seconds and f_D = 40 Hz. Several other simulations were carried out for various values of T and f_D and are not given here for space limitations.

We can conclude from these simulation results that the proposed algorithm has a remarkable ability of identifying the channel type in most of the cases. The algorithm fails only to differentiate between multipath and single path fading channels for low values of T and/or f_D. For $T > 0.5$ second (which is reasonable in wireless location applications), the algorithm can identify the channel type with a high accuracy even for low values of f_D.

3 An Adaptive Projection Technique

We now present an adaptive projection technique for channel estimation that exploits the a priori channel information obtained

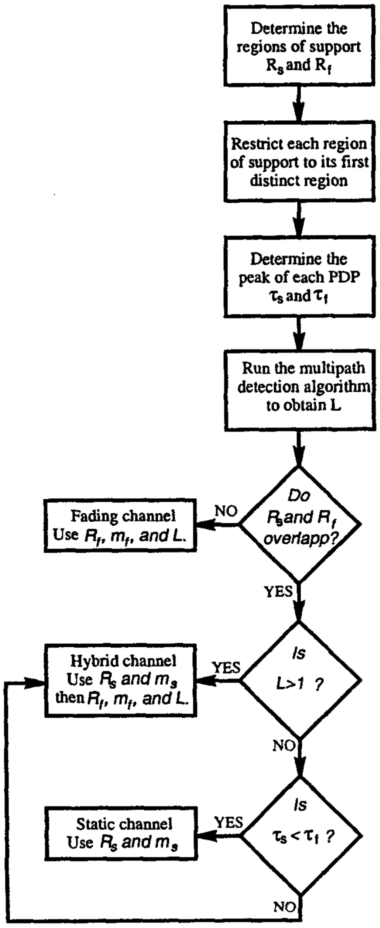

Figure 1. Flow diagram for channel type identification.

from the channel identification algorithm. The technique starts from the block least-squares estimation scheme of [8] and replaces the least-squares operation by an adaptive filter. The proposed method can be summarized as follows.

The a priori channel information from Section 2 is incorporated into the adaptive solution as follows:

1. The received signal $r(n)$ is applied to a bank of matched filters $s(n-\tau)$, each with a different delay, i.e., $r(n)$ is multiplied by locally generated replica of the transmitted sequence $s(n-\tau)$, at various values of the delay τ.
2. A parallel to serial converter is applied to the output of the matched filter bank $s(n-\tau)$, to form the signal $d(i)$.
3. An adaptive filter of weight vector $\boldsymbol{h}_i$ is used to estimate the channel multipath components at the i^{th} iteration. The regressor vector $\boldsymbol{u}_i$ is formed using delayed replica of the known pulse shape.

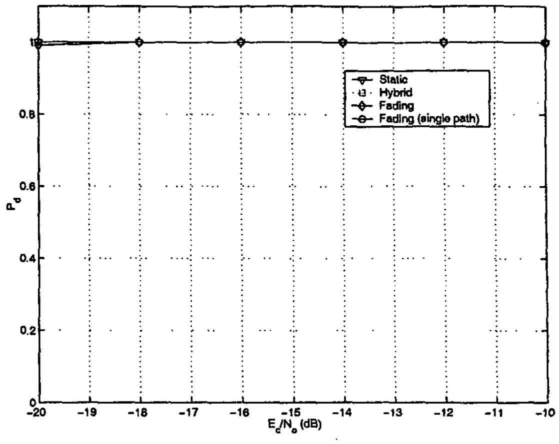

Figure 2. P_d vs. E_c/N_o for f_D = 40 Hz and T = 0.5 sec.

4. Successive projections are applied to the adaptive filter weight vector $\boldsymbol{h}_i$ every N_p iterations, in the following manner

$$\begin{aligned}\boldsymbol{h}_{i+1} &= \text{proj}\left[\boldsymbol{h}_i + \mu(i)\boldsymbol{u}_i^T\left(d(i) - \boldsymbol{u}_i\boldsymbol{h}_i\right)\right],\ i = N_p, 2N_p,. \\ &= \boldsymbol{h}_i + \mu(i)\boldsymbol{u}_i^T\left(d(i) - \boldsymbol{u}_i\boldsymbol{h}_i\right),\ i \neq N_p, 2N_p, \ldots\end{aligned}$$

   Here N_p is an integer greater than or equal to one and less than or equal to the total number of iterations performed.
5. The successive projections are based on information obtained from the lower branches of the block diagram in Figure 3. The first branch extracts information about the channel region of support and maximum amplitude. This information is extracted by non-coherently averaging the output of the matched filter bank to form $J(\tau)$. The second branch is used to detect the channel type as explained earlier in the chapter as well as the existence of overlapping multipath components and estimating their number as given in the previous chapter. The adaptive filter weight vector is successively projected on the set of all possible elements satisfying the constraints obtained from the three branches. The adaptive filter weight vector is iterated till it reaches steady state.
6. The weight vector is then averaged non-coherently to avoid attenuation in the amplitude of the output signal due to changes in the channel phase. The output of the non-coherent averaging is used to obtain the time and amplitude of arrival of the prompt ray.

3.1 Simulation Results

The robustness of the proposed algorithm in resolving overlapping multipath components is tested by computer simulations. In

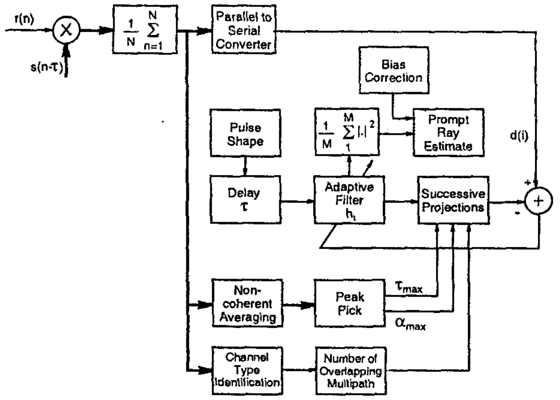

Figure 3. Adaptive multipath resolving scheme.

the simulations, a typical IS-95 signal is generated, pulse-shaped, and transmitted through a multipath various channels. The total power gain of the channel components is normalized to unity.

Figure 4 is a sample simulation that compares the output of the proposed algorithm to the output of the block least-squares multipath resolving technique of [8] for a two-ray fading multipath channel whose static amplitude response is shown in the first plot of the figure. The second and third plots respectively show the output of block least-squares and block regularized least-squares stages. It is clear that both least-squares techniques lead to significant errors in the estimation of the time and amplitude of arrival of the first arriving ray. The last plot shows the output of the proposed estimation scheme. It is clear that the proposed algorithm is significantly more accurate than least-squares techniques.

4 Conclusions

In this paper we presented a channel identification algorithm that extracts a priori channel information. This information is then used by an adaptive filter to resolve overlapping multipath components in a robust manner.

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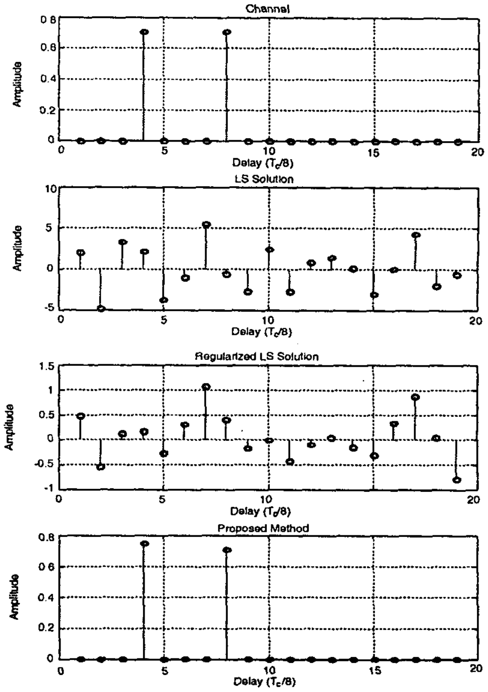

Figure 4. Simulation results.

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