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Wireless Position Location: Fundamentals, Implementation Strategies, and Sources of Error

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Abstract

This paper presents an overview of basic RF position location strategies which are feasible for ubiquitous deployment by cellular-type wireless system providers. Limitations on practical ability to locate mobile RF transmitters and the effects of real world channel degradation on direction-finding and time difference of arrival systems are also discussed.

I. INTRODUCTION

The ability to locate the source of RF transmissions has been of considerable interest for many years. Historically, the main interest for wireless position location has been for military, law-enforcement, and safety applications - either to find people in distress or to isolate and neutralize people who are causing distress. More recently, interest has also emerged in using wireless position location for Intelligent Transportation System applications such as incident management, traffic routing, fleet management, and E-911 telephone service [1].

In this paper, we discuss the fundamental function of position location (PL) techniques that are compatible with the existing base of mobile users in a large-scale (cellular-type) position location system. We also consider performance limitations and sources of error in direction finding (DF) and time-difference-of-arrival (TDOA) PL techniques. Finally we focus on the effects of multipath propagation as a significant source of estimation error for cellular-type position location and examine some possible methods of mitigating the detrimental effects of multipath.

II. BASIC POSITION LOCATION TECHNIQUES

A number of system designs have been proposed as feasible solutions to the wireless PL problem [1]. Because there are over 48 million handsets in use in the U.S. alone (as of mid-1997), any widely deployed PL system will likely need to be compatible with the existing base of operational handsets [2], [3], [4]. GPS-based and other techniques where synchronization and/or calculations must be performed by the mobile transmitter would require replacing most existing mobile units with modified handsets. Such replacement may not be feasible in the near term. We therefore limit discussion in this paper to those techniques which can be used with existing handsets. PL techniques that can be used with existing handsets may be classified into one of three basic approaches: beacon location techniques, direction finding techniques, and time difference of arrival techniques. Each of these methods is briefly described below.

Beacon location methods involve placing a large number of simple receivers (beacons) at known locations in a region of interest. Beacons might be placed throughout a city or spread out along roads and highways. Each beacon then listens or "sniffs" for a known signal from a mobile transmitter and measures the received signal strength. The relative link quality between the beacon and the mobile location is used to determine the location of the mobile. The beacon which receives the strongest signal from a mobile is deemed to be the closest beacon to the mobile. The coordinates of that beacon (or perhaps a weighted average of several nearby beacons) which receives the strongest signal from a given mobile then becomes an estimate of the mobile location. The advantage of beacon-type systems is in the simplicity and low cost of implementation. The disadvantage of beacon-type

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systems is that they typically provide poor quality position location estimates.

Under a 1996 FCC Rule Making Order [2], wireless service providers are required to provide a cell-site location mechanism in their wireless systems by 1997 as a step toward providing more accurate location of cellular and PCS mobile units in the future. This can be viewed as a crude type of beacon location system, where the individual base-stations are the beacons, and a single-site location (SSL) system is used. By about 2002, service providers are required to achieve the capability to identify the location of a mobile unit making a 911 call to within a radius of no more than 125 meters in 67 percent of all cases. In order to provide mobile position coordinates with enough precision to satisfy future requirements, techniques other than beacon location will be required.

Possibly the most intuitive PL method uses the angle-of-arrival (AOA) of a signal received from a mobile at two or more base stations. From the AOA estimate, a line of bearing (LOB) from the base station to the mobile transmitter can be drawn. Multiple LOBs, drawn from different base station locations, intersect at the estimated location of the mobile. Estimation of AOA, commonly referred to as DF, can be accomplished either with a mechanically steered narrow beamwidth antenna or with an electronically steered array of antennas. The accuracy of DF techniques depends on a number of factors (discussed subsequently). The advantages of DF techniques (versus TDOA) are that a PL estimate may be determined with as few as two base stations (provided the mobile is not on or near a line joining the two base stations), and that no time synchronization between base stations is required. The disadvantages of a DF system are that they require relatively large and complex hardware, and that the position estimate degrades as the mobile moves farther from the base station(s).

Another PL technique, TDOA, calculates the differences in time-of-arrival of a mobile signal at multiple (two or more) pairs of stations. Each TDOA measurement yields a hyperbolic curve along which the mobile may lie. The intersection of these curves then yields an estimate of position. Assuming that multiple base stations receive a signal transmitted by a mobile user, and that all of the base stations have a synchronized time reference, correlation techniques may be employed to estimate the TDOA of the mobile signal at each base station.

Given the TDOA, we can calculate the difference in propagation distance to each base station, since the propagation distance is simply the propagation time multiplied by the speed of propagation (approximately 3×10^8 m/s). Expressing the relationship mathematically (for a two dimensional case),

$$R_{i,j} = ct_{i,j} = \sqrt{(X_i - x)^2 + (Y_i - y)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2} \quad (1)$$

where $X_{i,j}$ and $Y_{i,j}$ are the (known) coordinates of the ith and jth base stations, $t_{i,j}$ is the (estimated) difference in propagation time from the mobile to the ith and jth base stations, c is the propagation speed, $R_{i,j}$ is the (calculated) difference in propagation distance from the mobile to the ith and jth base stations, and x and y are the (unknown, but desired) coordinates of the mobile transmitter.

From two base stations, we find one equation (a hyperbola) with two unknowns (the x, y coordinates of the mobile), so another independent TDOA measurement is needed in order to generate a position solution. Thus, at least three base stations are required to perform position location with TDOA. The set of equations (1) is nonlinear, but many efficient solution methods have been developed, e.g., [1], [5], [6], [7].

A comment is needed here on the problem of PL estimation when no line of sight exists. A basic assumption behind both DF and TDOA techniques is that a line-of-sight propagation path exists between the mobile and the base stations. Given a line-of-sight path, even if multipath is present, we have only to determine which path is the first-arriving path (e.g. by cross-correlation) in order to identify the line-of-sight path. However, if no line-of-sight exists, PL accuracy will suffer. This remains an open problem.

III. DF IMPLEMENTATION ISSUES

As mentioned earlier, AOA may be measured either with a mechanically steered narrow beamwidth antenna or with a fixed array of antennas. Clearly the more practical approach for the problem here is to use an antenna array. A common DF array configuration is a uniform linear array (ULA). In ULA, the antennas lie on a straight line and have equal inter-element spacing. Typically the inter-element spacing is on the order of one-half the wavelength corresponding to the received signal carrier frequency. The number of elements in such an array typically ranges from 4-10.

In a high performance DF system, each antenna feeds a separate receiver, with the mixers and A/D converters in all receivers being driven by the same oscillators and clocks. This must be done in order to preserve coherence between the signals received at each antenna. Once the received signals have been sampled, they are converted to complex baseband format. The signals are then passed to DSP hardware, where the DF algorithm resides. A wide variety of algorithms can be used to estimate AOA, each having its own advantages and disadvantages (e.g., see [8]).

The classical approach to DF is to steer the main beam of the array over the region of interest and measure the received power. This is referred to as the beamforming approach. The main drawback of beamforming is that the angular resolution is limited by the beamwidth of the array. The half-power beamwidth of a linear array of antennas is approximately equal to $1/L$ (in radians,) where L is the array aperture.

In many situations we must be able to resolve closely spaced multipath delays. In flat fading, the delay spread is very small relative to the signal bandwidth, so the multipath components will all be strongly correlated. Since delay spread and angular spread are interrelated [9], [10], we must often be able to handle small angular spread.

Resolving closely spaced correlated signals can be accomplished using a Maximum Likelihood (ML) DF algorithm, such as used in [4]. These algorithms require a multidimensional search, but efficient techniques for performing such a search have been developed. Another approach is to use spatial smoothing followed by some high resolution algorithm such as MUSIC [11], [12], [13], [14]. This approach is less computationally intensive but does not perform as well as an ML technique. Besides the algorithm selected, factors which affect DF accuracy include SNR, integration time, number of antennas, hardware nonidealities, and array calibration error.

Among the issues in DF implementation, the most critical in terms of limiting performance is array calibration. High resolution DF requires that the array response (effectively the array beam pattern) be known very precisely. Typically this requires calibrating the antenna array, since the array will not behave ideally because of such effects as antenna coupling, near-field scattering, etc. Array calibration must be periodically updated as well. Calibrating an array mounted on a tower in an urban area may be very difficult and expensive. This, combined with possible zoning and aesthetic problems associated with installing an array of antennas, are impediments to using DF-based PL systems.

IV. TDOA IMPLEMENTATION ISSUES

The classical approach to estimating TDOA is to compute the conventional cross-correlation of a signal arriving at two base stations. The TDOA estimate is taken as the delay which maximizes the cross-correlation function. The cross-correlation is also used to determine at which base station the signal arrived first. These two pieces of information yield an unambiguous hyberbolic curve. A key limitation to conventional cross-correlation is that the time resolution of the TDOA estimate, in the presence of multipath, is limited to approximately $1/B$, where B is the bandwidth of the received signal. For example, when receiving a 1 MHz signal, the time delays can only be resolved to within $1\mu s$, or within 300 meters.

The temporal resolution limit of conventional cross-correlation can be explained by analogy with the problem of resolving closely spaced sinusoids. It is well known that a periodogram cannot resolve two sinusoids that are more closely spaced in frequency than $1/N$, where N is the number of data samples. In the frequency domain, the true spectrum of two sinusoids is smeared by convolution with the Fourier transform of a rectangular window. Similarly, the true temporal characteristics of the channel are smeared by windowing in the frequency domain. If the temporal features are finer than $1/B$ where B is the bandwidth of the signal, the temporal features cannot be resolved, at least by using cross-correlation.

Assume for the moment that we cannot resolve multipath components that arrive within $1/B$ seconds of each other. Table I shows the distance that a signal can propagate in $1/B$ seconds. This is the potential PL error that can occur if the first arriving component is not resolved. Note that even with IS-95 it will be necessary to resolve multipath components that are more closely spaced than $1/B$. This illustrates the need for high resolution estimation of TDOA. A general approach for performing high resolution estimation of TDOA is discussed later, but first we discuss other other factors which affect the accuracy of a TDOA position estimate.

Standard	Bandwidth	PL Error - c/B
AMPS	30 kHz	10,000 m
GSM	200 kHz	1,500 m
IS-95	1.25 MHz	240 m

TABLE I

PL ERROR WITH MULTIPATH TIME-DELAY RESOLUTION LIMITED TO $1/B$.

A. *Signal Processing Considerations*

The Cramer-Rao Lower Bound (CRLB) places a lower bound on the variance of a parameter estimate that can be achieved by any unbiased estimator. The CRLB for TDOA estimation depends on SNR, Integration Time, Signal Bandwidth, and number of multipath components present. However, [3] reports that in a practical implementation of a TDOA PL system, hardware limitations and channel degradations are dominant sources of TDOA estimation error.

The strength of the signal (SNR) received at each base station directly impacts the quality of the TDOA estimate and determines the best PL estimate we can expect to achieve. In the case of very low SNR signals, the abiltiy to form good TDOA estimates can be significantly impaired. Since cellular-type wireless systems are designed to minimize the number of base stations receiving a high-strength signal, the lack of signals with adequate SNR at multiple base staions can cause significant variation in PL accuracy in TDOA systems. We should note however that accurate TDOA estimates can be obtained even if only one of the base stations receives a signal with high SNR.

Co-channel interference effectively reduces the SNR of the signal and thus degrades the quality of the TDOA estimate by raising the CRLB. In highly crowded RF environments, co-channel interference has the potential to be a significant degrading factor in PL estimates. However, measurements reported in [15] show that even in urban/suburban cellular-type radio environments, co-channel interference is not typically a significant problem.

B. *Hardware Requirements*

In order to implement a TDOA-based PL system, the receivers at all cell-sites must be synchronized. This presents a disadvantage in complexity as compared to a single or dual site DF system. One way to provide synchronization is to derive the timing reference from GPS. Another approach is to use Rubidium or Cesium clocks. It is important that all mixers and oscillators in the receiver be derived from exactly that same timing reference.

It also is important that the phase response of the receiver be as linear as possible. This is to allow measurement of small phase differences. It might be necessary to compensate for non-linear phase response by calibrating the receiver by injecting a known signal into the front end.

C. *Channel Effects*

Mobile radio channels are distinctive for their multipath propagation characteristics [10]. Multipath reduces the accuracy of TDOA estimates in position location systems. Multiple copies of the same signal, arriving at different times, cause small scale fading (possibly leading to reduced SNR) and increase the variance of TDOA estimates.

References [15] and [3] both report that mitigation of multipath, based on field experience, is a critical aspect of accurate PL estimates. Among the performance-limiting factors discussed above, multipath propagation has the potential to be a dominant factor for PL estimate degradation in TDOA systems. Under many practical, "real world" channel conditions, if steps are not taken to mitigate the effects of multipath, it will not be possible to estimate the position of the mobile within the limits required for many applications.

It has been noted that the temporal resolution of conventional approaches is limited by the autocorrelation width of the transmitted signal. However, other approaches can be used to achieve better resolution. In the area of frequency estimation, it is well known that sinusoids which are more closely spaced than $1/T$ where T is the observation interval cannot be resolved by conventional Fourier-based techniques, such as the periodogram. Other techniques which make more assumptions about the data can achieve higher resolution, such as by fitting an autoregressive (AR) model to the data, or by modeling the data as sinusoids in white noise (e.g., see [16]). In an analogous fashion there exist methods for high resolution estimation of multipath delay parameters.

One approach is to use a high resolution frequency estimator with the time-series replaced by an estimated channel transfer function [17]. Model the channel impulse response $h(t)$ as a sum of discrete multipath components,

$$h(t) = \sum_{i=1}^{M} \alpha_i \delta(t - \tau_i), \tag{2}$$

where there are M discrete delay components, and α_i is the complex amplitude for delay τ_i. Then the Fourier transform of $h(t)$ yields the transfer function

$$H(\omega) = \sum_{i=1}^{M} \alpha_i e^{-j\omega\tau_i}. \tag{3}$$

We see that the transfer function consists of a sum of M discrete frequency components. Thus any spectrum estimator can also be used to estimate time delays by replacing the time-series in the frequency estimator with the transfer function $H(\omega)$. Other high resolution approaches can be derived from the perspective of Maximum Likelihood, or by exploiting more information on the channel or on the transmitted signal. For example, see [18] and references therein.

V. SUMMARY

Under the constraint of being compatible with the large installed base of cellular-type mobile transmitters, direction finding and/or TDOA systems emerge as practical solutions to the wireless position location problem. Each approach has its advantages.

DF systems have the advantage that they require as few as two base stations in order to formulate a PL estimate and they do not require inter-base station time synchronization. The disadvantages of DF systems are relatively expensive hardware and the need to compute and maintain accurate array calibration. TDOA systems are relatively inexpensive to implement. However, they require "hearability" at a minimum of three base stations, and all base stations must be synchonized with each other to nanosecond accuracy. Both systems require the resolution of closely spaced multipath components in order to provide desired accuracy. It is believed that the cost and maintenance advantages of TDOA-based systems may make TDOA-based systems a more attractive PL solution.

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