Estimation of the mobile station velocity in micro-cellular systems with non-isotropic scattering

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***Abstract*-This paper presents a new method for estimating the velocity of a mobile station (MS) in a typical micro-cellular system with non-isotropic scattering. The proposed estimator uses the zero-crossing rates of the in-phase component, and the means of the instantaneous frequency (IF) and the absolute IF of the received signal at the MS antenna. It is also shown that using the above mentioned statistics of the received signal, the Rice factor and the directivity parameter can be estimated too. Unlike the existing velocity estimators, the proposed estimator is unbiased when the scattering distribution is non-isotropic.**

Index Terms- velocity estimation, non-isotropic scattering, scattering distribution, Rice factor, directivity parameter.

1. INTRODUCTION

Accurate estimates of the velocity of a mobile station (MS) are necessary for effective handover and dynamic channel assignment in cellular systems and also for designing adaptive power control algorithms for code-division multiple access (CDMA) systems[1, p.48],[2]. Several methods for estimating the velocity of an MS have been presented in the literature. These include the use of the zero-crossing rate[1] (ZCR) of the in-phase or quadrature components of the received signal [3] as well as the rate of maxima[2] (ROM), level crossing rate (LCR) [3], and the auto-covariance (COV) of the envelope of the received signal [4]. It has been shown in [5] that the performance of all the above mentioned techniques, which are based on the statistics of either the envelope or quadrature components of the received signal, deteriorates in the presence of shadowing. In [6], an estimator for the velocity of an MS is proposed which is based on the 1st order moment of the instantaneous frequency (IF) of the received signal. The proposed estimator is proven to outperform the other estimators in the presence of shadowing.

All the aforementioned velocity estimators are derived with the assumption that the distribution of the scattering component is isotropic. While this assumption may be valid in a typical macro-cellular system, it is not generally true in a micro-cellular system [7, p.40]. Therefore, those estimators will be significantly biased when being used to estimate the velocity of an MS moving in a micro-cellular environment.

This paper presents a new velocity estimator which takes into account the scattering distribution. The proposed estimator uses the ZCR of the in-phase component and the statistics of the IF of the received signal to estimate the velocity. The remainder of this paper is organized as follows: Section 2 describes the model and statistics of the received signal. In section 3, using the statistics derive in section 2, the proposed estimator is presented. New estimators for the Rice factor and directivity parameter are also given in section 3. Section 4 concludes the paper.

2. CHARACTERISTICS OF THE RECEIVED SIGNAL

2.1. Model of the Received Signal

The received signal at the MS is assumed to follow the model given by [3]:

$$y(t) = x(t) + (m_i \cos 2\pi f_c t - m_q \sin 2\pi f_c t) \qquad (1)$$

where f_c is the carrier frequency, m_i and m_q are due to the presence of a Line of Sight (LoS) component and $x(t)$ represents the scatter components of the received signal. The signal $x(t)$ can be written as:

$$x(t) = x_i(t)\cos(2\pi f_c t) - x_q(t)\sin(2\pi f_c t) \qquad (2)$$

where $x_i(t)$ and $x_q(t)$ are the in-phase and quadrature components, respectively. For a sufficiently large number of incoming waves ($N \geq 6$, see[8]), the in-phase and quadrature components of $x(t)$ in (2) tend to be independent zero-mean Gaussian processes with variance σ^2 . The envelope of the signal $y(t)$ which is given by

$$|y(t)| = \sqrt{(x_i(t) + m_i)^2 + (x_q(t) + m_q)^2} \qquad (3)$$

[1] The ZCR is defined as the average numbers of positive-going zero crossings per second.

[2] The ROM is defined as the average number of maxima per second.

has a Ricean distribution [7], with Rice factor $K = (m_i^2 + m_q^2)/(2\sigma^2)$. In the absence of an LoS component the means m_i and m_q are equal to zero and the envelope is Rayleigh distributed.

The IF of the received signal is defined as:

$$f_{i,y}(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \tag{4}$$

where

$$\varphi(t) = \tan^{-1}\left(\frac{x_q(t)}{x_i(t)}\right). \tag{5}$$

The proposed velocity estimator in this paper uses the statistics of the IF and ZCR of the quadrature components of the received signal.

2.2. Power Spectral Density and the Spectral Moments of the Received Signal

In [7, p.47] , the power spectral density (PSD) of the signal $x(t)$ in (2) is given by:

$$S_X(f) = \begin{cases} \dfrac{\sigma^2}{2\sqrt{f_m^2 - (f-f_c)^2}}[G(\theta)p(\theta) + G(-\theta)p(-\theta)]; & |f-f_c| < f_m \\ 0 & ; |f-f_c| > f_m \end{cases} \tag{6}$$

where f_m is the maximum Doppler frequency shift, $p(\theta)$ is the scattering distribution, and $G(\theta)$ is the gain of the MS antenna with θ the angle of incidence of the incoming wave. The maximum Doppler frequency shift is defined as $f_m = v/\lambda$ where v is the velocity of the mobile unit and λ is the wavelength of the received signal.

Here, the von-Mises density which has proved a suitable tool for studying the effects of the scattering distribution in a wireless environment [9], is used as a model for $p(\theta)$. This p.d.f. is given by:

$$p(\theta) = \frac{1}{2\pi I_0(\chi)} e^{\chi\cos\theta} \qquad ; \chi \ge 0, -\pi \le \theta \le \pi \tag{7}$$

where the parameter χ determines the directivity of the incoming waves and $I_n(.)$ is the modified Bessel function of the first kind of order n. It can be easily verified that for $\chi = 0$ the scattering distribution is isotropic ($p(\theta) = 1/2\pi$), while for $\chi > 0$ it is non-isotropic and as χ increases, the incoming waves become more directive. If a vertical mono-pole antenna is used then $G(\theta) = 3/2$ ([10, p.218]). With $G(\theta) = 3/2$, using the scattering distribution given in (7) for $p(\theta)$ and $\cos\theta = (f - f\ )/f_m$ ([7, p.47]), the PSD given in (6) becomes:

$$S_X(f) = \begin{cases} \dfrac{a_0}{2\pi I_0(\chi)\sqrt{f_m{}^2 - (f-f_c)^2}} e^{\chi(\frac{f-f_c}{f_m})} & ; |f-f_c| < f_m \\ 0 & ; |f-f_c| > f_m \end{cases} \tag{8}$$

where $a_0 = 3\sigma^2/2$. For $\chi = 0$ the above equation reduces to the PSD in the isotropic case given in [7, p.48].

The n^{th} spectral moment of $x(t)$ in (2) is defined as [11]:

$$a_n = (2\pi)^n \int_0^\infty (f - f_c)^n S_X(f)\, df . \tag{9}$$

Using (8), after some simple algebra, it can be shown that:

$$a_1 = a_0(2\pi f_m)\frac{I_1(\chi)}{I_0(\chi)} \tag{10}$$

$$a_2 = a_0(2\pi f_m)^2\left(\frac{I_0(\chi) + I_2(\chi)}{2I_0(\chi)}\right) \tag{11}$$

$$a_4 = a_0(2\pi f_m)^4\left(\frac{3I_0(\chi) + 4I_2(\chi) + I_4(\chi)}{8I_0(\chi)}\right) \tag{12}$$

The statistics of the received signal derived in the next section are functions of the spectral moments given in the equations (10)-(12).

2.3. Statistics of the Received Signal

In this section, using the results given in section 2.2, the formulas for the ZCR of the in-phase/quadrature component and the means of the IF and absolute IF of the received signal are derived. These statistics are used in the next section to derive a new estimator for the velocity.

Based on the results in [11], the ZCR of the in-phase/quadrature component of $x(t)$ is derived as:

$$N_{ZCR} = \frac{1}{2\pi}\sqrt{\frac{a_2}{a_0}}. \tag{13}$$

Also, using the results in [11], the mean of the IF and absolute IF are given by:

$$E\left[f_{i,y}\right] = \frac{1}{2\pi}\frac{a_1}{a_0}\, e^{-K} \tag{14}$$

$$E\left[\left|f_{i,y}\right|\right] = \frac{1}{2\pi}\sqrt{\frac{a_2}{a_0}}\, I_0\left(\frac{K}{2}\right) e^{-\frac{K}{2}}. \tag{15}$$

Using the spectral moments given in (10)-(12), N_{ZCR}, $E\left[f_{i,y}\right]$, and $E\left[\left|f_{i,y}\right|\right]$ can be represented as functions of the Rice factor, directivity parameter and velocity. Therefore, the equations (13)-(15) can be solved simultaneously to obtain estimates of K, f_m and χ. In the next section, we use this fact to derive a new velocity estimator

3. THE PROPOSED VELOCITY ESTIMATOR

3.1. Estimating the Rice Factor and the Directivity Parameter

We observed in the previous section that in order to estimate the velocity, prior estimation of K and χ are needed. Here, it is shown how those parameters can be derived from N_{ZCR}, $E\left[f_{i,y}\right]$, and $E\left[\left|f_{i,y}\right|\right]$.

From the equations (13) and (15) we have:

$$\frac{E\left[\left|f_{i,y}\right|\right]}{N_{ZCR}} = I_0\left(\frac{K}{2}\right) e^{-\frac{K}{2}}. \qquad (16)$$

Also, using the equations (13) and (14) we obtain:

$$\frac{E\left[f_{i,y}\right]}{e^{-K} N_{ZCR}} = \frac{I_1(\chi)\sqrt{2}}{\sqrt{I_0(\chi)\left(I_0(\chi)+I_2(\chi)\right)}}. \qquad (17)$$

It follows from the equations (16) and (17) that estimates of K and χ can be obtained by first estimating N_{ZCR}, $E\left[f_{i,y}\right]$, and $E\left[\left|f_{i,y}\right|\right]$, and then solving those equations numerically for K and χ [1]. The Rice factor K can alternatively be estimated using the explicit formulas for K in terms of the moments of the envelope [12] and also in terms of the statistics of the IF of the received signal [13].

We will observe in the next section that the bias in the estimated velocity due to the error in the estimation of the directivity parameter is negligible for $\chi \geq 5$. Therefore, an approximation of (17) which gives $\chi < 5$ with a reasonable small bias can be used. Using the curve-fitting procedure, the right side of (17) was approximated with an exponential function of χ and a closed form equation for χ was obtained as follows:

$$\chi = \ln \frac{1}{1 - \dfrac{E\left[f_{i,y}\right]}{e^{-K} N_{ZCR}}} = \ln \frac{e^{-K} N_{ZCR}}{e^{-K} N_{ZCR} - E\left[f_{i,y}\right]} \qquad (18)$$

In order to see how good the above approximation is, for given values of N_{ZCR}, $E\left[f_{i,y}\right]$, and K, the exact and approximated values of the directivity parameter χ are computed using (17) and (18). The results are plotted in Fig. 1. We observe that instead of solving (17) numerically for χ, equation (18) can be used. The difference between the true value of χ and its approximation is small for $\chi < 5$. It is seen that the contribution of this error in estimating a given velocity is negligible.

[1] Look-up tables can also be used to find K and χ.

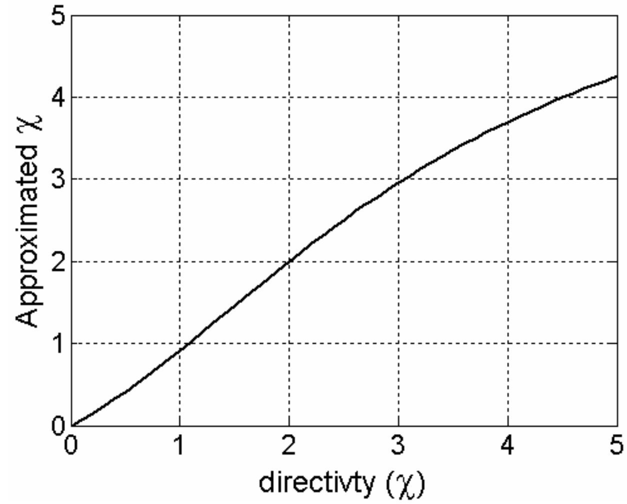

Fig. 1. For given values of N_{ZCR}, $E\left[f_{i,y}\right]$, and K, directivity χ is computed from (17) and the approximated χ is computed using (18).

3.2. Estimating the Velocity

After estimating the Rice factor and the directivity parameter, one can use any of the equations (13)-(15) to estimate the velocity. Here, the velocity estimator based on N_{ZCR} in (13) is presented. From (13) and using $f_m = v/\lambda$, an estimate of the velocity is obtained as:

$$v = \lambda N_{ZCR} \sqrt{\frac{2I_0(\chi)}{I_0(\chi)+I_2(\chi)}}. \qquad (19)$$

For $\chi = 0$, equation (19) reduces to

$$v_{iso} = \lambda N_{ZCR}\sqrt{2} \qquad (20)$$

which is the ZCR-based velocity estimator with the assumption of isotropic scattering given in [3]. In order to study the significance of using the velocity estimator given in (19) in the case of non-isotropic scattering v/v_{iso} is plotted versus χ in Fig. 2. It is seen that for $\chi \geq 5$, the velocity estimator in (20) exhibits a bias of almost 25% in estimating a given velocity. Fig. 2 also shows that the increase in the bias of the estimator in (20) is negligible for $\chi \geq 5$. This proves that the closed form formula for χ given in (18) which computes the directivity parameter in the range of $\chi < 5$, can be used instead of (17).

In order to further illustrate this fact, for given values of N_{ZCR}, $E\left[f_{i,y}\right]$, and K assuming $v = 50\ Km/h$, we have used the set of equations {(16), (17), and (19)} instead of {(16), (18), and (19)} and computed the approximated velocity as a function of χ. The results are shown in Fig. 3. We observe that the set of equations {(16), (18), and (19)} have found the approximated velocity with a bias of less than 5%.

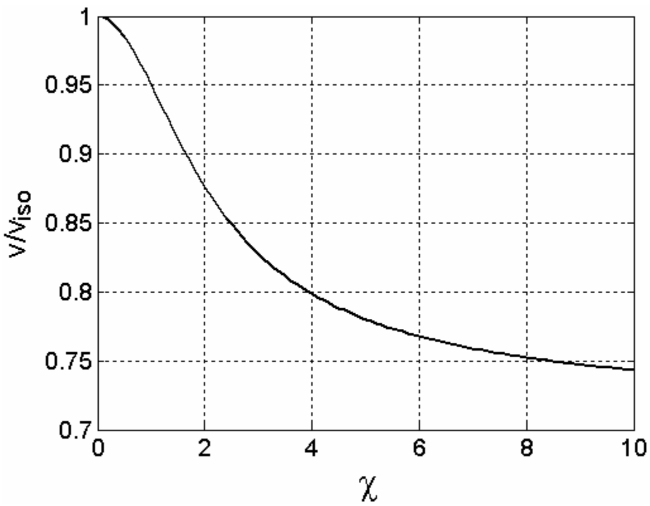

Fig. 2. The effect of the non-isotropic scattering on the velocity estimator in (20).

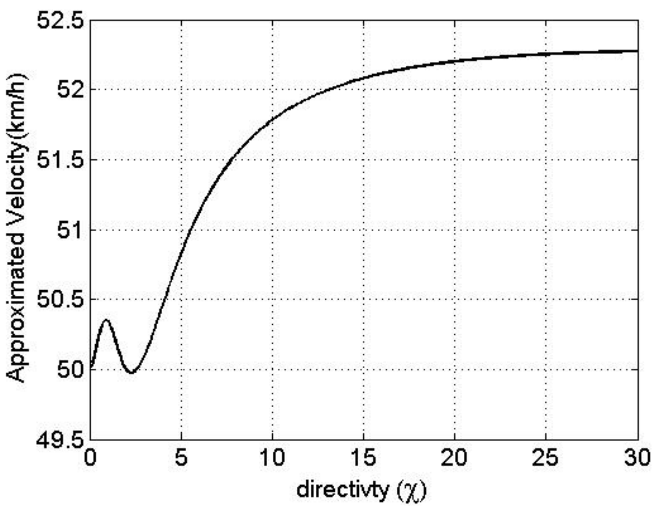

Fig. 3. Given N_{ZCR} , $E\left[f_{i,y}\right]$, and K , for $v = 50\ Km/h$, the approximated velocity is computed using the set of equations {(16), (18) and (19)}

4. CONCLUSIONS

New estimators for the velocity of an MS, the Rice factor, and the directivity parameter of the incoming waves in a typical micro-cellular system with non-isotropic scattering were proposed. The estimators were based on the ZCR of the in-phase and the means of the IF of the received signal. The proposed velocity estimator is simple but needs prior estimation of the Rice factor and directivity parameter.

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