MOBILE VELOCITY AND DIRECTION OF MOVEMENT ESTIMATION IN NLOS MULTIPATH ENVIRONMENT

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ABSTRACT

In this paper, we propose a new method to jointly estimate the Mobile Velocity (MV) and the Direction of Movement (DM). We exploit the NLOS multipath environment with Uniform Linear Arrays (ULAs) at the receiver. We consider the Gaussian and the Laplacian angular distributions for the incoming angle of arrivals, for being the most used ones in the literature. The proposed method uses the magnitudes and the phases of the received signals Cross-Correlation Functions (CCFs). We take as a benchmark the Tow Rays (TR) approach for the MV estimates. Performance is assessed via Monte Carlo simulations. Using the Root Mean Square Error (RMSE) as a measure of performance, our new estimator performs well over wide MV and DM ranges and outperforms the TR one for the MV estimation.

Index Terms— mobile velocity, direction of movement, cross-correlation function, SIMO configuration, NLOS multipath environment.

1. INTRODUCTION

The mobile velocity estimation plays an important role in wireless applications. Indeed, it is used for dynamic channel assignment, handoff and adaptive transmission. The knowledge of the mobile speed provides also information about the fading severity and improves the link quality. Different techniques were studied for the mobile speed estimation. In [1], a Maximum Likelihood method based on a polynomial approximation of the auto-correlation function is used. Level crossing rate approaches were also considered in the literature for the mobile velocity estimation as in [2]. In the latter, a Doppler adaptive noise suppression process in the frequency domain is adopted to reduce the effect of the additive noise. These two estimators (i.e. [1] and [2]) show high computational complexity since they use heavy mathematical resolution techniques while exploiting the auto-correlation function led to low-complexity approaches as in [3] and [4]. In [3], the derivatives of the auto-correlation function are considered and the incoming waves distribution is taken into account. While, in [4] a Two-Rays (TR) approximation offers closed-form expressions and considers the presence of residual carrier frequency offset. Recently, we proposed a joint estimator of the mean Angle of Arrival (AoA), the Angular Spread (AS) and the maximum Doppler Spread (DS) [5]. Our estimator is based on the cross-correlation functions (CCFs) and provides accurate estimates for the mean AoA, AS and satisfactory results for the maximum DS. In [6], maximum DS and mean AoA estimator is developed, based on the characteristics in the power spectrum of mobile fading of Single Input Single Output (SISO) and Single Input Multiple Output (SIMO) channels. Indeed, the spectrum of the received signal is used to estimate the maximum DS by finding its peak. In [7], a mobile station velocity estimator is developed. It is based on the spatial correlation of the shadow fading, azimuth and delay spreads of a mobile station velocity. A mobile velocity and direction of movement approach is derived in [8] for a mobile to mobile configuration in a MIMO system. To the best of our knowledge, the direction of movement estimation has not been addressed for the mobile to base station configuration.

In this work, we exploit the magnitudes and phases of the cross-correlation matrix at different time lags in order to estimate the mobile velocity with a low complexity approach. Then, we deduce the direction of movement of the mobile. The angular distribution of the incoming AoAs is taken into account in the cross-correlation closed-form derivation. Without loss of generality, only Gaussian and Laplacian angular distributions versions of the algorithm are presented in this paper. The same approach can be applied for other angular distributions. This paper is organized as follows. In section II, we describe the considered signal model. We also derive closed-form expressions of the CCFs of the received signals in a SIMO configuration for both Gaussian and Laplacian angular distributions. In section III, we develop the new velocity and direction of movement estimator denoted by CCFE. In section IV, we present and discuss the obtained results before drawing out some concluding remarks in section V.

Notation: We use $|.|$ for the magnitude and arg for phase. The uppercase and lowercase letters represent, respectively, the matrices and scalars. The $\hat{.}$ denotes the estimated values.

2. SIGNAL MODEL

We consider the uplink transmission over a NLOS multipath environment from a single source to N_a Uniform Linear Array (ULA) at the receiver as shown in Fig. 1. The received signal at the i^{th} antenna element is modeled as follows [9]:

$$
\begin{aligned}
x_i(t) &= \sigma_{x_i} \lim_{P \to +\infty} \frac{1}{\sqrt{P}} \sum_{p=1}^{P} a_p \exp j\left[\omega_D \cos(\theta_p)t + \phi_p\right] \\
&+ n_i(t), \qquad (1)
\end{aligned}
$$

where

$\sigma_{x_i}^2$	power of the received signal,
P	number of multipaths,
a_p	random unknown complex constants normalized to satisfy $\lim_{P\to+\infty} p^{-1}\sum_{p=1}^{P}\lvert a_p\rvert^2 = 1$, so that $\sigma_{x_i}^2 = E[\lvert x_i(t)\rvert^2] - \sigma_{n_i}^2$,
$\sigma_{n_i}^2$	power of the Additive White Gaussian Noise (AWGN), $n_i(t)$, at the i^{th} antenna,
θ_p	AoAs of the received signals follow an angular distribution with a mean and a standard deviation defined by the mean AoA, θ_m, and the AS, σ, respectively,
ϕ_p	phases uniformly distributed over $(-\pi\ \pi]$,
ω_D	normalized maximum DS,
α	direction of movement defined as the angle between the direction of the mobile and the antenna axis.

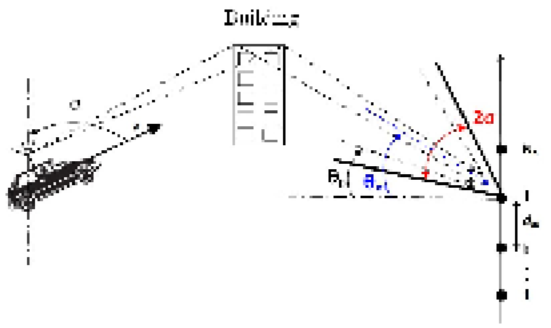

Fig. 1. Incoming waves model for uplink transmission from a single mobile source.

The normalized maximum DS, ω_D, is given by $\omega_D = 2\pi F_D T_s = (2\pi v f_c T_s)/C$, where F_D is the Doppler frequency, T_s is sampling rate, f_c is the carrier frequency and $C = 3 \times 10^8$ m/s is the speed of light. Hence, estimate the mobile velocity, v, is therefore equivalent to estimate the Doppler spread ω_D.

The cross-correlation matrix of the received signals is given by:

$$
\begin{aligned}
\mathbf{R}_{kl}(\tau) &= \frac{E[x_k(t)x_l^*(t+\tau)]}{\sqrt{E[\lvert x_k(t)\rvert^2]E[\lvert x_l(t)\rvert^2]}}, \\
&= \int_{-\pi}^{\pi} P(\theta_p; \theta_m, \sigma) \exp\left(-j\frac{2\pi}{\lambda} d_{kl} \sin(\theta_p)\right) \\
&\quad \exp(-j\omega_D \tau \cos(\theta_p - \alpha)) d\theta_p, \qquad (2)
\end{aligned}
$$

with $P(\theta_p; \theta_m, \sigma)$ is the Probability Density Function (PDF) of the incoming AoAs. d_{kl} is the distance between the k^{th} and the l^{th} antenna elements. In this paper, we consider both Gaussian and Laplacian angular distributions for the incoming AoAs [10]. We recall that our estimator is based on the CCFs. Our approach is divided in two steps. First, we derive a closed-form expressions of the CCF and, subsequently, we solve an equations system where the unknowns are the parameters to be estimated. In the remainder of this section, we derive closed-form expressions of the CCF for each angular distribution.

- *Gaussian angular distribution:*

The PDF of the Gaussian angular distribution is giving by:

$$
P(\theta_p, \theta_m, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(\theta_p - \theta_m)^2}{2\sigma^2}\right]. \qquad (3)
$$

In this work, we assume small ASs, σ. Indeed, in macrocell environments, the AS does not exceed 10^o [9] and [11]. In this case, the linearization $(\sin(\theta_p) \approx \sin(\theta_m) + (\theta_p - \theta_m)\cos(\theta_m))$ is applied to ensure regular integrals. We obtain the following closed-form expression, $\mathbf{R}_{kl}(\tau)$, for the Gaussian angular distribution using the entity (eq. 15.73 in [12]):

$$
\begin{aligned}
\mathbf{R}_{kl}(\tau) &= \exp\left[-\frac{\sigma^2}{2}\left(-\omega_D\tau\cos(\theta_m - \alpha) - \frac{2\pi}{\lambda}d_{kl}\sin(\theta_m)\right)^2\right] \\
&\quad \exp[-j\frac{2\pi}{\lambda}d_{kl}\cos(\theta_m) - \omega_D\tau\sin(\theta_m - \alpha)]. \qquad (4)
\end{aligned}
$$

- *Laplacian angular distribution:*

The PDF of the Laplacian angular distribution is defined by:

$$
P(\theta_p, \sigma, \theta_m) = \frac{1}{\sigma\sqrt{2}} \exp\left[-\frac{\lvert\theta_p - \theta_m\rvert}{\frac{\sigma}{\sqrt{2}}}\right]. \qquad (5)
$$

Assuming a small AS, the approximation $(\cos(\theta_p) \approx \cos(\theta_m) - (\theta_p - \theta_m)\sin(\theta_m))$ can be considered. After some algebraic manipulations and using (eq.15.68 in [12]), we obtain the cross-correlation coefficient for the Laplacian angular distribution $\mathbf{R}_{kl}(\tau)$ as follows:

$$\mathbf{R}_{kl}(\tau) = \frac{1}{1+\frac{\sigma^2}{2}\left[\omega_D\tau\sin(\theta_m-\alpha) + \frac{2\pi}{\lambda}d_{kl}\cos(\theta_m)\right]^2}\cdot \exp\left[-j\frac{2\pi}{\lambda}d_{kl}\sin(\theta_m) - \omega_D\tau\cos(\theta_m-\alpha)\right]. \quad (6)$$

The obtained closed-form expressions of the cross-correlation coefficients are used in the next section in order to jointly estimate the mobile velocity and the direction of movement. The estimated cross-correlation coefficients are given by:

$$\hat{\mathbf{R}}_{kl}(\tau) = \frac{1}{N_s-\tau}\sum_{m=1}^{N_s-\tau} x_k(m)\, x_l(m+\tau), \quad (7)$$

where N_s is the number of the received signal samples.

3. FORMULATION OF THE NEW MV AND DM ESTIMATOR

In this section, we derive the Cross-Correlation Function based Estimator (CCFE). To this end, the cross-correlation matrix is considered at different time lags to estimate the mobile velocity and then deduce the direction of movement using (4) and (6). Both Gaussian and Laplacian versions are developed here.

3.1. Gaussian Distribution

The magnitudes and phases of the CCF closed-form expressions are exploited separately at a time lag $\tau \neq 0$ as follows:

$$|R_{kl}(\tau)| = \exp\left[-\frac{\sigma^2}{2}\left(\omega_D\tau\sin(\theta_m-\alpha) + \frac{2\pi}{\lambda}d_{kl}\cos(\theta_m)\right)^2\right], \quad (8)$$

$$\angle R_{kl}(\tau) = -\frac{2\pi}{\lambda}d_{kl}\sin(\theta_m) - \omega_D\tau\cos(\theta_m-\alpha). \quad (9)$$

Considering the second zero time lag $\tau = 0$, yields to the following expressions:

$$|R_{kl}(0)| = \exp\left[-\frac{\sigma^2}{2}\left(-\frac{2\pi}{\lambda}d_{kl}\cos(\theta_m)\right)^2\right], \quad (10)$$

$$\angle R_{kl}(0) = -\frac{2\pi}{\lambda}d_{kl}\sin(\theta_m). \quad (11)$$

Since we take into account the incoming waves angular distribution of the received signals, we need to estimate their mean AoA and standard deviation AS. The obtained estimates are then used to deduce the mobile velocity. In that case, the mean AoA is expressed using the phase of the estimated cross-correlation coefficient, $\hat{R}_{kl}$, in (11):

$$\hat{\theta}_m = \arcsin\left(-\frac{\angle\hat{R}_{kl}(0)}{\frac{2\pi}{\lambda}d_{kl}}\right). \quad (12)$$

The standard deviation is then deduced from the magnitude of the cross-correlation coefficient, $\hat{R}_{kl}(0)$, defined in (10) and it is given by:

$$\hat{\sigma} = \frac{\sqrt{-\ln(|\hat{R}_{kl}(0)|)}}{\frac{\sqrt{2}\pi}{\lambda}d_{kl}\cos(\hat{\theta}_m)}. \quad (13)$$

Using the mean AoA, AS estimates and by differentiating the magnitudes and phases of the cross-correlation coefficient at the two considered time lags, we obtain the following mobile velocity estimator expression:

$$\hat{\omega}_D^2 = 1/\tau^2\Bigg(\left[\angle\hat{R}_{kl}(0) - \angle\hat{R}_{kl}(\tau)\right]^2 + \left[\frac{\sqrt{2}}{\hat{\sigma}}\left(\sqrt{-\ln(|\hat{R}_{kl}(0)|)} - \sqrt{-\ln(|\hat{R}_{kl}(\tau)|)}\right)\right]^2\Bigg).$$

The mobile direction of movement is then deduced using the mean AoA expression defined in (12) and the maximum DS estimate as follows:

$$\hat{\alpha} = \hat{\theta}_m - \arcsin\left(\frac{\angle\hat{R}_{kl}(0) - \angle\hat{R}_{kl}(\tau)}{\hat{\omega}_D\tau}\right) \quad (14)$$

3.2. Laplacian Distribution

As for the Gaussian version, we consider separately the magnitude and the phase of the cross-correlation coefficients as follows:

$$|R_{kl}(\tau)| = \frac{1}{1+\frac{\sigma^2}{2}\left[\omega_D\tau\sin(\theta_m-\alpha) - \frac{2\pi}{\lambda}d_{kl}\cos(\theta_m)\right]^2}. \quad (15)$$

The phase of the CCF $\angle R_{kl}(\tau)$ admits the same expression as in (9). We also, consider the cross-correlation matrix at a zero time lag $\tau = 0$ as follows:

$$|R_{kl}(0)| = \frac{1}{1+\frac{\sigma^2}{2}\left[-\frac{2\pi}{\lambda}d_{kl}\cos(\theta_m)\right]^2}, \quad (16)$$

As for the Gaussian phase of the cross-correlation coefficients, we obtain the same expression of $\angle R_{kl}(0)$ defined in (11), which yields to the same estimate of the mean AoA, as

in (12).
The standard deviation, is then deduced using the mean AoA estimate and the magnitude of the estimated cross-correlation coefficient, $\hat{R}_{kl}(0)$, as:

$$\hat{\sigma} = \frac{\sqrt{\frac{1}{|\hat{R}_{kl}(0)|} - 1}}{\frac{\sqrt{2}\pi}{\lambda} d_{kl} \cos(\hat{\theta}_m)}. \quad (17)$$

The mobile velocity estimate is then obtained using the magnitudes and phases of the cross-correlation coefficient defined in (8), (10), (9) and (11):

$$\hat{\omega}_D^2 = \left(\left[\frac{\sqrt{2}}{\hat{\sigma}} \left(\sqrt{\frac{1}{|\hat{R}_{kl}(0)|} - 1} - \sqrt{\frac{1}{|\hat{R}_{kl}(\tau)|} - 1} \right) \right]^2 + \left[\angle \hat{R}_{kl}(0) - \angle \hat{R}_{kl}(\tau) \right]^2 \right) / \tau^2. \quad (18)$$

Since we obtain the same expression of the cross-correlation coefficients phases with both Gaussian and Laplacian angular distributions defined in (9) and (11), the mobile direction estimate admits the same derived expression as in (14).

4. SIMULATION RESULTS

We assess the performance of our approach by means of Monte-Carlo simulations with $N_s = 1024$ samples. We consider a Rayleigh SIMO channel with N_a elements spaced by a half wavelength at the receiver. In this work, we consider $N_a = 5$ but other configurations can be applied. We adopt the channel model described in [9] for the SIMO configuration with Gaussian and Laplacian angular distributions instead of the Von-Mises one. The signal to noise ratio is set at $20\, dB$, the carrier frequency at $f_c = 0.9\ Ghz$ and the sampling time at $T_s = 1/15000\ s$. We take as a benchmark the TR approach [4] for the mobile velocity estimates.

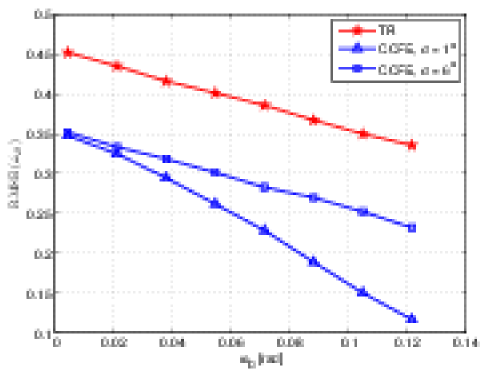

Fig. 2. RMSE of the mobile velocity estimation for the Gaussian angular distribution.

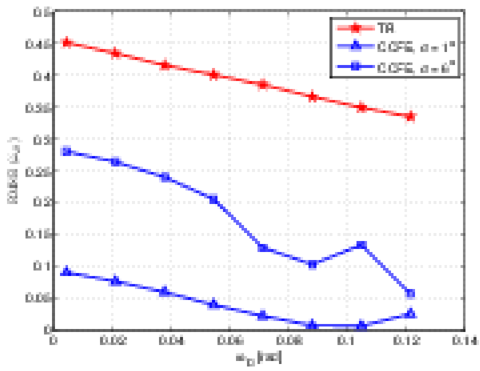

Fig. 3. RMSE of the mobile velocity estimation for the Laplacian angular distribution.

In Fig. 2, we investigate the mobile velocity estimation for the Gaussian angular distribution. This simulation is performed at a mean AoA, $\theta_m = 10^0$ for both low and high AS values(i.e. $\sigma = 1^o$ and 6^o). Our estimator is valid for any mobile speed. Indeed, we study the mobile velocity estimation at a speed range between $10\ Km/h$ and $350\ Km/h$ (i.e. $\omega_D T_s$ between 0.005 and 0.12 rad). As one can notice, the CCFE algorithm outperforms the TR one for both studied scenarios. We notice that the error rate increases for high AS values (i.e $\sigma = 6^o$) this is due to the considered Taylor expansion in the closed-form expression of the CCF. But, even for high AS values the CCFE still achieves accurate estimates comparing to the TR algorithm. We note that, our approach provides accurate estimates especially at a high mobile velocity.

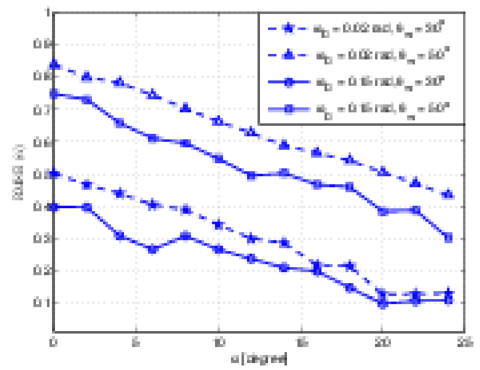

Fig. 4. RMSE of the mobile direction of movement estimation at $\sigma = 1^o$ for the Gaussian angular distribution.

We recall that our approach is based on the cross-correlation coefficient, which is function of the angle spread, distance between antenna elements and the mean AoA. Knowing that AOA distribution gives similar spatial correlation for the same angular spread [10] and [13], we obtain close RMSEs for the considered angular distributions as illustrated in Fig. 2

and Fig. 3.

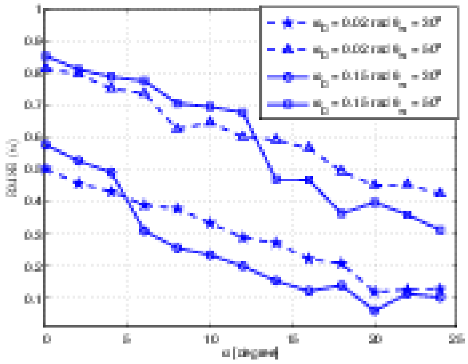

Fig. 5. RMSE of the mobile direction of movement estimation at AS $\sigma = 1^{\circ}$ for the Laplacian angular distribution.

The direction of movement estimation is evaluated for both Gaussian and Laplacian angular distributions in Fig. 4 and 5, respectively. We plot the results obtained with the estimated velocities for both low and high mobile speeds and at different mean AoA values (i.e. $\theta_m = 30^{\circ}$ and 50°). Since the mobile direction estimate expression is function of the mobile velocity and we obtain a lower error rate of the mobile velocity estimates for high velocities, our approach performs accurate RMSEs especially at a high mobile speed.

5. CONCLUSION

A new low complexity approach is proposed in this paper for the mobile velocity and the direction of movement estimation. The magnitudes and phases of the SIMO cross-correlation coefficients are exploited to simultaneously estimate the desired parameters. Both Gaussian and Laplacian angular distributions are considered in a NLOS multipath environment. Simulation results showed that, our approach outperforms the TR algorithm for the maximum DS estimation. Exhaustive computer simulations were performed for the direction of movement estimation and the results showed accurate estimates.

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