

Velocity Estimation in Wideband Mobile Stations Equipped With Multiple Antennas

Dmitry Umansky
Faculty of Engineering and Science
University of Agder
Service Box 509, N-4898, Grimstad, Norway
Email: dmitry.umansky@uia.no

Matthias Pätzold
Faculty of Engineering and Science
University of Agder
Service Box 509, N-4898, Grimstad, Norway
Email: matthias.paetzold@uia.no

Abstract—A new method is proposed for estimating the velocity of wideband mobile stations (MSs) equipped with multiple antennas. The MS speed is determined using the well-known relationship between the direction-of-arrivals (DOAs) and the Doppler frequency shifts experienced by the multipath signal components. The method is based on the assumption that the multipath signal components with the DOAs confined to a small angular interval are clustered in the delay domain. Additionally, we assume that different intervals of the DOAs correspond to different intervals of the propagation delays. The performance of the proposed method is assessed by simulations. The algorithm has a low computational cost and is therefore suitable for real-time implementations.

I. INTRODUCTION

During the last two decades, a number of publications has been devoted to the problem of estimating the MS velocity from the received signal in cellular networks. Such interest is due to the fact that significant improvements in the performance of wireless communication systems are possible if the MS speed is known. For example, the knowledge of the MS velocity allows to minimize the number of handovers in multilayer cellular networks. Furthermore, the information about the MS speed can be used to tune up different adaptive signal processing algorithms implemented in the transceivers.

Several methods for estimating the MS velocity can be found in the literature, see e.g., [1]–[8]. The performance evaluation of some of the estimation algorithms, as well as their comparison, are presented in [9, Chapter 5]. According to the theoretical and simulation-based analysis provided in the references, the main factors that cause degradation in the performance of the available velocity estimators are the additive noise, presence of shadowing, and the nonisotropic scattering environment. An additional factor, which is often omitted from the consideration, is the limited time interval over which the channel statistics have to be estimated.

Although the existing velocity estimators can be employed without any changes in wideband multiple-input multiple-output (MIMO) systems, it is of interest to investigate how additional *degrees of freedom*, i.e., signal bandwidth and multiple antennas at a MS, can be utilized to improve the accuracy of the velocity estimation for different propagation scenarios. The results of the investigations might be useful in the context

of developing the newly emerged Ultra Mobile Broadband (UMB) [10] and mobile WiMAX [11] technologies.

In this paper, we propose a new MS velocity estimation method designed for wideband MIMO communication systems. In our method, the speed of the MS is estimated using the well-known relationship between the DOAs and the Doppler shifts that characterizes the multipath signal components. According to [12, Chapter 7], the distribution of DOAs is a function of delays. The assumption that we make regarding the propagation environment is that the multipath components arriving at the MS from a certain bounded interval of DAOs can be uniquely identified with a certain range of propagation delays. This assumption allows us to simplify the otherwise complicated parameter estimation algorithms that can be applied to simultaneously estimate the DOAs and the corresponding Doppler frequencies of the multipath components. The performance of the proposed MS velocity estimator has been evaluated on simulated channel time-variant frequency responses (TVFR). The presented results demonstrate that the suggested velocity estimation algorithm is less sensitive to noise and nonisotropic scattering compared to several other known methods. It is also shown that the performance of the proposed MS speed estimator is affected by the available signal bandwidth.

The rest of the paper is organized as follows. In Section II, we describe the model of the channel TVFR. The MS velocity estimation method is presented in Section III. Section IV provides the results of the performance evaluation. Concluding remarks are given in Section V.

II. THE TVFR OF THE CHANNEL

In this section, we establish the model for the TVFR of a mobile MIMO radio propagation channel. In MIMO systems, the MS and the base station (BS) are equipped with antenna arrays consisting of N_{MS} and N_{BS} elements, respectively. For simplicity reasons and without loss of generality, we let $N_{BS} = 1$.

It is assumed that the TVFR $\mathbf{H}(f', t) = [H_1(f', t), \dots, H_{N_{MS}}(f', t)]^T$ of the mobile radio channel

consists of a finite number N of multipath components, i.e.,

$$\mathbf{H}(f', t) = \sum_{n=1}^N \mathbf{g}(\phi_n) c_n e^{j(2\pi f_{d_n} t - 2\pi f' \tau'_n + \theta_n)} \quad (1)$$

where f' and t denote the frequency and time variables, respectively, and $H_i(f', t)$, $i = 1, \dots, N_{MS}$, is the TVFR of the i -th subchannel. The operator $(\cdot)^T$ signifies the vector transposition. Each of the N multipath components is characterized by the path gain c_n , Doppler frequency f_{d_n} , propagation delay τ'_n , phase shift θ_n , and the DOA ϕ_n . Here, we implicitly assume that the planar electromagnetic waves propagate horizontally.

The steering vector $\mathbf{g}(\phi)$ in (1) is defined as [13]

$$\mathbf{g}(\phi) = [g_1(\phi) e^{-jk_0 \langle \mathbf{k}, \mathbf{r}_1 \rangle}, \dots, g_{N_{MS}}(\phi) e^{-jk_0 \langle \mathbf{k}, \mathbf{r}_{N_{MS}} \rangle}]^T \quad (2)$$

where the vector \mathbf{r}_i , $i = 1, \dots, N_{MS}$, specifies the location of the i -th MS antenna array element with respect to a chosen reference point; \mathbf{k} is a unit vector pointing in the direction of the wave propagation; k_0 is the free-space wavenumber, related to the wavelength λ by $k_0 = 2\pi/\lambda$. The operator $\langle \cdot, \cdot \rangle$ denotes the scalar product of two vectors. The radiation pattern of the i -th antenna array element is given by $g_i(\phi)$, $i = 1, \dots, N_{MS}$. If the MS is equipped with a uniform linear array (ULA), we presume that the radiation pattern of the MS antenna array is effectively restricted to the range of $\phi \in [-\pi/2, \pi/2]$ (see, e.g., [14]), where the DOA ϕ is measured with respect to (w.r.t.) the normal to the linear antenna array.

In practice, the TVFR $\mathbf{H}(f', t)$ has to be estimated, e.g., using pilot tones as in orthogonal frequency division multiplexing (OFDM) communication systems [12]. The errors in the estimated TVFR $\hat{\mathbf{H}}(f', t)$ are represented by a complex spatially uncorrelated (independent) additive white Gaussian noise (AWGN) vector $\mathbf{w}(f', t)$, i.e.,

$$\hat{\mathbf{H}}(f', t) = \mathbf{H}(f', t) + \mathbf{w}(f', t) \quad (3)$$

where each component of the vector $\mathbf{w}(f', t) = [w_1(f', t), \dots, w_{N_{MS}}(f', t)]^T$ has zero-mean and variance $2\sigma_w^2$. In the following, we assume the TVFR $\mathbf{H}(f', t)$ is estimated at discrete frequencies $f'_m = -B/2 + m\Delta f' \in [-B/2, B/2]$, $m = 0, \dots, M-1$, and at discrete time instances $t_k = k\Delta t \in [0, T]$, $k = 0, \dots, K-1$, where B and T denote the frequency bandwidth and the time observation interval, respectively. The frequency sampling interval $\Delta f'$ and the time sampling interval Δt are constants. The time sampling interval Δt is supposed to be less than $1/(2f_{d_{\max}})$ with the maximum Doppler frequency defined as $f_{d_{\max}} = v/\lambda_c$, where v is the speed of the MS and $\lambda_c = c/f_c$ ¹ with c denoting the speed of light.

III. VELOCITY ESTIMATION ALGORITHM

In this section, we describe the algorithm proposed for estimating the MS velocity. The basic idea behind the algorithm comes from the well-known relationship between the

¹In a typical wideband communication system the inequality $B/f_c \ll 1$ still holds, where f_c is the center frequency of the modulated bandpass signal.

Doppler frequency f_{d_n} and the DOA ϕ_n of the n -th multipath component in (1). Under the condition that the Doppler effect is caused only by the MS movement, this relationship can be expressed as

$$f_{d_n} = \frac{v}{\lambda_c} \cos(\phi_n - \alpha_v) \quad (4)$$

where v is the MS velocity and α_v designates the direction of the MS movement.

A. Least-Squares Velocity Estimator

Suppose that estimates of the DOAs $\{\hat{\phi}_l\}$ and the Doppler frequencies $\{\hat{f}_{d_l}\}$ of $L \leq N$ multipath components in (1) are available. The least-squares (LS) estimator of the MS velocity v and the direction of the MS movement α_v can be expressed as

$$\{\hat{v}, \hat{\alpha}_v\} = \arg \min_{\{v, \alpha_v\}} \left\{ \sum_{l=1}^L \left(\hat{f}_{d_l} - \frac{v}{\lambda_c} \cos(\hat{\phi}_l - \alpha_v) \right)^2 \right\}. \quad (5)$$

Using the identity

$$\frac{v}{\lambda_c} \cos(\hat{\phi}_l - \alpha_v) = \frac{v}{\lambda_c} [\cos(\hat{\phi}_l) \cos(\alpha_v) + \sin(\hat{\phi}_l) \sin(\alpha_v)] \quad (6)$$

we can define the system of linear equations

$$\mathbf{A}\mathbf{b} = \mathbf{f}_d \quad (7)$$

where

$$\mathbf{A} = \begin{bmatrix} \cos(\hat{\phi}_1) & \sin(\hat{\phi}_1) \\ \vdots & \vdots \\ \cos(\hat{\phi}_L) & \sin(\hat{\phi}_L) \end{bmatrix}, \quad (8)$$

$$\mathbf{b} \equiv \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} v/\lambda_c \cos(\alpha_v) \\ v/\lambda_c \sin(\alpha_v) \end{bmatrix}, \quad (9)$$

and

$$\mathbf{f}_d = [\hat{f}_{d_1}, \dots, \hat{f}_{d_L}]^T. \quad (10)$$

The LS solution of (7) is given by

$$\hat{\mathbf{b}} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{f}_d. \quad (11)$$

Thus, the LS estimate of the MS velocity that solves the minimization problem in (5) can be written as

$$\hat{v} = \lambda_c \sqrt{\hat{b}_1^2 + \hat{b}_2^2} \quad (12a)$$

$$\hat{\alpha}_v = \arctan \left(\frac{\hat{b}_2}{\hat{b}_1} \right). \quad (12b)$$

B. Estimation of DOAs and the Doppler Frequencies

Hypothetically, it seems to be an attractive approach to select the multipath components in (1) clustered around a known DOA $\hat{\phi}_l$ by using, e.g., the beamforming techniques [15]. Then, assuming the selected multipath components have approximately the same Doppler frequency, it is relatively easy to obtain the estimate \hat{f}_{d_l} . In practice, however, the small aperture (see, e.g., [13]) of an antenna array at the MS makes it impossible to construct a spatial filter (beamformer) with good

selectivity properties² in the angular domain. On the other hand, in wideband communication systems, the ‘aperture’ in the frequency domain, determined by the signal bandwidth B , is relatively large. Thus, the multipath components in (1) with the propagation delays clustered around a known delay $\tilde{\tau}'_l$ can be selected. Furthermore, if there is a strong correlation between the DOAs and the propagation delays of the multipath components, then we can assume that the components clustered in the delay domain around $\tilde{\tau}'_l$ are also clustered in the angular domain and, consequently, have approximately the same Doppler frequency.

The above-mentioned considerations have led to the following algorithm for estimating the DOAs $\{\phi_l\}$ and the Doppler frequencies $\{f_{d_l}\}$, $l = 1, \dots, L$.

Step 1. Select the multipath components with the propagation delays, which are close to a specified delay $\tilde{\tau}'_l$ chosen as described below. For this purpose, pass the estimated TVFR $\hat{H}_i[m, k] = \hat{H}_i[m\Delta f', k\Delta t]$, $i = 1, \dots, N_{MS}$, of the i -th subchannel through a delay bandpass filter with the transfer function centered at $\tilde{\tau}'_l$. The filtering operation can be implemented in the form of a discrete Fourier transform (DFT) as

$$y_i[k; \tilde{\tau}'_l] = \frac{1}{M} \sum_{m=0}^{M-1} \hat{H}_i[m, k] e^{-j2\pi\tilde{\tau}'_l\Delta f' m} \quad (13)$$

where $y_i[k; \tilde{\tau}'_l]$ denotes the sampled signal at the output of the bandpass filter.

Step 2. Estimate the DOA ϕ_l . Assuming the antenna array calibration data as well as the locations of the antenna elements w.r.t. the reference point is available at the MS, the DOA ϕ_l can be estimated using the beamforming method (see, e.g., [13], [15])

$$\hat{\phi}_l = \arg \max_{\phi_l} \left\{ \frac{\mathbf{g}^H(\phi_l) \left(\frac{1}{K} \sum_{k=0}^{K-1} \mathbf{y}[k; \tilde{\tau}'_l] \mathbf{y}^H[k; \tilde{\tau}'_l] \right) \mathbf{g}(\phi_l)}{\mathbf{g}^H(\phi_l) \mathbf{g}(\phi_l)} \right\} \quad (14)$$

where $\mathbf{y}[k; \tilde{\tau}'_l] = [y_1[k; \tilde{\tau}'_l], \dots, y_{N_{MS}}[k; \tilde{\tau}'_l]]^T$, $\mathbf{g}(\phi)$ is defined in (2), and the operator $[\cdot]^H$ denotes the complex conjugate transpose.

Step 3. Estimate the Doppler frequency f_{d_l} by allocating a maximum of the periodogram, i.e.,

$$\hat{f}_{d_l} = \arg \max_{f_{d_l}} \left\{ \frac{1}{K} \left| \sum_{k=0}^{K-1} z[k; \tilde{\tau}'_l, \hat{\phi}_l] e^{j2\pi f_{d_l} \Delta t k} \right|^2 \right\} \quad (15)$$

where the sampled function $z[k; \tilde{\tau}'_l, \hat{\phi}_l]$ is given by

$$z[k; \tilde{\tau}'_l, \hat{\phi}_l] = \mathbf{g}^H(\hat{\phi}_l) \mathbf{y}[k; \tilde{\tau}'_l]. \quad (16)$$

The Steps 1–3 presented above are illustrated with a signal flow chart in Fig. 1.

Note that the choice of the delay bandpass filter used in Step 1 was mainly governed by the simplicity of implementation. For example, the DFT in Step 1 can be readily computed

²By the selectivity properties, we understand the width of the main lobe and the level of the side lobes in the filter transfer function.

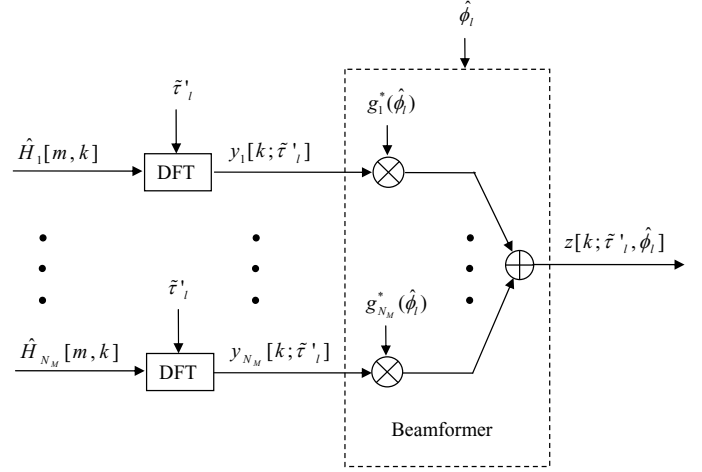


Fig. 1. Signal flow chart for estimating the DOAs and the Doppler frequencies.

using the fast Fourier transform (FFT). It might be possible, however, to improve the characteristics of the filter, e.g., by introducing the data windowing [14], [16].

Based on the conducted simulations, we suggest to set $3 \leq L \leq 10$ and use as $\{\tilde{\tau}'_l\}$ the locations of the L highest peaks in the impulse response of the first subchannel obtained by taking the FFT of $\hat{H}_1[m, k]$ w.r.t. the frequency index m .

On obtaining the estimates $\{\hat{\phi}_l, \hat{f}_{d_l}\}$, $l = 1, \dots, L$, the MS velocity is determined as described in Section III-A.

In deriving the LS estimator of the MS velocity (5), we have not presumed any statistical properties of the estimates $\{\hat{\phi}_l, \hat{f}_{d_l}\}$. In the Appendix, we establish the conditions under which the LS velocity estimator (5) is the maximum likelihood (ML) estimator.

IV. PERFORMANCE RESULTS

In this section, we present the results of the performance evaluation for the MS velocity estimation algorithm described in the previous section.

The performance of the proposed MS velocity estimator has been assessed on a number of TVFRs (1) generated using a simple geometrical model. In this model, the distance D between the BS and the MS is assumed to be 750 m. The MS is equipped with a ULA consisting of two ($N_{MS} = 2$) omnidirectional antenna elements separated by a half wavelength distance. The signal frequency band is centered at $f'_c = 2$ GHz. The normal to the MS antenna array points towards the BS. The scatterers are uniformly distributed in the region between the BS and the MS. The dimensions of the region are determined by the maximum allowed propagation delay $\tau'_{\max} = 1/\Delta f'$. Thus, the DOAs $\{\phi_n\}$ of the multipath components [see (1)] lie in the range $[-\pi/2, \pi/2]$ and, therefore, can be unambiguously estimated. The path gains $\{c_n\}$ are realizations of i.i.d. random variables, each having a uniform distribution in the interval $[0, 1]$. The path gains are first normalized, so that $\sum_{n=1}^N c_n^2 = 1$,

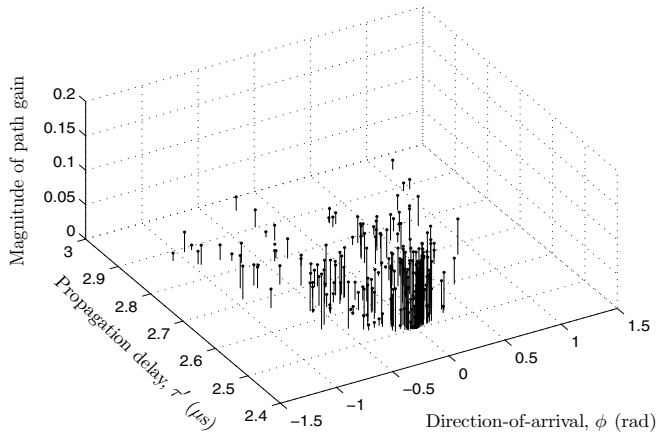


Fig. 2. Example of the simulated multipath components in the delay-DOA plane.

then each of them is multiplied by the exponential factor $\exp[\log(0.1)(\tau'_n - \tau'_{\min})/(\tau'_{\max} - \tau'_{\min})]$, where $\tau'_{\min} = D/c$. The chosen multiplication factor represents the exponential decay normally observed in the measured channel power-delay profile (PDP) [17]. The direction of the MS movement α_v is an outcome of a random number generator having a uniform distribution in the interval $[0, 2\pi)$. The other parameters are specified as below:

- Number of multipath components: $N = 230$;
- Time interval between snapshots: $\Delta t = 1$ ms;
- Number of snapshots: $K = 100$;
- Interval between frequencies: $\Delta f' = 3.125 \cdot 10^5$ Hz.

Note that the propagation delay τ'_n of the n -th multipath component is a function of the DOA ϕ_n in the synthesized TVFR of the channel. An example of the simulated multipath components in the delay-DOA plane is depicted in Fig. 2.

The performance of the MS velocity estimator is evaluated in terms of the normalized bias $E\{(\hat{v} - v)/v\}$ and the mean-squared relative error (MSRE) $E\{[(\hat{v} - v)/v]^2\}$ of the estimates. The operator $E\{\cdot\}$ denotes the ensemble averaging. These two characteristics are shown in Figs. 3 and 4, respectively, for different values of the signal-to-noise ratio (SNR). It can be observed that the normalized bias and the MSRE are almost independent of the actual MS speed. As expected, with increasing SNR, the velocity estimates become less biased and have smaller MSRE.

Figures 5 and 6 demonstrate the degree to which the performance of the proposed velocity estimation algorithm depends on the available signal bandwidth B . It can be seen that for $B \geq 10$ MHz the normalized bias and the MSRE do not change significantly. A somewhat smaller bias is observed for $B = 5$ MHz at the expense of a greater MSRE in the velocity estimates, especially for the smaller MS speed values.

We have also compared the performance of the proposed MS velocity estimation algorithm with several existing methods, namely: the instantaneous frequency (IF) method [6],

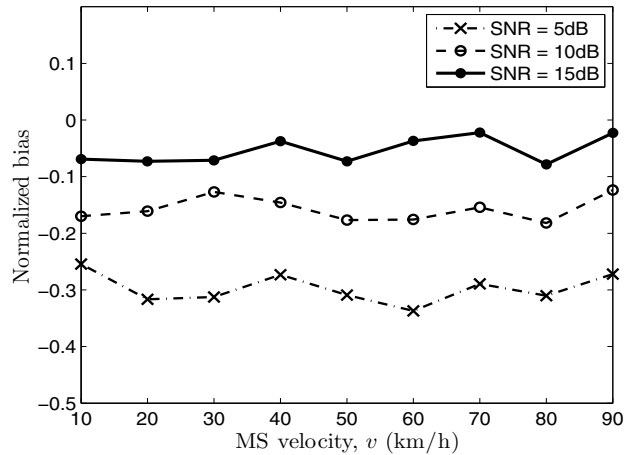


Fig. 3. Normalized bias as a function of the MS velocity and the SNR ($B = 20$ MHz).

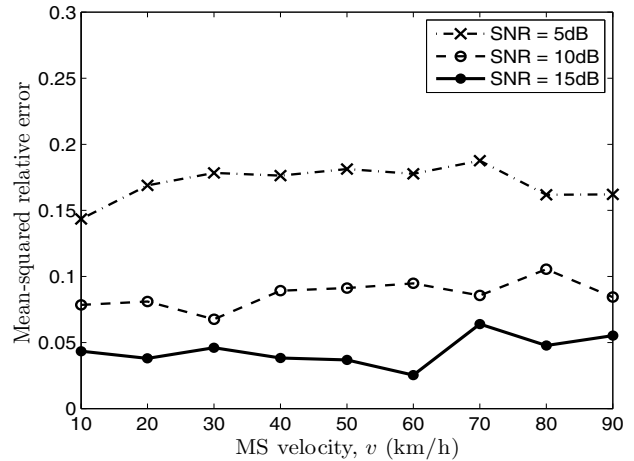


Fig. 4. Mean-squared relative error as a function of the MS velocity and the SNR ($B = 20$ MHz).

the level-crossing rate (LCR) method [1], the zero-crossing rate (ZCR) method [1], and the covariance-based (COV) estimation method [2]³. All of these methods assume isotropic scattering. To satisfy this assumption, the performances of the velocity estimators have been compared based on the TVFRs, generated using the geometrical one-ring simulation model, described, e.g., in [18]. In this model, the scatterers are located on a ring. The DOAs $\{\phi_n\}$ are realizations of i.i.d. random variables, each having a uniform distribution in the interval $[-\pi, \pi]$. All path gains $\{c_n\}$ are equal to $1/\sqrt{N}$. To avoid the ambiguity in the estimation of the DOAs $\{\phi_n\}$, three neighboring elements of an 8-element omnidirectional uniform circular array (UCA) are used as the MS antenna. The other simulation model parameters are unchanged compared to

³The channel statistics required for the velocity estimation by using the IF, LCR, ZCR, and COV methods have been averaged over M frequencies and N_{MS} subchannels.

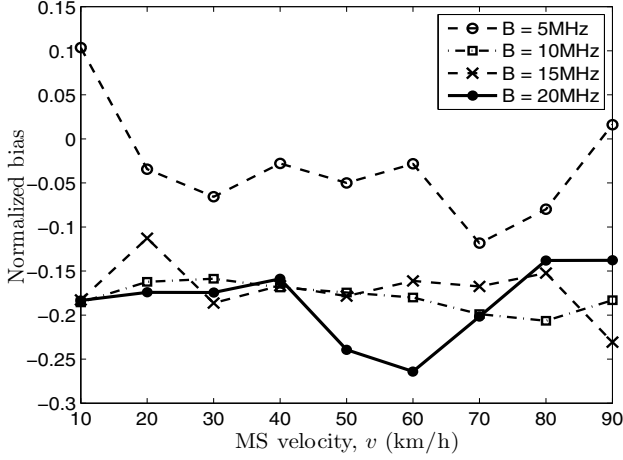


Fig. 5. Normalized bias as a function of the MS velocity and the bandwidth (SNR = 10 dB).

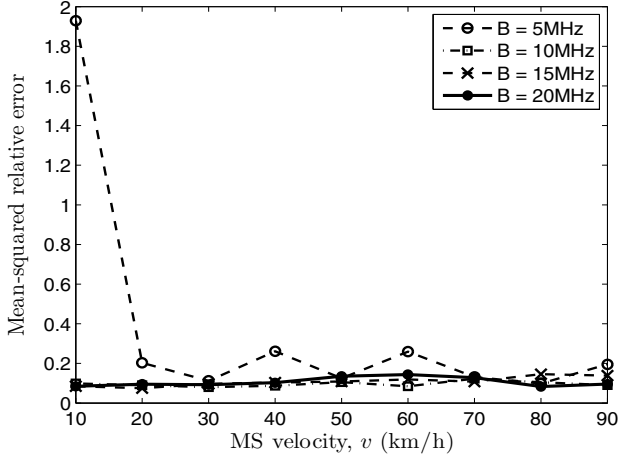


Fig. 6. Mean-squared relative error as a function of the MS velocity and the bandwidth (SNR = 10 dB).

the channel simulator described above. The Rician K -factor, which is zero in this propagation scenario, is assumed known in the IF velocity estimation method.

The normalized bias and the MSRE of the velocity estimates obtained using the aforementioned estimation methods are depicted in Figs. 7 and 8, respectively. It can be observed that the proposed velocity estimation method demonstrates smaller bias and smaller MSRE almost in the whole range of the considered MS speeds.

V. CONCLUSION

In this article, we have presented a new method for the velocity estimation in wideband MSs equipped with multiple antennas. The velocity is estimated by employing the well-known relationships between the DOAs, the MS speed, and the Doppler frequencies of the multipath components representing the TVFR of the channel. The method is based on

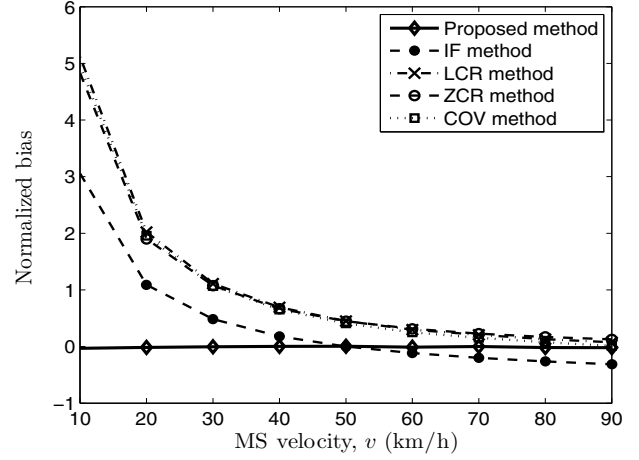


Fig. 7. Normalized bias as a function of the MS velocity (SNR = 10 dB, $B = 20$ MHz).

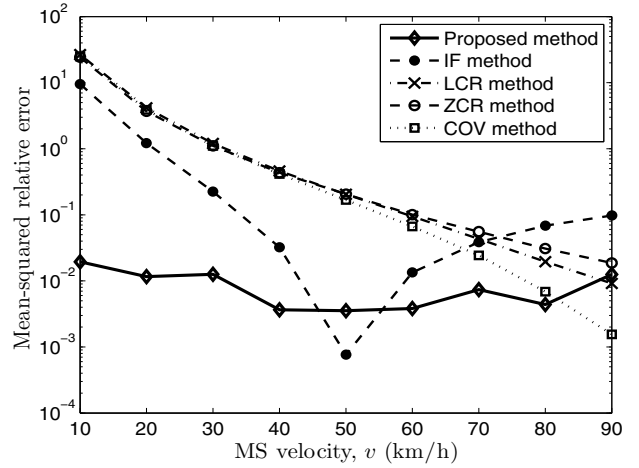


Fig. 8. Mean-squared relative error as a function of the MS velocity (SNR = 10 dB, $B = 20$ MHz).

the assumption that intervals of the DOAs can be uniquely identified with intervals of the propagation delays.

Using computer simulations, the performance of the proposed MS velocity estimation method has been evaluated for different SNRs and different signal bandwidths. It has been demonstrated that the new estimation algorithm is not restricted to isotropic scattering scenarios. The proposed velocity estimator appears to be more robust to noise compared to several other existing MS speed estimation methods.

APPENDIX

We assume that the estimates $\{\hat{f}_{d_l}\}$ and $\{\hat{\phi}_l\}$, $l = 1, \dots, L$, are realizations of the corresponding random variables (RVs). Each pair of the RVs $\{\hat{\phi}_l, \hat{f}_{d_l}\}$ is characterized by the joint PDF

$$p_{\hat{\phi}_l, \hat{f}_{d_l}}(\hat{\phi}_l, \hat{f}_{d_l}) = p_{\hat{\phi}_l}(\hat{\phi}_l) p_{\hat{f}_{d_l} | \hat{\phi}_l}(\hat{f}_{d_l} | \hat{\phi}_l) \quad (17)$$

where $p_{\hat{\phi}_l}(\hat{\phi}_l)$ denotes the PDF of $\hat{\phi}_l$ and $p_{\hat{f}_{d_l}|\hat{\phi}_l}(\hat{f}_{d_l}|\hat{\phi}_l)$ is the conditional PDF of \hat{f}_{d_l} .

Suppose that the following conditions are fulfilled.

1) The L pairs of the RVs $\{\hat{\phi}_l, \hat{f}_{d_l}\}$ are mutually independent, i.e.,

$$p_{\hat{\phi}_1, \dots, \hat{\phi}_L, \hat{f}_{d_1}, \dots, \hat{f}_{d_L}}(\hat{\phi}_1, \dots, \hat{\phi}_L, \hat{f}_{d_1}, \dots, \hat{f}_{d_L}) = \prod_{l=1}^L p_{\hat{\phi}_l}(\hat{\phi}_l) p_{\hat{f}_{d_l}|\hat{\phi}_l}(\hat{f}_{d_l}|\hat{\phi}_l). \quad (18)$$

2) The conditional PDFs $p_{\hat{f}_{d_l}|\hat{\phi}_l}(\hat{f}_{d_l}|\hat{\phi}_l)$ are given by

$$p_{\hat{f}_{d_l}|\hat{\phi}_l}(\hat{f}_{d_l}|\hat{\phi}_l) = \frac{1}{\sqrt{2\pi\sigma_{\hat{f}_d}^2}} \exp\left\{-\frac{(\hat{f}_d - \mu_{\hat{f}_{d_l}})^2}{2\sigma_{\hat{f}_d}^2}\right\} \quad (19)$$

with the mean values $\mu_{\hat{f}_{d_l}} = v/\lambda_c \cos(\hat{\phi}_l - \alpha_v)$ and the unknown variance $\sigma_{\hat{f}_d}^2$.

Substitute (19) into (18). Since PDFs are nonnegative functions, it immediately follows that the joint PDF (18) is maximized when the MS velocity v and the movement direction α_v take the values $\{\hat{v}, \hat{\alpha}_v\}$ defined in (5). Thus, under the conditions (18) and (19), the estimator in (5) is the ML estimator of the MS velocity.

REFERENCES

- [1] M. D. Austin and G. L. Stüber, "Velocity adaptive handoff algorithms for microcellular systems," *IEEE Trans. Veh. Technol.*, vol. 43, no. 3, pp. 549–561, Aug. 1994.
- [2] A. Sampath and J. M. Holtzman, "Estimation of maximum Doppler frequency for handoff decisions," in *IEEE 43th Vehicular Technology Conf.*, Secaucus, NJ, USA, May 1993, pp. 859–862.
- [3] K. D. Anim-Appiah, "On generalized covariance-based velocity estimation," *IEEE Trans. Veh. Technol.*, vol. 48, no. 5, pp. 1546–1557, Sep. 1999.
- [4] R. Narasimhan and D. C. Cox, "Speed estimation in wireless systems using wavelets," *IEEE Trans. Commun.*, vol. 47, no. 9, pp. 1357–1364, Sep. 1999.
- [5] K. E. Baddour and N. C. Beaulieu, "Robust Doppler spread estimation in nonisotropic fading channels," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 2677–2682, Nov. 2005.
- [6] G. Azemi, B. Senadji, and B. Boashash, "Mobile unit velocity estimation based on the instantaneous frequency of the received signal," *IEEE Trans. Veh. Technol.*, vol. 53, no. 3, pp. 716–724, May 2004.
- [7] M. Türkboylari and G. Stüber, "Eigen-matrix pencil method-based velocity estimation for mobile cellular radio systems," in *2000 IEEE Int. Conf. on Communications (ICC 2000)*, vol. 2, New Orleans, LA, USA, Jun. 2000, pp. 690–694.
- [8] W. Sheng and S. D. Blostein, "SNR-independent velocity estimation for mobile cellular communications systems," in *Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Processing (ICASSP'02)*, vol. 3, Orlando, Florida, USA, May 2002, pp. 2469–2472.
- [9] M. Ibnkahla, *Signal Processing for Mobile Communications Handbook*. CRC Press, 2004.
- [10] J. Gozalvez, "Ultra Mobile Broadband [Mobile Radio]," *IEEE Veh. Technol. Mag.*, vol. 2, no. 1, pp. 51–55, Mar. 2007.
- [11] B. Li *et al.*, "A survey on mobile WiMAX," *IEEE Commun. Mag.*, vol. 45, no. 12, pp. 70–75, Dec. 2007.
- [12] A. F. Molisch, *Wireless Communications*. Chichester: Wiley-IEEE Press, 2005.
- [13] D. H. Johnson and D. E. Dudgeon, *Array signal processing: Concepts and Techniques*. NJ: Prentice Hall, 1993.
- [14] P. Stoica and R. L. Moses, *Spectral Analysis of Signals*. NJ: Prentice Hall, 2005.
- [15] B. D. Van Veen and K. M. Buckley, "Beamforming: A versatile approach to spatial filtering," *IEEE ASSP Mag.*, vol. 5, no. 2, pp. 4–24, Apr. 1988.
- [16] E. O. Brigham, *The Fast Fourier Transform and Its Applications*. NJ: Prentice Hall, 1988.
- [17] V. Erceg *et al.*, "A model for the multipath delay profile of fixed wireless channels," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 3, pp. 399–410, Mar. 1999.
- [18] M. Pätzold and B. O. Hogstad, "A space-time channel simulator for MIMO channels based on the geometrical one-ring scattering model," *Wireless Communications and Mobile Computing*, vol. 4, no. 7, pp. 727–737, Nov. 2004.