On Time-of-arrival Positioning in a Multipath Environment

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***Abstract*— Wireless geolocation in a multipath environment is of particular interest for wideband communications. The conventional approach makes use of first-arriving signals only. In this paper, we investigate whether and under what conditions processing multipath delays should enhance the positioning accuracy. The best achievable positioning accuracy is evaluated in terms of the Cramer-Rao Low Bound (CRLB) and the generalized-CRLB (G-CRLB), depending on whether prior statistics of non-line-sight (NLOS) induced errors are available. We then show that such prior statics are critical to the accuracy improvement when the multipath delays are processed. Furthermore, the degree of accuracy enhancement depends on two major factors: the strength of multipath components and the variance of NLOS induced errors. The corresponding positioning receivers are also discussed. In [1], [2], we developed an analysis of the time-of-arrival (TOA) positioning method in an NLOS environment, assuming single path propagation. The main results obtained there are extended and applied to the multipath case in this paper.**

I. Introduction

Position location using signals that are subject to multipath propagation has been an important issue for wideband mobile communication systems. Many research efforts have been devoted to finding better solutions in recent years. The common approach is to perform geolocation based on first-arriving signals only [3], [4], which reduces the mulipath geolocation problem to the conventional single-path model. However, the second and later arriving signals, which are due to non-line-of-sight (NLOS) propagation, should also carry information regarding the position of interest. Hence, it is reasonable to stipulate that processing some of the multipath components in addition to the first arriving ones may improve the positioning accuracy. However, to the best of our knowledge, few studies have been reported on this issue.

In this paper, we shall investigate the above question by examining the time-of-arrival (TOA) method in a multipath environment. In [1], [2], we presented an analysis for the TOA method in a single-path NLOS environment. The main results obtained there are extended and applied to the multipath case in this paper. The best achievable estimation accuracy is first evaluated in terms of the Cramer-Rao Lower Bound (CRLB) and the generalized-CRLB (G-CRLB), depending on whether prior statistics on NLOS induced errors are available. The associated positioning receivers are also presented. We then discuss the practical implications of the above analytical results by examining several numerical results. Finally, we propose a geolocation method using multipath components, which incorporate both analytical and numerical consideration. Two main conclusions we draw are

- Processing multipath components can improve positioning accuracy only when prior statistics on NLOS induced errors are available.
- The degree of accuracy enhancement depends on the strength of multipath components adopted and the variance of related NLOS errors. The stronger the multipath components are and the smaller the variance of the NLOS delays is, the more significant the accuracy improvement we can expect.

The rest of this paper is organized as follows. Problem formulation is considered first in Section II. Then analytical results are presented in Section III. Several numerical examples are discussed next in Section IV. We propose a multipath geolocation method in Section V, and make a brief conclusion in the last section.

II. Problem Formulation

Consider a synchronous communication system. The radio signal that travels from an MS to a given BS may be subject to multipath propagation. Our objective is to seek an optimum scheme to estimate the MS position.

Let $\mathcal{B} = \{1, 2, \cdots, B\}$ be the set of indices of all the base stations involved, whose locations $\{\boldsymbol{p}_b = (x_b\ y_b)^T,\ b \in \mathcal{B}\}$ are known. Denote the set of M BSs that do not receive any LOS signals by $\mathcal{NL} = \{1, 2, \cdots, M\}$. The complement of $\mathcal{NL}$, denoted by $\mathcal{L}\ (= \mathcal{B} \backslash \mathcal{NL})$, is the set of BSs whose first-arrivals are LOS signals, with its cardinality being $L = B - M$. The received signal at BS_b is

$$r_b(t) = \sum_{i=1}^{N_b} A_{bi} \cdot s(t - \tau_{bi}) + n_b(t), \quad \text{for } b \in \mathcal{B}, \qquad (1)$$

where $s(t)$ is the signal waveform, $n_b(t)$'s are independent complex-valued white Gaussian noise processes with spectral density $N_0/2$, N_b is the number of multipaths to BS_b, A_{bi}

and τ_{bi} are the signal amplitude and delay corresponding to the i-th multipath component of $r_b(t)$. Specifically, the delay τ_{bi} is expressed as

$$\tau_{bi} = \frac{1}{c}\left\{\sqrt{(x_b - x)^2 + (y_b - y)^2} + l_{bi}\right\}, \ b \in \mathcal{B} \quad (2)$$

where $c = 3 \times 10^8$m/s is the speed of light, and l_{bi} is the corresponding NLOS propagation induced path length error with $\{l_{b1} = 0, \ b \in \mathcal{L}\}$. The parameters to be estimated are the MS position $\boldsymbol{p} = (x \ y)^T$ and the NLOS path lengths denoted by

$$\boldsymbol{l} = \left(\ \boldsymbol{l}_1^T \ \ \boldsymbol{l}_2^T \ \ \cdots \ \ \boldsymbol{l}_B^T \ \right)^T,$$

where

$$\boldsymbol{l}_b = \begin{cases} (l_{b1} \ \ l_{b2} \ \ \cdots \ \ l_{bN_b})^T, & \text{for } b \in \mathcal{NL}, \\ (l_{b2} \ \ l_{b2} \ \ \cdots \ \ l_{bN_b})^T, & \text{for } b \in \mathcal{L}, \end{cases}$$

with $0 < l_{b1} < l_{b2} < \cdots < l_{bN_b}$. Note that $\{l_{b1} = 0, \ b \in \mathcal{L}\}$ are excluded from $\boldsymbol{l}$. We define vector $\boldsymbol{\theta}$ by concatenating $\boldsymbol{p}$ and $\boldsymbol{l}$, i.e., $\boldsymbol{\theta} = \left(\boldsymbol{p}^T \ \boldsymbol{l}^T\right)^T$.

We can write the joint probability density function (p.d.f.) of the observables $\{r_b(t), \ b \in \mathcal{B}\}$ conditioned on $\boldsymbol{\theta}$ as

$$f_{\boldsymbol{\theta}}(\boldsymbol{r}) \propto \prod_{b=1}^{B} \exp\left\{-\frac{1}{N_0}\int\left|r_b(t) - \sum_{i=1}^{N_b} A_{bi}s(t-\tau_{bi})\right|^2 dt\right\}. \quad (3)$$

III. Best achievable positioning accuracy and optimum receivers

A. Derivation of Fisher information matrix

We first evaluate the *Fisher Information Matrix* (FIM) of $f_{\boldsymbol{\theta}}(\boldsymbol{r})$ in Eq. (3), which is important to our discussion of both the CRLB and the G-CRLB next.

The FIM is defined by

$$\mathbf{J}_{\boldsymbol{\theta}} \stackrel{\text{def}}{=} E_{\boldsymbol{\theta}}\left[\frac{\partial}{\partial\boldsymbol{\theta}}\ln f_{\boldsymbol{\theta}}(\boldsymbol{r}) \cdot \left(\frac{\partial}{\partial\boldsymbol{\theta}}\ln f_{\boldsymbol{\theta}}(\boldsymbol{r})\right)^T\right]. \quad (4)$$

We show

$$\mathbf{J}_{\boldsymbol{\theta}} = \mathbf{H} \cdot \mathbf{J}_{\boldsymbol{\tau}} \cdot \mathbf{H}^T, \quad (5)$$

where $\mathbf{H}$ and $\mathbf{J}_{\boldsymbol{\tau}}$ can be decomposed as

$$\mathbf{H} = \frac{1}{c}\begin{pmatrix} \mathbf{H}_{NL} & \mathbf{H}_L \\ \mathbf{I} & \mathbf{0} \end{pmatrix}, \quad \mathbf{J}_{\boldsymbol{\tau}} = \begin{pmatrix} \mathbf{\Lambda}_{NL} & \mathbf{0} \\ \mathbf{0} & \mathbf{\Lambda}_L \end{pmatrix}, \quad (6)$$

and $\mathbf{I}$ is an identity matrix of appropriate order. Subscripts "NL" and "L" mean the BS set $\mathcal{NL}$ and $\mathcal{L}$, respectively. The submatrices of $\mathbf{H}$ and $\mathbf{J}_{\boldsymbol{\tau}}$ can be further decomposed as

$$\begin{aligned} \mathbf{H}_{NL} &= \begin{pmatrix} \mathbf{G}_1 & \mathbf{G}_2 & \cdots & \mathbf{G}_M \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \end{pmatrix}, \\ \mathbf{H}_L &= \begin{pmatrix} \mathbf{G}_{M+1} \ \ \mathbf{G}_{M+2} \ \ \cdots \ \ \mathbf{G}_B \\ \text{diag}(\mathbf{D}_1, \ \mathbf{D}_2, \ \cdots, \mathbf{D}_L) \end{pmatrix}, \\ \mathbf{\Lambda}_{NL} &= \text{diag}\left(\ \mathbf{\Psi}_1, \ \ \mathbf{\Psi}_2, \ \ \cdots \ \ \mathbf{\Psi}_M \ \right), \ \text{ and} \\ \mathbf{\Lambda}_L &= \text{diag}\left(\ \mathbf{\Psi}_{M+1}, \ \ \mathbf{\Psi}_{M+2}, \ \ \cdots \ \ \mathbf{\Psi}_B \ \right), \end{aligned} \quad (7)$$

where

$$\begin{aligned} \mathbf{G}_b &= \begin{pmatrix} \cos\phi_b \\ \sin\phi_b \end{pmatrix}\underbrace{\left(\ 1 \ \ 1 \ \ \cdots \ \ 1 \ \right)}_{N_b}, \\ \mathbf{D}_i &= \left(\ \mathbf{0} \ \ \mathbf{I}_{(N_{M+i}-1)} \ \right), \quad \text{for } 1 \le i \le L, \end{aligned} \quad (8)$$

$\mathbf{I}_{(N_{M+i}-1)}$ is the identity matrix of order $(N_{M+i} - 1)$, angle ϕ_b is determined by

$$\phi_b = \tan^{-1}\frac{y - y_b}{x - x_b},$$

and $\mathbf{\Psi}_b$ is an $N_b \times N_b$ matrix. The diagonal terms of $\mathbf{\Psi}_b$ can be shown as

$$[\mathbf{\Psi}_b]_{ii} = 8\pi^2\beta^2 \cdot R_{bi}, \quad (9)$$

where

$$R_{bi} = \frac{\int |A_{bi}s(t)|^2 dt}{N_0}$$

is the SNR, and β is the effective bandwidth of the signal waveform $s(t)$. The off-diagonal terms of $\mathbf{\Psi}_b$ represents the interference among multipath components of $r_b(t)$. For CDMA signals with chip rate W, they have a closed-form expression

$$\begin{aligned} [\mathbf{\Psi}_b]_{ij} = 8\pi^2 \cdot \text{Re}\left[\frac{A_{bi} \cdot A_{bj}^*}{N_0}\right] \cdot \Bigg[&\frac{W}{k_{b_{ij}}}\sin(k_{b_{ij}}W) \\ &+ \frac{2}{k_{b_{ij}}^2}\cos(k_{b_{ij}}W) - \frac{2}{k_{b_{ij}}^3 W}\sin(k_{b_{ij}}W)\Bigg], \end{aligned} \quad (10)$$

for $i \neq j$, where $k_{b_{ij}} = 2\pi(\tau_{bi} - \tau_{bj})$.

B. Analysis for the situation when no prior NLOS statistics are available

The Cramer-Rao Lower Bound (CRLB) sets a lower limit for the covariance matrix of any unbiased estimate of unknown parameters [5]. The CRLB is defined in terms of the inverse of the FIM, i.e.,

$$E_{\boldsymbol{\theta}}\left[(\hat{\boldsymbol{\theta}} - \boldsymbol{\theta})(\hat{\boldsymbol{\theta}} - \boldsymbol{\theta})^T\right] \ge \mathbf{J}_{\boldsymbol{\theta}}^{-1}, \quad (11)$$

where "$\mathbf{A} \ge \mathbf{B}$" should be interpreted as that matrix $(\mathbf{A} - \mathbf{B})$ is non-negative definite, and $E_{\boldsymbol{\theta}}(\cdot)$ is to take expectation conditioned on $\boldsymbol{\theta}$. The diagonal terms of the CRLB matrix provide lower bounds for the mean-square errors of the individual components of $\boldsymbol{\theta}$, i.e.,

$$E(\hat{\theta}_i - \theta_i)^2 \ge \left[\mathbf{J}_{\boldsymbol{\theta}}^{-1}\right]_{ii}. \quad (12)$$

Since the accuracy of $\hat{\boldsymbol{p}}$ is of our primary interest, we shall concentrate on $\left[\mathbf{J}_{\boldsymbol{\theta}}^{-1}\right]_{2\times2}$, the first 2×2 diagonal submatrix of $\mathbf{J}_{\boldsymbol{\theta}}^{-1}$. We show that

$$\left[\mathbf{J}_{\boldsymbol{\theta}}^{-1}\right]_{2\times2} = c^2\left[\left(\mathbf{H}_L\mathbf{\Lambda}_L\mathbf{H}_L^T\right)^{-1}\right]_{2\times2}, \quad (13)$$

i.e., the positioning accuracy depends *solely* on $\{r_b(t), \ b \in \mathcal{L}\}$, or the possible contribution from $\{r_b(t), \ b \in \mathcal{NL}\}$ is completely removed.

The minimum positioning error is related to $\left[\mathbf{J}_{\boldsymbol{\theta}}^{-1}\right]_{2\times 2}$ as

$$\mathcal{P}_{CR-multi} \stackrel{\text{def}}{=} \left(\sqrt{E\left[(\hat{x}-x)^2+(\hat{y}-y)^2\right]}\right)_{\min} = \sqrt{\text{trace}(\left[\mathbf{J}_{\boldsymbol{\theta}}^{-1}\right]_{2\times 2})}. \tag{14}$$

Denote by $\mathcal{P}_{CR-LOS}$ the minimum positioning error based on the first-arriving LOS components. We find

$$\left|\frac{\mathcal{P}_{CR-multi}-\mathcal{P}_{CR-LOS}}{\mathcal{P}_{CR-multi}}\right| \leq 0.02$$

in most cases we examined. Therefore, when no prior NLOS statistics are available, it is of practical interest to perform geolcoation using first-arriving LOS signals only, which falls into category of the conventional multipath approaches.

C. Analysis of the situation when prior NLOS statistics are available

Suppose that the p.d.f. of NLOS induced errors, $p_{\boldsymbol{l}}(\boldsymbol{l})$, can be obtained beforehand. It is reasonable to assume that $\boldsymbol{l}_b$'s are independent, thus

$$p_{\boldsymbol{l}}(\boldsymbol{l}) = p_{\boldsymbol{l}_1}(\boldsymbol{l}_1)\cdot p_{\boldsymbol{l}_2}(\boldsymbol{l}_2)\cdots p_{\boldsymbol{l}_B}(\boldsymbol{l}_B).$$

The accuracy limit now is represented by the generalized-CRLB (G-CRLB). Analogous to the relationship between the CRLB and the FIM, the G-CRLB is defined as the inverse of the *information matrix* $\mathbf{J}$ [5], i.e.,

$$E\left\{(\hat{\boldsymbol{\theta}}-\boldsymbol{\theta})(\hat{\boldsymbol{\theta}}-\boldsymbol{\theta})^T\right\} \geq \mathbf{J}^{-1}, \tag{15}$$

where $\mathbf{J}$ consists of two components

$$\mathbf{J} = \mathbf{J}_D + \mathbf{J}_P. \tag{16}$$

The subscripts "D" and "P" stand for "data" and "prior" information, respectively. The component $\mathbf{J}_D$ and $\mathbf{J}_P$ are defined as

$$\mathbf{J}_D = E\left[\frac{\partial}{\partial\boldsymbol{\theta}}\log f_{\boldsymbol{\theta}}(\boldsymbol{r})\cdot\left(\frac{\partial}{\partial\boldsymbol{\theta}}\log f_{\boldsymbol{\theta}}(\boldsymbol{r})\right)^T\right], \tag{17}$$

and

$$\mathbf{J}_P = E\left[\frac{\partial}{\partial\boldsymbol{\theta}}\log p_{\boldsymbol{\theta}}(\boldsymbol{\theta})\cdot\left(\frac{\partial}{\partial\boldsymbol{\theta}}\log p_{\boldsymbol{\theta}}(\boldsymbol{\theta})\right)^T\right], \tag{18}$$

respectively, where $E[\cdot]$ is to take expectation.

It can be shown that

$$\mathbf{J}_D = \mathbf{J}_{\boldsymbol{\theta}}, \quad \text{and} \quad \mathbf{J}_P = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\Omega}^{-1} \end{pmatrix} \tag{19}$$

with

$$\boldsymbol{\Omega} = \begin{pmatrix} \boldsymbol{\Omega}_1, & \boldsymbol{\Omega}_2, & \cdots, & \boldsymbol{\Omega}_B \end{pmatrix}, \tag{20}$$

where

$$\boldsymbol{\Omega}_b = E\left[\frac{\partial}{\partial\boldsymbol{l}_b}\log p_{\boldsymbol{l}_b}(\boldsymbol{l}_b)\cdot\left(\frac{\partial}{\partial\boldsymbol{l}_b}\log p_{\boldsymbol{l}_b}(\boldsymbol{l}_b)\right)^T\right].$$

If $p_{\boldsymbol{l}_b}(\boldsymbol{l}_b)$ follows a multivariate Gaussian distribution, $\boldsymbol{\Omega}_b$ is the covariance matrix associated with this Gaussian distribution.

The position accuracy is given by $\left[\mathbf{J}^{-1}\right]_{2\times 2}$. In addition, it can be shown that the optimum receiver that can asymptotically achieve the G-CRLB for position estimates consists of two components: estimating multipath delays using the correlation method at all the BSs and the MAP estimation of the MS position utilizing all available multipath delay estimates. However, the following numerical results suggest use of a subset of multipath estimates would be sufficient for the accuracy improvement.

IV. Numerical Results

In this section, we explore the practical implications of the analytical results obtained in the previous section, by examining several numerical examples. Parameter specifications adopted in these examples are discussed first.

Consider a cellular CDMA system with seven BSs as shown in Figure 1, with the cell radius of 1000m. An MS transmits signals with the chip rate W. The effective bandwidth β can be approximated in terms of W as

$$\beta \approx \frac{W}{\sqrt{3}}.$$

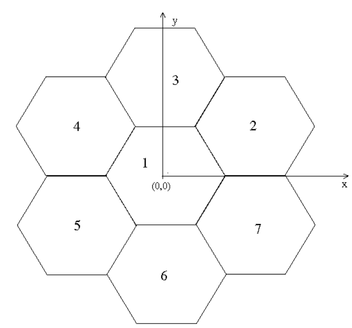

Fig. 1. A Cellular system with seven base stations.

The signal strength of the first-arriving NLOS component of a received signal is set to be 6dB below that of the corresponding LOS component (which may be absent). The relative amplitudes of NLOS multipath components are determined according to the multipath gain model selected. Two multipath gain models are employed. One is the exponential gain model, where multipath components arriving consecutively have kdB difference in strength, and k is often taken to be 6. The other is the equal gain model, which is equivalent to the exponential model with $k = 0$dB. In general, the relative multipath delays comply with the following two criteria:

1) The minimum delay resolution is $1/W$. That is

$$\tau_{b(i+1)} - \tau_{bi} \geq \frac{1}{W}, \text{ for } 1 \leq i \leq N_b - 1, \text{ and } b \in \mathcal{B}. \tag{21}$$

2) The delay between the first and the last arriving signals is less than the cell radius:

$$c|\tau_{b1} - \tau_{bN_b}| \leq \text{the radius of a cell}, \quad \text{for } b \in \mathcal{B}. \quad (22)$$

Specifically, we let the delays of first arriving signals be all zero, i.e., $\tau_{b1} = 0$, for $b \in \mathcal{B}$. The other delays τ_{bi}, for $1 < i \leq N_b$, are generated according to

$$\tau_{bi} = (i-1)\frac{\mathcal{S}}{W} + \mu_{bi}, \qquad (23)$$

where μ_{bi}'s are independent random variables uniformly distributed over $[-\frac{0.5}{W}, \frac{0.5}{W}]$, and $\mathcal{S} \geq 1$ is the normalized delay separation between two adjacent multipaths, where the normalization is with respect to the chip duration $1/W$. The first term can be viewed as the principal separation between the i-th and the first components, while the second term represents a small perturbation. It is understood that the selection of $\mathcal{S}$ should comply with the criteria of Eqs. (21) and (22).

In the following numerical examples, we shall focus on a "complete NLOS situation" where no LOS paths exist. Three assumptions are made: 1. the p.d.f. of $\boldsymbol{l}$ can be acquired beforehand; 2. $\boldsymbol{l}_b$'s are statistically independent; 3. the elements of any $\boldsymbol{l}_b$ are independent, and follow the same Gaussian distribution. Analogous to the CRLB, we define for this case the MMSE in terms of the G-CRLB, $\mathbf{J}^{-1}$, as

$$\mathcal{P}_{G-CR-multi} \stackrel{\text{def}}{=} \sqrt{\text{trace}([\mathbf{J}^{-1}]_{2\times 2})}.$$

A. The relationship between the number of multipaths processed and the positioning accuracy

Let $W = 5$Mcps, $\mathcal{S} = 3$ and the standard deviation of the NLOS errors be 15m. Figure 2 shows the numerical curves of $\mathcal{P}_{G-CR-multi}$ vs. the number of multipaths processed for the two gain models. The top two curves correspond to the exponential gain models with decay rate k being 6dB and 3dB. The bottom curve is for the equal gain model. The three curves converge at the point where only the first-arriving (NLOS) signals are used. It is seen that when more multipath components are utilized, the positioning accuracy improves. However, the improvement gets "saturated" at 3 and 5 multipaths for the top two curves, since the other components are too weak to be useful. In contrast, continuous improvement is observed for the equal gain model. That is to say, in order to enhance the positioning accuracy, it is sufficient to process strong multipath components exclusively. In this case, for instance, those components with strength of more than 6dB below that of their associated first-arriving signals can be neglected.

B. The relationship between the standard deviation of NLOS delays and the positioning accuracy

With the same parameter specifications, we plot in Figure 3 $\mathcal{P}_{G-CR-multi}$ vs. the standard deviation of NLOS errors for three cases, the equal model and the exponential gain model with k being 3dB and 6dB. As expected, the positioning error increases as the standard deviation of the NLOS errors become larger, due to less accurate "information" about the NLOS delays. This is consistent with the result obtained for the single-path model [2].

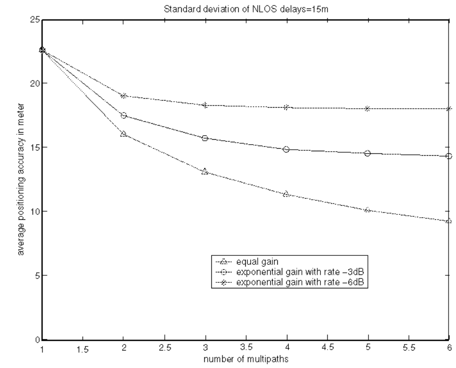

Fig. 2. $\mathcal{P}_{G-CR-multi}$ vs. the number of multipaths processed with the equal gain and exponential gain models.

	chip rate (Mcps)	no. of multipaths
1	1	2
2	5	4
3	100	20

TABLE I

Three sets of CDMA system specifications

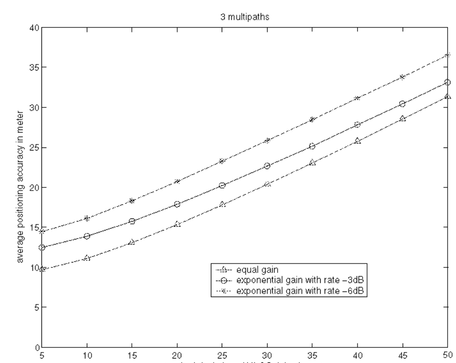

Fig. 3. The positioning accuracy $\mathcal{P}_{G-CR-multi}$ vs. the standard deviation of NLOS delays with the equal gain and exponential gain models.

C. Accuracy comparison of three sets of system specifications

In the last example, we compare the geolocation precision for the three sets of system parameters listed in Table I. Assume that received signal energy is same for each set of specifications. We consider the relative signal strengths and delays of multipaths as specified in Figure 4. In particular, for the system with $W = 1$Mcps, the received signal at each base station contains two paths with the strength 6dB and 12dB below their corresponding non-existent LOS signal. When the chip rate rises to 5Mcps, each path is resolved into two separate paths with 60% and 40% of energy of the previous path. Likewise, in the case of 100Mcps, one path

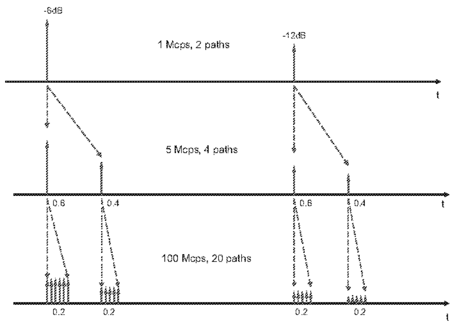

Fig. 4. The relative signal strengths and delays of multipaths for the three sets of system specifications in Table I.

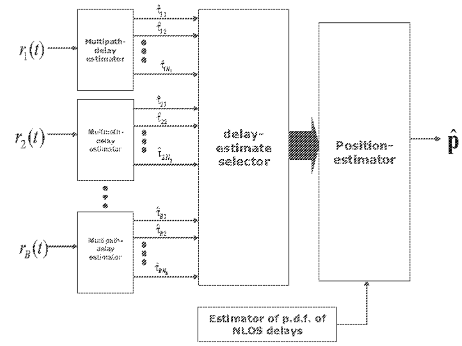

Fig. 6. The positioning receiver using the delay estimates of multipath components for a synchronous system.

detected by the 5Mcps system further splits into 5 equal-strength paths. The time delays of each set of multipaths are generated with $\mathcal{S} = 3$. In Figure 5, we plot $\mathcal{P}_{G-CR-multi}$ vs. the standard deviation of the NLOS delays for the three sets of system parameters. It is seen that even in the complete NLOS environment processing more multipath components with a higher chip rate can achieve a good geolocation accuracy.

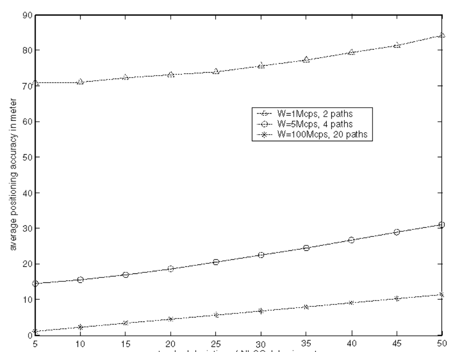

Fig. 5. Comparison of $\mathcal{P}_{G-CR-multi}$ for three sets of system specifications.

V. Modified Positioning Scheme

We modify the analytically optimal receiver associated with the G-CRLB (see Section III-C) by incorporating our observations in the previous section.

When prior NLOS statistics can be obtained beforehand, we need to process the multipath components with sufficient strength and smaller deviation of the NLOS induced delay errors. Accordingly, the modified receiver consists of the following three parts, as illustrated in Figure 6: 1. estimate the delays of multipath components. 2. select the appropriate multiopath delay estimates. 3. perform MAP estimation of the MS position.

VI. Conclusion

In this paper, we investigate whether and under what condition utilizing multipath delay estimates besides the first arrivals may enhance the position accuracy. By examining the CRLB and the G-CRLB for the geolocation using multipath components, we make two main conclusions: 1.) when prior NLOS information is not available, the MLE based on LOS delay estimates is an appropriate choice; 2.) otherwise, the MAP estimator exploiting delay estimates of the multipath components with sufficient strong strength and small variance of related NLOS errors can achieve better accuracy than use of first-arrivals alone.

It is noticed that processing multipath components can inevitably increase the computational complexity. Therefore, in practice, a decision regarding whether to adopt multipath related measurements should depend on the tradeoff between the computational complexity and the possible accuracy improvement.

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