ESTIMATION OF THE VELOCITY OF MOBILE UNITS IN MICRO-CELLULAR SYSTEMS USING THE INSTANTANEOUS FREQUENCY OF THE RECEIVED SIGNALS

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1. ABSTRACT

Handover processes in micro-cellular systems are more involved than in cellular systems. In particular, micro-cellular systems suffer from the so-called *corner effect* where line-of-sight between the mobile station and the base station is suddenly lost when the mobile rounds a corner. As a result, the received signal drops rapidly below threshold level and the call can be lost. It has been shown that, if an accurate estimation of the velocity of the mobile unit is available, the call can be rescued by applying short temporal window averaging on the received signal. Current methods for estimating the velocity of mobile units in micro-cellular systems are based on the level crossing rate of the envelope of the received signals. This paper presents a new velocity estimator based on the instantaneous frequency of the received signal. The performance of the proposed estimator is shown to be superior to that of the level crossing rate method. The average relative error of the proposed estimator is down to below 8% whereas that of the LCR method reaches 14%.

2. INTRODUCTION

Inter-cell handover is the process whereby a call in progress is maintained while the mobile station (MS) passes through different cells. Handovers in cellular systems are less involved than in micro-cellular systems where the number of handovers per call is increased while the time available to process them is decreased [4]. In micro-cellular systems, the base station (BS) is at lamp post level. As a result, micro-cellular systems suffer from the so called *corner effect* where line-of-sight (LOS) between the BS and a MS is suddenly lost when the mobile user turns a corner (Fig. 1) [4].

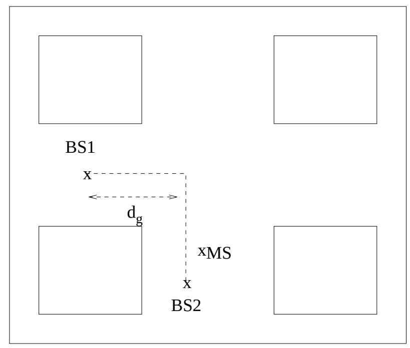

Fig. 1. The MS turns round the corner. LOS from the current BS (BS1) is lost and LOS is established between the MS and the target BS (BS2).

A direct consequence of the corner effect is that the power of the received signal drops rapidly below threshold level and an emergency handover needs to be processed towards a target BS for the call to be maintained (Fig. 2).

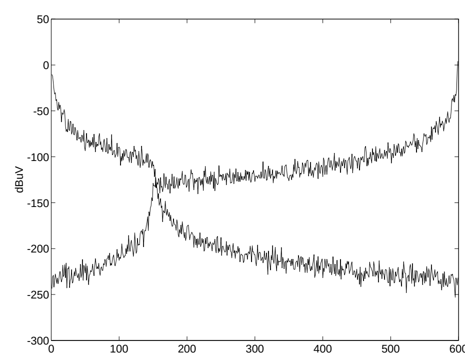

Fig. 2. The signal received from BS1 suddenly drops as the MS turns round the corner. The signal received from BS2 suddenly increases as LOS is established.

This drop in signal strength can be detected by applying short temporal window averaging on the received signals [8]. However, this technique is velocity dependent and is optimal only when an accurate estimation of the velocity of the mobile user is available [1].

Current methods for velocity estimation use the statistics of the envelope of the received signal. Methods based on the level crossing rates (LCR), zero crossing rates (ZCR) and covariance approximation (COV) have been used. Of these, ZCR based methods have received the most attention due to their simplicity and good performance [1]. The high relative error is the main drawback of these methods.

This paper proposes an alternative approach for estimating the velocity of the MS based on the instantaneous frequency (IF) of the received signal. Section 3 formulates the short-term fading model for the received signals and their characteristics. LCR based estimators are described in sections 4. In section 5, the proposed IF based velocity estimator is derived. Section 6 reviews existing techniques for IF estimation. Section 7 presents simulation of the proposed estimator and discusses its performance. Section 8 gives some concluding remarks.

3. SHORT-TERM FADING MODEL

In a typical cellular environment, a MS is usually surrounded by local scatterers so that the plane waves will arrive from many directions without a direct LOS component. With this assumption, the received signal is well characterizes as a narrow-band Gaussian random process specified by Lee's model [6]. This model assumes that the received bandpass signal is

$$s(t) = \mathcal{I}(t)cos\omega_c t - \mathcal{Q}(t)sin\omega_c t \tag{1}$$

where ω_c is the angular carrier frequency and, for sufficiently large incoming waves ($N \geq 6$ [5]), both $\mathcal{I}(t)$ and $\mathcal{Q}(t)$ tend to zero-mean Gaussian processes, each with variance σ^2 that are independent. The envelope $e(t)$ and the phase $\psi(t)$ are defined through the transformation

$$\mathcal{I}(t) = e(t)cos\psi(t)$$
$$\mathcal{Q}(t) = e(t)sin\psi(t) \; .$$

It is well known that the envelope $e(t)$ and the phase $\psi(t)$ are Rayleigh and uniformly distributed, respectively. Typical plot of received signal envelope and its histogram is shown in Fig. 3.

Using the above short-term fading model, it can be shown that the probability density function of the random signal $\dot{\psi}(t)$ is [6]

$$\rho(\dot{\psi}) = \frac{1}{\sqrt{2}\beta v}[1 + \frac{2}{(\beta v)^2}\dot{\psi}^2]^{\frac{-3}{2}} \; . \tag{2}$$

In the above equation, β is the wave number ($\frac{2\pi}{\lambda}$), λ is the carrier wavelength, and v is the velocity of the MS.

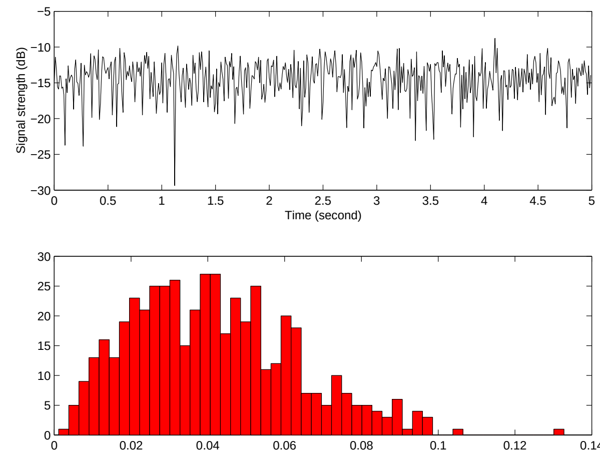

Fig. 3. (a) Typical plot of received signal envelope $e(t)$ (dB); (b) Histogram of $e(t)$ shows that it can be modeled as a Rayleigh distribution.

4. THE LCR OF THE RECEIVED SIGNAL

The LCR is defined as the average number of positive-going crossings per second a signal makes of a predetermined level A. The LCR of $y(t)$ at a given level A is [6]

$$n(y = A) = \int_0^\infty \dot{y} \; p(y = A, \dot{y}) \; d\dot{y} \; . \tag{3}$$

Using the short-term fading model of section 3, the LCR of $s(t)$ can be derived as follows [6]

$$n(\frac{s}{\sqrt{2\sigma^2}} = R) = \frac{\beta v}{\sqrt{2\pi}} R \; exp(-R^2) \tag{4}$$

where v is the velocity of the MS and

$$\sigma^2 = E[\mathcal{I}^2] = E[\mathcal{Q}^2] \; .$$

From (4), the LCR can be used to provide a velocity estimate of the MS as follows

$$\hat{v}_{lcr} = \frac{\sqrt{2\pi}}{\beta R} n_0 \; exp(R^2) \tag{5}$$

where n_0 is the average number of positive-going level R crossings that the signal $\frac{1}{\sqrt{2\sigma^2}}s(t)$ makes per second.

5. THE PROPOSED ESTIMATOR

The proposed estimator is derived from the maximum likelihood estimator (MLE) of the velocity of the MS based on the IF of the received signal. The IF of $s(t)$ is defined as [2]

$$f_i(t) = \frac{1}{2\pi}\frac{d\psi(t)}{dt} \; . \tag{6}$$

Given observed values $\dot{\Psi}_i$ of $\dot{\psi_i(t)}$, the likelihood of v as a function of $\dot{\psi}_i(t)$ where $i = 1, 2, ..., n$ is defined as [7]

$$lik(v) = \rho(\dot{\psi}_1(t), \dot{\psi}_2(t), ..., \dot{\psi}_n(t)|v) \ . \qquad (7)$$

If the $\dot{\Psi}_i$ are assumed to be independent and identically distributed (i.i.d.), their density is the product of the marginal densities, and the likelihood is

$$lik(v) = \prod_{i=1}^{n} \rho(\dot{\Psi}_i|v) \ . \qquad (8)$$

The maximum likelihood estimator of v is obtained by maximizing the log likelihood of $lik(v)$ given by

$$\ell(v) = \sum_{i=1}^{n} log\{\rho(\dot{\Psi}_i|v)\} \ . \qquad (9)$$

From (2) the log likelihood of an i.i.d. sample $\dot{\Psi}_1, \dot{\Psi}_2, ..., \dot{\Psi}_n$ is

$$\begin{aligned} \ell(v) &= \sum_{i=1}^{n} log\{\frac{1}{\sqrt{2}\beta v}[1 + \frac{2}{(\beta v)^2}\dot{\Psi}_i^{\,2}]^{\frac{-3}{2}}\} \\ &= -nlog\{\sqrt{2}\beta v\} - \frac{3}{2}\sum_{i=1}^{n} log\{1 + \frac{2}{(\beta v)^2}\dot{\Psi}_i^{\,2}\}. \end{aligned} \qquad (10)$$

The MLE is obtained by setting the first derivative of the log likelihood to zero, which results in the following nonlinear equation

$$\frac{6}{\beta^2 \hat{v}_{mle}^2} \sum_{i=1}^{n} \frac{\dot{\Psi}_i^{\,2}}{1 + \frac{2}{(\beta \hat{v}_{mle})^2}\dot{\Psi}_i^{\,2}} = n \ . \qquad (11)$$

which can be solved iteratively.

According to the *large sample theory for MLEs [7]*, the MLE is asymptotically unbiased and its asymptotic variance is

$$var(\hat{v}_{mle}) \simeq \frac{1}{nI(v)} \qquad (12)$$

where

$$I(v) = E\left[\left(\frac{\partial}{\partial v}\, log\ \rho(\dot{\psi}|v)\right)^2\right] \ . \qquad (13)$$

Note that under smoothness assumptions on $\rho(\dot{\psi}|v)$, $1/nI(v)$ is the Cramer-Rao lower bound which gives a lower bound on the variance of any unbiased estimator of v. Since the exact variance of the MLE, $\hat{v}_{mle}$, can not be computed in closed form, we approximate it by the asymptotic variance. From (2) and (13), we find that

$$I(v) = E\left[\left(\frac{-1}{v} + \frac{6}{\beta^2 v^3}\frac{\dot{\psi}^2}{1 + \frac{2}{(\beta v)^2}\dot{\psi}^2}\right)^2\right] \ .$$

But

$$E\left[\frac{\dot{\psi}^2}{1 + \frac{2}{(\beta v)^2}\dot{\psi}^2}\right] = \frac{(\beta v)^2}{6}$$

and

$$E\left[\left(\frac{\dot{\psi}^2}{1 + \frac{2}{(\beta v)^2}\dot{\psi}^2}\right)^2\right] = \frac{(\beta v)^4}{20}$$

therefore

$$I(v) = \frac{0.8}{v^2}$$

and finally

$$var(\hat{v}_{mle}) \simeq \frac{v^2}{0.8n} \ . \qquad (14)$$

Equation (14) shows that $var(\hat{v}_{mle})$ converges to zero as n approaches infinity.

In (11), the summation is over n different realizations of the random process $\dot{\psi}$. However, in practice, a single finite duration data record is available. Assuming ergodicity, and since $\frac{2}{(\beta v)^2} \ll 1$, the proposed velocity estimator is obtained from the MLE estimator as

$$\hat{v} = \frac{1}{\beta}\sqrt{\frac{6}{M}\sum_{k=0}^{M-1}\dot{\psi}(k)^2} \qquad (15)$$

where $\dot{\psi}$ is the IF of one realization of the received signal and M is the duration of the recorded signal. Equation (15) shows that an estimate of the velocity of the MS can be made by estimating the IF of the received signal $s(t)$.

6. IF ESTIMATION

Equation (15) indicates that the performance of the proposed estimator depends on the accurate estimation of the IF of the received signal. There are many well established methods for estimating the IF of a signal [2, 3]. These methods include differentiation of the phase and smoothing thereof, extraction of the peak from time-frequency representations, and adaptive frequency estimation techniques such as the phase locked loop.

One particular method of IF estimation used in this paper is based on measuring the number of zero-crossings. In order to reduce the variance of the zero-crossing estimate, the number of crossings within a window with specified length are averaged and used to form the estimate [3].

7. SIMULATION AND DISCUSSIONS

The received signal was modeled using (1). The number of waves arriving at the receiver, N, was set equal to 10. The sampling frequency is 300 Hz and the signal duration was chosen to be 10 $second$. The IF of the received signal was estimated using the zero-crossing estimation algorithm. The performance of the proposed velocity estimator was compared with that of the LCR velocity estimator. The average relative error for each velocity was computed over 100 realizations of the received signal. Fig. 4 shows the average relative error as a function of the velocity of the MS for the proposed estimator and for the LCR estimator. It appears that the maximum error for $\hat{v}$ is reduced to less than 8% whereas that of the $\hat{v}_{lcr}$ is around 14%.

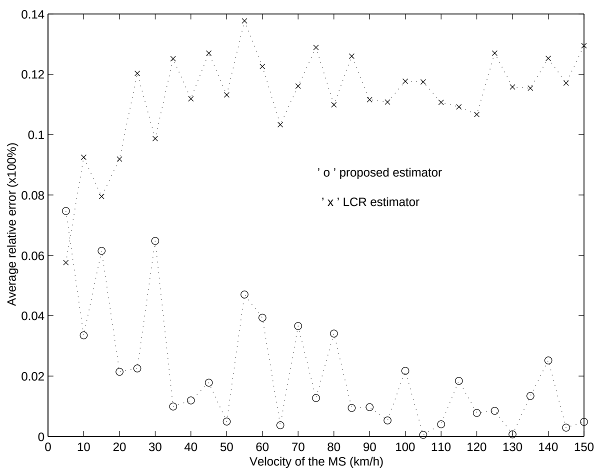

Fig. 4. Average relative error for the LCR estimator and the proposed estimator at different velocities of the MS.

Fig. 5 shows the variance of the proposed estimator as a function of the number of samples M and compares it to the Cramer-Rao (CR) lower bound. It appears that, as a result of the approximation $\frac{2}{(\beta v)^2} \ll 1$, the ergodicity assumption and errors in the IF estimation, the variance of the proposed estimator is still higher than the CR bound.

8. CONCLUSION

This paper presents an alternative method for estimating the velocity of mobile units in micro-cellular systems. The estimation of the velocity is used to design mobile speed sensitive handover algorithms that will compensate for the corner effect in micro-cellular systems. The proposed velocity estimator is an approximation of the maximum likelihood estimator and is based on estimating the instantaneous frequency of the received signal. It is shown that the performance of the proposed estimator is superior to that of the level-crossing rate estimator which is currently used as a velocity estimator. The use of the proposed estimator could therefore result in a major improvement of current handover processes.

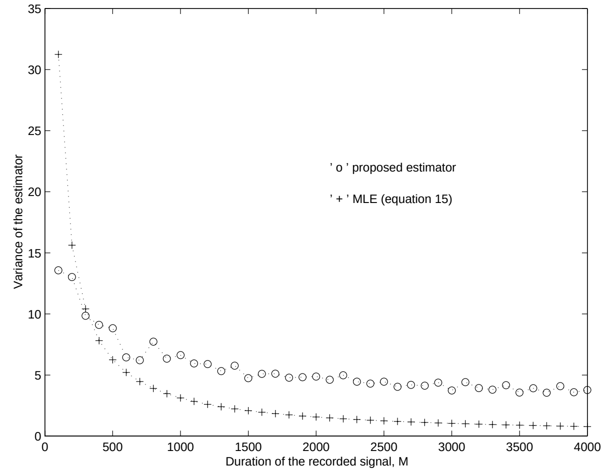

Fig. 5. Variance of the proposed estimator compared to the Cramer-Rao lower bound.

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