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Direct emitter geolocation under local scattering ☆

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ABSTRACT

Emitter geolocation under local scattering environment is explored. We derive an analytic model for the received signal where the local scattering environment is modeled as a stochastic process using the Gaussian Angle of Arrival (GAA) model. For the signal model we provide both optimal and sub-optimal, computationally-simpler, 1-step (direct) emitter geolocation algorithms. The proposed algorithms enable to estimate the emitter 's position directly, using the received signal samples. The proposed algorithms extract the emitter position information from both fading channel statistics and temporal correlations when the fading channel is quasi-static. It is shown that the devised 1-step algorithms outperform 2-step emitter geolocation algorithms, formerly proposed for the problem. Numerical examples are provided to illustrate the performance. The results are compared with the theoretical performance projected by the Cramér–Rao lower bound.

1. Introduction

The method of single-step geolocation (a.k.a. Direct-Position-Determination/DPD) has been shown to be an efficient geolocation method that outperforms conventional two-step geolocation methods (separately estimating location-dependent parameters and then the location itself), under low signal-to-noise ratio (SNR) conditions in a variety of systems and applications [1–9]. Yet, in most of the publications investigating DPD performance, the emitting source is modeled as a point source. While enabling some important insights into the fundamental limitations of single-step emitter geolocation, the rather simplistic point-source model rarely provides a high-fidelity representation of the emitter signal in a multipath-dense environment. Such an environment is typically crowded with scatterers surrounding the emitter and reflecting its signal towards the receiving array. In such case, the emitter is not perceived as a point but rather as a "scattered" or as a "distributed" source.

The advancement in smart antenna technology during the 1990s has motivated the development of spatial/temporal channel models to facilitate accurate performance prediction of multi-antenna systems. The paper by Ertel et al. [20] provides a comprehensive summary of these multi-antenna channel models. Most of these models are based on a combination of spatial and temporal numerical channel modeling, for which analytic analysis is difficult. One of these channel models, termed Gaussian Angle of Arrival (GAA), was proposed by Zetterberg [10], and was later adopted by Ottersten, Trump and others [11–17]. The GAA model was developed for obtaining a statistical description of the array correlation under nar row-band Rayleigh fading channels, often characterizing macro-cell cellular environments in suburban areas. The model assumes that the emitter lies within a cluster of scatterers, generating multiple reflections of the emitter's signal. The associated angle of arrival (AOA) at an antenna array has a Gaussian distribution.

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Since its publication, the GAA model has been applied mainly to AOA-estimation problems of distributed sources under various channel and signal models [13–25]. However, very little attention was given to geolocation of such distributed sources. This paper aims to bridge this gap by incorporating the GAA model into geolocation problem model and deriving single-step algorithms for locali zing distributed sources under Rayleigh fading channel conditions.

Main contributions: We formulate the signal model for geolocation of an emitting source in the presence of local scattering under quasi-static temporal Rayleigh fading, using multiple base-station antenna arrays. We extend the GAA model covariance matrix derivation, originally developed for uniform-linear arrays (ULA), to arbitrary-shaped antenna arrays. For this model we derive both optimal and computationally-simpler, sub-optimal, single-step (direct) geolocation algorithms for emitter geolocation. Based on both numerical performance and complexity analysis, we introduce the recommended algorithm for the problem. In addition, we provide a detailed derivation of the Cramér Rao lower bound (CRLB) for the received signal model. Using numerical analysis of the CRLB expressions we highlight expected estimation accuracy under different temporal-fading and scattering conditions.

Paper organization: Section 2 outlines the problem formulation. Then Section 3 provides several optimal and sub-optimal algorithms for 1-step geolocation of a static emitter under local scattering. Numerical performance examples of the devised algorithms are given in Section 4, and their computational-complexity is analyzed in Section 5. Final conclusions are given in Section 6, and in the Appendix we provide the derivation of the CRLB for the problem.

2. Problem formulation

2.1. Spatial model

Consider a stationary emitter that at an unknown time, t_0, begins to transmit a narrow band signal with an envelope of $s(t)$. The signal bandwidth is W, which satisfies the condition $W \ll f_c$, where f_c is the carrier frequency.[1] The emitter's signal is intercepted by L geographically separated Base-Stations (BS), each is equipped with an antenna-array with M antenna elements.

As depicted in Fig. 1, the emitter is surrounded by $\overline{N}_{sc}$ closely spaced scatterers (which are assumed to be about the same height or higher than the emitter). The scatterers generate multiple reflection rays of the emitter's signal around the emitter. The emitter signal observed by each of the receiving arrays is built up by a super-position of these independent rays. This phenomenon is known as "local scattering". The emitter is assumed to be completely obscured by the scatterers such that there is no direct line of sight (LoS) between the emitter and any of the receiving arrays. In case there is a LoS between the scattered emitter and any of the arrays, the formed fading channel is called Ricean [17,23].

The rays emanating from the scatterers impinge on each array with a delay associated with the propagation time. The ray originating from the nth scatterer hits the ℓth array after $(\tau_\ell + \Delta\tau_{\ell n})$ s, where τ_ℓ denotes the nominal propagation time from the emitter located at $\mathbf{p} = [x, y]^T$ to the ℓth BS located at $\mathbf{q}_\ell = [\overline{x}_\ell, \overline{y}_\ell]^T$ (both defined in a global coordinates-system), and $\Delta\tau_{\ell n}$ denotes the excess time delay due to the signal reflected by the nth scatterer.

The nominal propagation time is given by

$$\tau_\ell = \frac{d_\ell}{c}$$
$$d_\ell = \|\mathbf{p} - \mathbf{q}_\ell\|^2 = \sqrt{(x - \overline{x}_\ell)^2 + (y - \overline{y}_\ell)^2} \tag{1}$$

where c denotes the propagation speed.

Commonly, it is assumed that all the time delays of the independent rays generated by the scatterers are small in comparison with the reciprocal of the signal bandwidth and therefore are unresolvable [18,19]. Thus, the following approximation may be used:

$$s(t - \tau_\ell - \Delta\tau_{\ell n} - t_0) \approx s(t - \tau_\ell - t_0) \triangleq s(t - \tilde{\tau}_\ell) \tag{2}$$

where $\tilde{\tau}_\ell \triangleq \tau_\ell - t_0$.

The noise-free signal received by the ℓth BS array can be described as

$$\mathbf{x}_\ell(t) = \mathbf{b}_\ell(t) \cdot s(t - \tilde{\tau}_\ell) \tag{3}$$

where $\mathbf{b}_\ell(t)$ is a $M \times 1$ vector describing the array's response to the channel at time t. Assuming that the nth ray received by the ℓth array has a complex gain, $\beta_{\ell,n}(t)$, and an angular perturbation, $\phi_{\ell,n}$, then array response may be described as a superposition of all the rays impinging on the array given by

$$\mathbf{b}_\ell(t) = \sum_{n=1}^{\overline{N}_{sc}} \beta_{\ell,n}(t) \mathbf{a}_\ell(\theta_\ell + \phi_{\ell,n}) \tag{4}$$

with $\mathbf{a}_\ell(\theta)$ being the ℓth array $M \times 1$ steering vector with its mth element located at $\mathbf{q}_{\ell,m} = [\overline{x}_{\ell,m}, \overline{y}_{\ell,m}]^T$ (where $\mathbf{q}_{\ell,m}$ is defined w.r.t. the array center located at $\mathbf{q}_\ell$). The response of this element to a signal arriving from position $\mathbf{p} = [x, y]^T$ is given by

$$[\mathbf{a}_\ell]_m = \frac{1}{\sqrt{M}} e^{(\imath 2\pi/\lambda)[\overline{x}_{\ell,m} \cos\theta_\ell(\mathbf{p}) + \overline{y}_{\ell,m} \sin\theta_\ell(\mathbf{p})]} \tag{5}$$

where $\imath = \sqrt{-1}$ and λ is the transmitted signal wavelength and (see e.g., [26])

$$\theta_\ell(\mathbf{p}) = \tan^{-1}\left(\frac{y - \overline{y}_\ell}{x - \overline{x}_\ell}\right) \tag{6}$$

In the sequel we adopt the GAA model for obtaining closed-form analytic expressions for the statistical distribution of the array response vectors. These expressions are shown to be position-dependent and therefore enable to extract the emitter position from multiple observations of the channel. The GAA model assumes that the nth ray complex gain is distributed as $\beta_{\ell,n}(t) \sim \mathcal{CN}(0, 1/\overline{N}_{sc})$, and the distribution of the angle perturbations generated by

[1] The propagation time of the signal across the array must be small compared to the signal's envelope rate of change, given by $1/W$. Let the array aperture be $Y = \tilde{A} \cdot \lambda$, where $\tilde{A}$ is an integer, which usually varies between 1 and 10. Then, at the propagation speed, c, we have $Y/c \ll 1/W \Rightarrow \tilde{A}/f_c \ll 1/W$. Thus, we have $W/f_c \ll 1/\tilde{A} \le 1 \Rightarrow W \ll f_c$.