

PERFORMANCE OF TOA ESTIMATION TECHNIQUES IN INDOOR MULTIPATH CHANNELS

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Abstract – In this paper the problem of TOA estimation in multipath channels are discussed. Brief introductions of TOA estimation techniques that can be used to improve the performance in multipath channels are presented. Some simulation results based on channel measurement data in indoor environment is presented to demonstrate and compare the performance of different TOA estimation techniques.

Keywords – TOA, performance, indoor, multipath.

1. INTRODUCTION

With the emergence of location-based applications, location-finding techniques are becoming increasingly important [1]. Time-of-arrival (TOA) is one of the most widely used location metrics in geolocation systems. The basic problem of TOA-based techniques is to accurately estimate the propagation delay of the radio signal arriving from the direct line-of-sight (DLOS) propagation path. Estimation of TOA falls into the field of signal parameter estimation, and it was studied in the literature for sonar, radar, and GPS applications [2,3]. In those traditional applications, the radio propagation channel is normally assumed to be single-path, only disturbed by additive white Gaussian noise (AWGN). But indoor geolocation systems suffer from severe multipath radio propagation situation. As a result, there is a need for studies of TOA estimation techniques in indoor multipath channels.

In this paper we discuss issues related to TOA estimation in multipath channels. Brief introductions of TOA estimation techniques that can be used to improve the performance in multipath channels are presented. Some simulation results based on channel measurement data in indoor environment is presented to demonstrate and compare the performance of different TOA estimation techniques.

The rest of the paper is organized as follows. In section II, we discuss some issues related to the estimation of TOA as well as time-difference of arrival (TDOA), which is an alternative of TOA and closely related to TOA estimation, in multipath channels. Then a brief introduction of the TOA estimation techniques is presented in section III. In section IV, some simulation results based on measurement data are presented to demonstrate the performance of TOA

estimation in indoor environments. At last, summary and conclusions are presented in section V.

II. TIME DELAY ESTIMATION IN MULTIPATH CHANNELS

A. TOA Estimation

The TOA estimation problem is defined as follows. A known radio signal $s(t)$ is emanated from a transmitter and the signal is monitored at a spatially separated receiver, which estimates the propagation delay of the signal from the transmitter to receiver. Assuming the radio propagation channel between transmitter and receiver is single-path and disturbed only by additive white Gaussian noise. Then the received signal can be mathematically expressed as

$$x(t) = \alpha s(t - D) + n(t), \quad (1)$$

where the parameter D is the signal propagation delay, α is the complex signal strength attenuation parameter, and $n(t)$ is additive white Gaussian noise. The maximum likelihood (ML) estimate of the propagation delay can be obtained by finding the value of τ that maximizes the correlation function of received signal $x(t)$ and transmitted signal $s(t)$ [2], that is

$$\begin{aligned} r_{xs}(\tau) &= \frac{1}{T_0} \int_{T_0} x(t)s(t-\tau)dt \\ &= \alpha r_{ss}(\tau - D) + v(\tau), \end{aligned} \quad (2)$$

where $r_{ss}(\tau)$ is the auto-correlation function of the transmitted signal and $v(\tau)$ is additive noise term. The correlation function $r_{xs}(\tau)$ is often referred to as delay profile while the function $|r_{xs}(\tau)|^2$ is referred to as power delay profile. In practice, the delay profile can be measured at receiver using a sliding correlator or a matched filter. The performance of the ML estimator is bounded by the Cramer-Rao lower bound (CRLB), which is the minimum variance of TOA estimation errors about the true time delay [2].

If the signal is transmitted through a multipath channel, which is modelled as

$$h(t) = \sum_{k=0}^{L_p-1} \alpha_k \delta(t - \tau_k), \quad (3)$$

where L_p is the number of multipath components, α_k and τ_k are complex amplitude and propagation delay of the k th path, respectively, the received signal becomes

$$\begin{aligned} x(t) &= s(t) \otimes h(t) + n(t) \\ &= \sum_{k=0}^{L_p-1} \alpha_k s(t - \tau_k) + n(t). \end{aligned} \quad (4)$$

In geolocation applications the propagation delay of the DLOS path τ_0 needs to be estimated. So that in this paper, the term TOA is used to only refer to the propagation delay of the DLOS path in multipath channels if not specified differently.

Using the same correlation receiver as used in the ML estimator derived with the single-path channel model, the delay profile measured in multipath channels is given by

$$r_{xx}(\tau) = \sum_{k=0}^{L_p-1} \alpha_k r_{xx}(\tau - \tau_k) + v(\tau). \quad (5)$$

We note that in contrast to that of single-path channels, in multipath channels the measured delay profile is a weighted sum of multiple shifted auto-correlation functions of the transmitted signal. In general, the same correlation technique is used for TOA estimation in multipath channels. As discussed in [4], whether the propagation delay of the DLOS is detectable or not largely depends on the instantaneous channel profile between transmitter and receiver and the characteristics of ranging systems such as signal bandwidth, receiver sensitivity, and receiver dynamic range. The receiver sensitivity specifies the minimum power level of a signal that can be detected and the receiver dynamic range defines the difference in the power level of the strongest and the weakest detectable signals. According to the detectability of the DLOS path, radio propagation channel profiles are classified into three categories for TOA estimation in indoor geolocation applications [4]. The first category is dominant direct path (DDP) case, in which the DLOS path is detectable by measurement systems and it is the strongest path in the channel profile. The second category is non-dominant direct path (NDDP) case, where the DLOS path is detectable by measurement systems but it is not the dominant path in the channel profile. The third category is undetected direct path (UDP) case where measurement systems cannot detect the DLOS path. The channel profiles can also be grouped simply into DLOS and NLOS (no-LOS) cases according to whether the DLOS path is detectable or not [1].

Figure 1 presents power delay profiles obtained using direct-sequence spread-spectrum (DSSS) signals with three

different channel profiles. In measuring delay profiles using DSSS signals, a maximal-length shift register sequence (m -sequence) is commonly used as pseudo-noise (PN) code. The auto-correlation function of the m -sequence is a triangular function similar to the one shown in Fig. 1a with a spread of $\pm T_c$ around the correlation peak, where T_c is the chip interval of the sequence. The spread of the correlation peak depends on the signal bandwidth since the bandwidth of baseband DSSS signals equals to $1/T_c$ without pulse shaping. When the channel is single-path, the propagation delay D can be determined using the ML estimator by finding the delay value that corresponds to the peak of the power delay profile shown in Fig. 1a and the variance of the estimate is bounded by the CRLB.

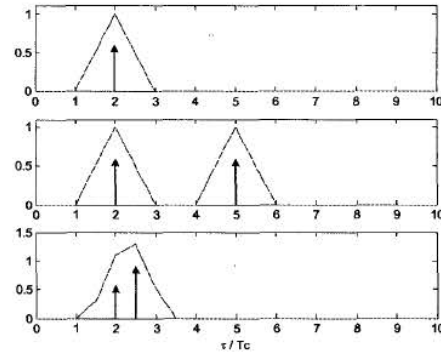


Fig. 1. Power delay profiles with different channel profiles. (a) Single-path channel with propagation delay $D = 2 \times T_c$; (b) two-path channel with signal attenuation parameters $\alpha_0 = \alpha_1$, and propagation delays $\tau_0 = 2 \times T_c$ and $\tau_1 = 5 \times T_c$; (c) two-path channel with signal attenuation parameters $\alpha_0 = 0.6 \times \alpha_1$, and propagation delays $\tau_0 = 2 \times T_c$, and $\tau_1 = 2.5 \times T_c$.

When a radio signal is passed through a multipath channel, the delay profile consists of multiple copies of delayed version of auto-correlation function of the transmitted signal as given by (5). Figure 1b shows the power delay profile obtained in a two-path channel. We can observe that when the difference between adjacent path delays is greater than $2 \times T_c$, clearly separated correlation peaks appear in the power delay profile so that the delay of the DLOS can be determined by finding the delay value that corresponds to the first peak. When the first peak is the strongest one of the delay profile, the channel belongs to the DDP category. When the first peak is not the strongest one but it is detectable with given receiver sensitivity and receiver dynamic range, it falls into the NDDP case. If the strength

of the first peak is below the receiver sensitivity or the difference between the strength of the first peak and the strongest peak exceeds the receiver dynamic range, the DLOS path is not detectable so that the channel profile falls into the UDP category. In this case, dramatically large TOA estimation errors may occur.

When the difference between adjacent delays is smaller than $2 \times T_c$, the two delayed correlation functions overlap. Due to the construction and deconstruction effects between the two overlapped correlation functions, as shown in Fig. 1c large delay estimation error occurs if the TOA is estimated by detecting the first peak of the power delay profile. Increasing signal bandwidth reduces the spread of the correlation peak and helps to resolve the DLOS path. However, it is practically impossible to increase the signal bandwidth freely due to the regulations on frequency spectrum usage posed by FCC. An alternative way of increasing the resolution lies in the application of advanced signal processing techniques as discussed in [5].

From the previous discussion we can conclude that the same ML estimator designed for AWGN channels can be used in multipath channels, but the performance of TOA estimation degrades significantly, which largely depends on the characteristics of the ranging system and the instantaneous channel profile that encountered. In summary, the following general principles can be used to improve the TOA estimation in multipath channels:

- Increase the receiver dynamic range and receiver sensitivity.
- Increase the resolution of estimation techniques by increasing the signal bandwidth or by employing advanced signal processing techniques.
- Place the ranging transmitter and receiver, or deploy the reference points of indoor geolocation systems, in a way to minimize the occurrence of NLOS propagation scenarios between the transmitter and receiver.

B. TDOA Estimation

TDOA is usually used in geolocation systems as an alternative of TOA [2]. The problem of TDOA estimation is generally modelled as follows. A signal is transmitted from a remote source and monitored at two spatially separated receivers. When the radio propagation channel between the transmitter and the receivers is assumed to be single-path AWGN channel, the received signals at two receivers can be mathematically represented by

$$\begin{aligned} x_1(t) &= s(t) + n_1(t) \\ x_2(t) &= \alpha s(t + D) + n_2(t), \end{aligned} \quad (6)$$

where α is the amplitude ratio of the signals observed at the two receivers and D is the difference in the arriving time of the signals observed at the two receivers. The noises $n_1(t)$ and $n_2(t)$ are assumed jointly independent stationary random process, and the transmitted signal $s(t)$ is assumed to be uncorrelated with the noises. The receivers are synchronized in time so that the TDOA to be estimated is the time delay D . Normally a cross-correlation technique, similar to the one used in estimating TOA, is used to estimate TDOA. First the delay profile, which is the cross-correlation function of the two received signals, is obtained,

$$\begin{aligned} r_{12}(\tau) &= \frac{1}{T_0} \int_{T_0} x_1(t)x_2(t-\tau) dt \\ &= \alpha r_{ss}(\tau - D) + v(\tau), \end{aligned} \quad (7)$$

where T_0 represents the observation time interval, the auto-correlation function of the transmitted signal $r_{ss}(\tau)$ is the same as in (2), and $v(\tau)$ is additive noise term.

Then the TDOA is estimated by finding the value of delay that maximizes the delay profile in (7). A generalized correlation method can also be used in estimating TDOA, where each of the two received signals is pre-filtered. With proper choice of pre-filters, the estimation of TDOA can be improved using the generalized correlation method [6]. The CRLB can be derived for the variance of the TDOA estimation errors about the true value [2,6].

When the signal is propagated through multipath channels, the received signals at the two receivers are given by,

$$\begin{aligned} x_1(t) &= \sum_{k=0}^{L_{p1}-1} \alpha_{1k} s(t - \tau_{1k}) + n_1(t), \\ x_2(t) &= \sum_{l=0}^{L_{p2}-1} \alpha_{2l} s(t - \tau_{2l}) + n_2(t), \end{aligned} \quad (8)$$

where the two sets of parameters $\{L_{p1}, \alpha_{1k}, \tau_{1k}\}$, $0 \leq k \leq L_{p1}-1$, and $\{L_{p2}, \alpha_{2l}, \tau_{2l}\}$, $0 \leq l \leq L_{p2}-1$, define the multipath channels between the transmitter and the two receivers, respectively. Then the cross-correlation function of the two received signals becomes

$$r_{12}(\tau) = \sum_{k=0}^{L_{p1}-1} \sum_{l=0}^{L_{p2}-1} \alpha_{1k} \alpha_{2l} r_{ss}(\tau - (\tau_{1k} - \tau_{2l})) + v(\tau). \quad (9)$$

We can observe that similar to the case of TOA estimation in multipath channels, the delay profiles for TDOA estimation consists of multiple copies of auto-correlation function of the transmitted signal with different delays. In multipath channels, the TDOA to be measured is the time difference between the propagation delays of the two DLOS paths, that is

$$TDOA = \tau_{10} - \tau_{20}. \quad (10)$$

From (9) we can observe that the TDOA cannot be detected by finding the delay value that corresponds to the first peak of the delay profile since the first occurring correlation function in the delay axis does not necessarily corresponds to the delay value $(\tau_{10} - \tau_{20})$. On the other hand, following a discussion similar to that about TOA estimation, we can deduce that in multipath channels, the delayed copy of the correlation function corresponding to the delay value $(\tau_{10} - \tau_{20})$ is not necessarily the strongest one in the delay profile given by (9). This means that in multipath channels there is ambiguity in detecting TDOA from the delay profiles since the correlation peak to be detected is neither the strongest one nor the first one for sure. An intuitive conclusion following this fact is that in multipath channels the estimation of TDOA is much harder than the estimation of TOA. Moreover, the CRLB derived for single-path channel model is no longer applicable for the estimate of the TDOA in multipath channels and dramatically large errors occur in TDOA estimation due to the complexity of multipath radio propagation channels.

Since in geolocation applications, the ranging signal $s(t)$ transmitted by a mobile terminal is usually known to reference points (RP), a more obvious way of estimating TDOA is to calculate the difference of TOA estimates measured by the two receivers. This method avoids the ambiguity in estimating TDOA from the delay profile (9) that we just mentioned, but it requires synchronization between the transmitter and both of the receivers while direct measurement of TDOA by cross-correlation method only requires synchronization between the two receivers.

III. TOA ESTIMATION TECHNIQUES

In general, signals of any format can be employed for TOA estimation using the ML estimation technique. But wideband DSSS signal is normally used for TOA-based ranging systems because of several advantages as compared with other alternatives [3]. One advantage of using DSSS signal for TOA estimation is its large bandwidth, which helps to resolve multipath signals as we presented in section II. Another advantage is that because of the processing gain of the correlation process in receivers, the DSSS signal-based ranging system performs much better than competing systems in suppressing interference from other radio systems operating in the same frequency band.

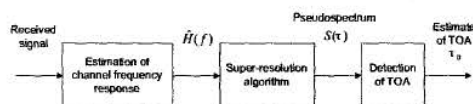


Fig. 2. Functional block diagram of the receiver of super-resolution TOA estimation systems.

The performance of TOA estimation can be improved using super-resolution techniques [5]. Figure 2 shows a functional block diagram of the receiver of super-resolution TOA estimation systems. The output signal of the correlator receiver is first used to estimate channel frequency response. Then a super-resolution algorithm is applied to the channel frequency response to detect TOA with improved resolution.

It's also shown in [5] that diversity techniques such as frequency diversity can be used to further improve the performance of super-resolution TOA estimation techniques. Diversity techniques take advantage of the random nature of the radio propagation channel and improve the estimation performance by combining uncorrelated signals at a number of diversity branches.

Interested readers can refer to [5] and references therein for more detailed discussion on the super-resolution algorithms and diversity techniques for improved estimation of TOA for indoor geolocation applications.

IV. SIMULATIONS FOR PERFORMANCE EVALUATION

In multipath channels the CRLB is not directly applicable because dramatically large TOA estimation errors may occur when the DLOS path is undetectable. There are no suitable indoor radio propagation channel models for performance evaluation of TOA estimation techniques. Consequently, in the literature, in designing TOA estimation techniques for multipath channels the performance evaluation is usually conducted by studying the resolution of estimation techniques based on computer simulations with simple two-path channel model. As we discussed previously, in addition to the resolution of estimation techniques, the radio channel characteristics has tremendous effects on the performance of TOA-based ranging systems in real application scenarios. So that in indoor areas, performance of TOA estimation techniques can be evaluated more appropriately by computer simulations based on channel measurements, by conducting field measurement using prototype systems, or by using the ray-tracing software to simulate the site-specific indoor radio channels. Due to the complexity of the indoor radio propagation channels, performance study based on these methods reveals much more realistic statistical results than the resolution study of estimation techniques with simple theoretical channel models.

Due to limitation on the space of this paper, in this section we only present some sample results obtained by computer simulations based on channel measurement data. Interested readers can refer to [5] for more detailed descriptions on the simulations and results. Figure 3 presents the percentage of measurement locations where absolute ranging errors are smaller than 3 meters obtained using three different TOA estimation techniques, i.e., DSSS signal-based cross-correlation techniques (DSSS/xcorr), super-resolution

Eigenvector method with forward and backward correlation matrix (EV/FBCM), and the super-resolution techniques with 10 frequency diversity branches using correlation matrix based diversity combining scheme (EV/FBCM/FD10-CMDCS). From the results we can observe that super-resolution techniques and diversity techniques can improve the performance of TOA estimation in indoor multipath environments when the signal bandwidth is small, such as 20 or 40MHz as shown in the figure. But when the signal bandwidth becomes larger, no much difference is observed. Figure 4 presents cumulative distribution function of ranging errors for a bandwidth of 20MHz with the three techniques. From the figure, we can clearly observe the difference between the three techniques. From the simulation results, it is also noted that in indoor environments, large estimation errors occur, which is a result of NLOS situations [1], even with as large a bandwidth as 160MHz, and that the CRLB derived with single-path AWGN channel model is not applicable for multipath channels.

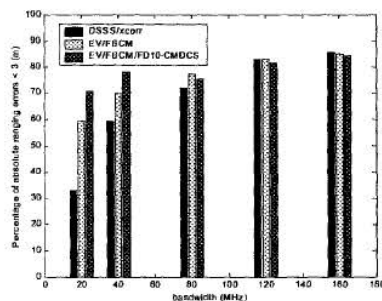


Fig. 3. Percentages of measurement locations where absolute ranging errors are smaller than 3 meters, obtained using three different TOA estimation techniques.

V. SUMMARY AND CONCLUSIONS

In this paper, we present a brief discussion on the issues and techniques for TOA estimation in multipath channels. Some simulation results based on channel measurement data in indoor environments are presented to demonstrate and compare the performance of TOA estimation techniques, including DSSS signal-based cross-correlation techniques, super-resolution techniques, and super-resolution techniques with diversity techniques. From the results we observe that when signal bandwidth is small the super-resolution and diversity techniques can be used to improve the TOA estimation performance. But when the signal bandwidth becomes larger, e.g., larger than 120MHz, almost no improvements are observed. From the results, we can also observe that the CRLB derived with single-path AWGN

channel model is no longer applicable for multipath channels.

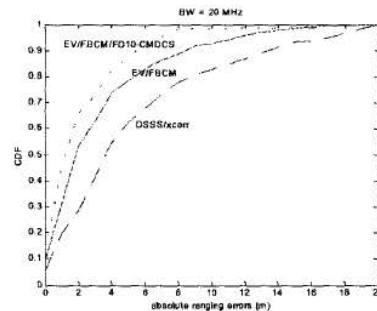


Fig. 4. Cumulative distribution function (CDF) of ranging errors for a bandwidth of 20MHz with three different TOA estimation techniques.

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