GLRT Detector for NLOS Error Reduction in Wireless Positioning Systems

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ABSTRACT

The objective of this paper is to determine the potentialities of an optimal detection scheme within the framework of subscriber location. Using a Generalized Likelihood Ratio Test (GLRT), an improved first arriving path detector from propagation channel estimates is derived. Furthermore, an expression for false alarm probability is provided and detector performance is evaluated for different configurations.

I. INTRODUCTION

From the viewpoint of subscriber location, accurate estimates of Time of Arrival (TOA) from received signal are required, and in order to use angular information, a proper first path detection acquires special relevance. See [1], [2] for details. However, first path arrived to the receiver may not necessarily be the one bearing the highest power.

Particularly, in the NLOS case, the first arrival may suffer attenuation higher than other later arrivals. Due of receiver is usually synchronized to the highest power path; it will provide a wrong TOA information. Hence, NLOS propagation will bias the TOA and TDOA measurements, even when high-resolution timing techniques are employed and there is no multipath interference [8].

For the case of Code Division Multiple Access (CDMA) Spread Spectrum Systems such as IS-95, and WCDMA a pilot channel or training sequences are provided, allowing channel estimation. These estimates are used to demodulate data channels and feed RAKE receivers. However RAKE receivers are based on the capture of the received signal power and thresholds used for path detection are set high enough to match the most powerful ones. As mentioned, unfortunately these do not necessarily include first arrival path in NLOS situations. See [6] for an approach similar to this contribution but based on the maximum power arrival.

The scheme proposed in this paper consists in searching the first arriving path from the channel vector estimates, and it could well be the case of WCDMA after target cell search [4], and channel estimates provided from Common Pilot Channel (CPICH). For this purpose, a lag window before the first RAKE finger component is studied, and a test is performed to discriminate properly between noise and signal (Figure 1).

Figure 1: Observed estimated channel along a lag searching window over different time slots. In a NLOS situation, the first arrival has a power significantly lower than the first RAKE finger.

With these premises, our data vector will be a collection of channel impulse response vectors infected with noise (when there is a signal arrival) or simply noise (when no signal is present at a certain lag).

In addition, it is proposed a relation between the variance of the LOS estimates and the detection and false alarm probabilities.

II. ESTIMATED CHANNEL MODEL

After matched filter, the estimated channel may be modeled as in (1):

\[ \hat{h}(\tau_o; t) = \alpha \exp(j\omega_d t) a + w(t) \] (1)

where the first term in the summation accounts for possible LOS component, \( \omega_d \) is the Doppler frequency, \( a \) is the array steering vector and their elements are expressed as follows,

\[ a_k = \exp\left(-j\frac{2\pi d_k}{\lambda}\sin(\theta_k)\right) \] (2)

and \( w \) models the scattered power estimation noise, as shown in (3):

\[ w(t) = w_s(t) + n(t) \] (3)

Noise \( n \) is assumed to be a temporally stationary, complex Gaussian random process, and temporally uncorrelated and independent of the channel vectors. Stacking the vector impulse response in time for each lag \( \tau_o \),
temporal window of size KT s, on compute and arrange all estimated channels within a
With the goal of estimating the first signal arrival, we component as a rank-one term in the correlation matrix.
Note that we are implicitly including the LOS (alternative
n
threshold shown in (5).
A Generalized Likelihood Ratio Test (GLRT) Detector follows:
This test is performed by first estimating ML signal parameters, as if signal were present, and then comparing likelihood of H1 with the true parameters replaced for their estimates to that of H0.
If temporal correlation between consecutive estimates is different to zero and below to one, we are treating the most general case of a Partially Coherent Distributed (PCD) source, and above expression leads to (6):
\[ L(X) = \frac{\text{pdf}(X|\hat{R}_h;H_1)}{\text{pdf}(X|\hat{R}_h;H_0)} > \gamma^* \] (5)
This test is performed by first estimating ML signal parameters, as if signal were present, and then comparing likelihood of H1 with the true parameters replaced for their estimates to that of H0.

IV. FALSE ALARM PROBABILITY
When secondary data is available (as for instance, channel estimates in lags where no signal is present), and it is used for noise variance (\( \sigma_n^2 \)) estimation, Constant False Alarm Rate (CFAR) Detectors may be built. See for i.e. [5]. Furthermore, it may be shown that false alarm probability \( P_{fa} \) is described approximately by:
\[ P_{fa} = Q_{\chi^2_{2pN_s}} \left\{ \frac{2}{N-1} \left[ \gamma' + pN_s \log(N\sigma_n^2) - 1 \right] \right\} \] (7)
where \( Q_{\chi^2}(.) \) defines the right tail cumulative function for a chi squared distributed variable with 2pN_s degrees of freedom, when K channel vectors and N_s sensors are used, and provided that the number of secondary data is high enough. The probability of detection is given by:
\[ P_D = \sum_{n=0}^{pN_s-1} C_n \exp \left( \frac{\gamma' - pN_s + pN_s \log(N\beta_n^2 - 1)}{\beta_n} \right) \] (8)
and,
\[ C_n = \prod_{i=0; i \neq n}^{N-1} \frac{1}{1 - \beta_i / \beta_n} \]
\[ G = \sum_{i=0}^{pN_s-1} \log(\lambda_i) \]
\[ \beta_n = N\lambda_n / \sigma_n^2 - 1 \]
\[ \lambda_n = \lambda_j / g_n^2 \quad \forall i = 1, N_s; j = 1, p \]
with \( \lambda_n \) and \( \lambda_r \) being the eigenvalues of \( \hat{R}_h \) and \( T_k \) respectively.
When an adequate probability of false alarm has been defined by selecting a threshold from (7), probability of detection will be given by channel characteristics. Note that \( P_D \) in (8) is a function of SNR, K, N_s, and temporal and spatial correlation.

V. EVALUATING FIRST ARRIVED PATH DETECTABILITY
In order to evaluate the performance of this detector, the first arrived path is supposed to be confined within a temporal window of length L samples before the first path available at RAKE receiver. Sampling is supposed to be at chip time and LOS path is placed randomly within this window.

\[ h = h(\tau_o) = \left[ h(\tau_o,0)^T \ h(\tau_o;T_s)^T \ ... \ h(\tau_o;(K-1)T_s)^T \right]^T \] \[ n \sim CN(0,\sigma_n^2 I) \]
\[ h \sim CN(0,\tilde{R}_h) \]
where \( T_k \) corresponds to the time interval between two consecutive estimations, and K is the number of estimates.
\( \tilde{R}_h \) is the channel vector correlation matrix from estimates, expressed in more general form by (4), and \( \sigma_n^2 \) is the noise variance:
\[ \tilde{R}_h = R_0 \otimes T_k + \sigma_n^2 I \] (4)
\( T_k \) is the temporal correlation matrix among different slots, \( R_0 \) contains the correlation coefficients between sensors, and \( \otimes \) is the Kronecker product operator.
Note that we are implicitly including the LOS component as a rank-one term in the correlation matrix.
Path searching process defined by (6) is repeated along the window until alternative $H_2$ is verified. If a new path is not detected, finger path is chosen as the earliest. $L$ has been set to 5Tc for figures shown in this paper. Mean square error is related to false alarm and detection probabilities by (9); where $p(n/m)$ corresponds to the probability of detecting an arrival at lag $n$ when arrival is located at lag $m$, and $\varepsilon_q$ is an error term included due to the temporal quantization of the delay axis, as 1 sample per chip. For uniform quantization, as it is the temporal correlation of the delay axis, as 1 sample per chip. For uniform quantization, as it is the case, its power is $1/12$.

$R_b$ has been computed using the distributed source model proposed in [7], and for Monte Carlo Simulations $10^7$ realization were used to evaluate Detection Probability and $10^5$ to evaluate false alarm. Scattering was simulated using a first order AR process. Temporal correlation factors of 0.1 and 0.999 are used

$$E\{e^2\} = \frac{1}{L} \sum_{m=1}^{L} \sum_{n=1}^{L} p(n/m) \cdot (m-n)^2 +$$

$$+ (1 - P_{fa})^{l-1} (1 - P_D) \sum_{n=1}^{l} n^2 + E\{e_q^2\}$$

(9)

$$p(n/m) = \begin{cases} 
P_{fa} (1 - P_{fa})^{n-1} & n < m \\
P_D (1 - P_{fa})^{n-1} & n = m \\
P_{fa} (1 - P_{fa})^{n-2} (1 - P_D) & n > m 
\end{cases}$$

$$\varepsilon_q \in [-1/2T_c, 1/2T_c]$$

For the case of correlated sensors an angular spread of 5 degrees and a mean direction of arrival of zero was supposed to compute.

Direct path arrives from broadside and sensors are linearly and uniformly spaced. Doppler frequency for direct path corresponds to a mobile speed of 50 km/h, N=100 and p=15 for figures 2-3 and 6.

Figure 2 shows that even with just one sensor and a poor SNR of 0 dB a good accuracy is achieved when a false alarm around $10^{-3}$ is chosen. Note that due to the fact that error characteristic exhibit minimum, some prior signal knowledge is worth to select threshold. In practice, however, there is little chance that this knowledge is available and, once the threshold is set, the paths arriving with lower SNR will not be detected.

Figure 3 shows how detection improves when scattering is highly correlated and a direct path is present compared to just scattering. On the contrary detection worsens when scattering is uncorrelated but this quality loss is negligible as it can be seen in figure 6 since performance improves sensibly. This effect may be more important for more reduced data records and it would be the case for high-speed units (temporally uncorrelated scattering).

Figure 4: First arrival detection rms error as a function of $P_a$ and the number of sensors. One sensor, and a highly correlated source.
as it can be seen in figures 4-5, and weaker signals may be detected.

Figure 5: First arrival detection rms error as a function of $P_a$ and the data records length. One sensor, highly correlated source and different configurations of the data matrix.

VI. SUMMARY AND CONCLUSIONS

A method for improving subscriber location accuracy by reducing NLOS propagation error has been described. A GLRT detector for PCD sources has been derived in (6), and some results have been shown for different environments and detector configurations. It has been shown that given a low SNR and a false alarm probability, by enhancing data records or increasing the number of sensors, better results are observed for temporally uncorrelated sources and uncorrelated sensors.

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