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Mobile Speed Classification for Cellular Systems over Frequency Selective Rician Fading Channels

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***Abstract*— In this paper, a new algorithm is proposed for estimating mobile speed of cellular systems over frequency selective Rician fading channels. Theoretical analysis is first derived and practical algorithm is proposed based on the analytical results. The algorithm employs a modified auto-covariance of received signal power to estimate the speed of mobiles. The algorithm is based on the received signals which contain unknown transmitted data, unknown frequency selective multipaths including line-of-sight (LOS) component, and random receiver noise. The algorithm works very well for frequency selective Rician fading channels with large ranges of Rice factor and angle of arrival of the LOS component. Simulation results indicate that the new algorithm is very reliable and effective to distinguish slow speed and fast speed mobiles. The algorithm is computationally efficient. It only requires simple arithmetic operations such as multiplications, additions and subtractions.**

I. Introduction

To accommodate growing demand for mobile communication services, hierarchical cellular networks, which have multiple layer cellular cells have been deployed in many urban areas [1]-[3]. For example, a two-layer hierarchical cellular network consists of microcells overlaid with macrocells, where a macrocell is the union of several microcells. Thus slow-moving mobiles are assigned to microcells and fast-moving mobiles are assigned to macrocells. This approach has an objective of decreasing handoff rate for fast moving mobiles. Hence, a reliable mobile speed estimator is desirable. Benefits of decreasing handoff rate include an increase in capacity for the system and a decrease in the number of dropped calls. As well, voice quality is improved due to reduction of the number of times this voice is muted for handoff.

In the last twelve years, mobile speed estimation has received extensive attention in the literature [4]-[24]. Many existing algorithms are developed based on the auto-covariance (or auto-correlation) of channel fading envelope (or channel fading squared envelope), where the fading coefficients are assumed to be known, and the signal-to-noise ratio (SNR) is very high (*i.e.*, noise is assumed negligible). These covariance-based (or correlation-based) algorithms can provide good estimation accuracy for: 1) frequency flat Rayleigh fading channel; and 2) frequency flat Rician fading channel when the Rice factor is small, and the angle of arrival of the line-of-sight (LOS) component is not close to ± 90 degrees. Unfortunately, most of these algorithms tend to fail for frequency selective Rayleigh fading channels and/or channels with practical SNR values. Furthermore, to our best knowledge, no algorithm has been proposed to date for estimating mobile speed under frequency selective Rician channels.

In this paper, the statistical property of received signal is analyzed in detail, where the received signal contains unknown transmitted data, unknown frequency selective multipaths, and random noise. A practical algorithm is proposed based on the theoretical analysis for mobile speed estimation. The new algorithm provides reliable estimation results for frequency selective Rician fading channels with realistic SNR values, where the Rice factor and the angle of arrival of the LOS component can be any practical values.

II. System Model and Preliminaries

Consider a wideband wireless system whose nth received signal symbol is given by

$$y(n) = \frac{1}{\sqrt{1+K}} \sum_{l=-L_1}^{L_2} h_l(n) x(n-l) + \frac{K}{\sqrt{1+K}} h_{LOS}(n) x(n) + v(n) \tag{1}$$

where $x(n)$ is the nth transmitted symbol, $v(n)$ is the additive white Gaussian noise, K is the Rice factor, $h_{LOS}(n)$ is LOS channel coefficient at time instant n, $h_l(n)$ is the lth tap fading channel coefficient at time instant n, L_1 and L_2 are non-negative integers, $L = L_1 + L_2 + 1$ is the fading channel length which depends on the transmit filter, power delay profile and the receive filter [25].

A. Assumptions on the Physical Fading Channel

The system model (1) is based on the channel assumptions stated in this subsection.

Consider a physical fading channel $g_c(t,\tau)$ given by

$$g_c(t,\tau) = \frac{g(t,\tau)}{\sqrt{1+K}} + \frac{K}{\sqrt{1+K}} h_{LOS}(t)\delta(\tau) \tag{2}$$

where $g(t,\tau)$ is wide-sense stationary uncorrelated scattering (WSSUS) [26] Rayleigh fading with normalized unit energy, and the LOS component is assumed to be $h_{LOS}(t) = \exp(j2\pi f_d t \cos\theta_0 + j\phi_0)$ with f_d being the maximum Doppler frequency, θ_0 and ϕ_0 being the angle of arrival and the initial phase, respectively.

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The composite fading channel, which is the cascade of the transmit pulse shaping filter $p_T(\tau)$, the physical fading channel, and the receive (matched) filter $p_R(\tau)$, is given by

$$h_c(t,\tau) = p_R(\tau) \otimes g_c(t,\tau) \otimes p_T(\tau) \quad (3)$$

where $p_R(\tau)$ and $p_T(\tau)$ are normalized root raised cosine filter with unit energy.

When the composite channel $h_c(t,\tau)$ is sampled with timing at $\tau = 0$ and symbol interval T_s, the LOS component $h_{LOS}(t)$ will only contribute to a single discrete-time tap $h_{LOS}(n)$ given by

$$h_{LOS}(n) = \exp\left(j2\pi f_d T_s n \cos\theta_0 + j\phi_0\right) \quad (4)$$

because of the root raised cosine filters $p_R(\tau)$ and $p_T(\tau)$. The scattering component $g(t,\tau)$ will contribute to $h_l(n)$, which is the sampled version of $p_R(\tau)\otimes g(t,\tau)\otimes p_T(\tau)$. Therefore, the discrete-time impulse response $h_l(n)$ is also Rayleigh fading with unit average energy.

B. Statistics of The Discrete-time Fading Channel

It is known [25] that even if the physical Rayleigh fading $g(t,\tau)$ is causal, the composite fading $p_R(\tau)\otimes g(t,\tau)\otimes p_T(\tau)$ is generally noncausal when $p_R(\tau)$ and $p_T(\tau)$ have zero delay. Therefore, the $h_l(n)$ is usually noncausal as indicated in (1). Moreover, even if $g(t,\tau)$ is WSSUS fading, $h_l(n)$ will generally have inter-tap correlation in addition to the temporal correlation. Adopting Clarke's two-dimensional (2-D) isotropic model [27] for the physical Rayleigh fading $g(t,\tau)$, we can obtain statistical properties of the discrete-time fading $h_l(n)$ as shown in [25]. Some key statistics are stated below.

The discrete-time fading $h_l(n)$ is wide-sense stationary zero-mean complex Gaussian, and its cross-correlation is given by

$$E\left\{h_{l_1}(n_1)h^*_{l_2}(n_2)\right\} = C_{l_1,l_2} J_0[2\pi f_d T_s(n_1-n_2)] \quad (5)$$

where $E(\cdot)$ stands for expectation, $(\cdot)^*$ denotes complex conjugate, C_{l_1,l_2} is the inter-tap correlation coefficient between l_1th tap and l_2th tap, $J_0(\cdot)$ is the zero-order Bessel function of the first kind. It is noted that for normalized Rayleigh fading channel, $\sum_{l=-L_1}^{L_2} C_{l,l} = 1$. It is also noted that C_{l_1,l_2} is usually non-zero for $l_1 \neq l_2$ even if the physical channel $g(t,\tau)$ is WSSUS fading [25], [28].

C. Assumption on the Transmitted Signal

Assuming that the binary information is equally likely and independent from bit to bit, and the wireless transmitters employ linear modulation such as M-ary phase shift keying (MPSK), then the transmitted signal $x(n)$ is zero-mean random variable with correlation given by

$$E\left\{x(n)x^*(m)\right\} = \delta(n-m) \quad (6)$$

where $\delta(\cdot)$ is Kronecker delta function.

III. Theoretical Analysis

In this section, we present some key second-order and fourth-order statistics of the received signal $y(n)$, which are useful for designing mobile speed estimation.

Definition: The autocorrelation of the received signal, the autocorrelation of the received signal power, and autocovariance of the received signal power are defined below

$$R_{yy}(m) = E\{y(n+m)y^*(n)\} \quad (7)$$
$$R_{2,2}(m) = E\left\{|y(n+m)|^2|y(n)|^2\right\} \quad (8)$$
$$V_{2,2}(m) = E\left\{\left[|y(n+m)|^2 - R_{yy}(0)\right]\left[|y(n)|^2 - R_{yy}(0)\right]\right\}. \quad (9)$$

Theorem: The received discrete-time signal $y(n)$ has the following statistics

$$R_{yy}(m) = \left(1+\sigma^2\right)\delta(m) \quad (10)$$

$$\begin{aligned} R_{2,2}(m) = & \frac{1}{(1+K)^2}\sum_{l=-L_1}^{L_2}\sum_{q=-L_1}^{L_2}|C_{l,q}|^2 J_0^2(\omega_d m T_s) \\ & + \frac{2KC_{0,0}}{(1+K)^2} J_0(\omega_d m T_s)\cos(\omega_d m T_s\cos\theta_0) \\ & + \left(1+\sigma^2\right)^2 + \left[\frac{2K(1-C_{0,0})}{(1+K)^2} + 2\sigma^2 + \sigma^4\right]\delta(m) \end{aligned} \quad (11)$$

$$\begin{aligned} V_{2,2}(m) = & \frac{1}{(1+K)^2}\sum_{l=-L_1}^{L_2}\sum_{q=-L_1}^{L_2}|C_{l,q}|^2 J_0^2(\omega_d m T_s) \\ & + \frac{2KC_{0,0}}{(1+K)^2} J_0(\omega_d m T_s)\cos(\omega_d m T_s\cos\theta_0) \\ & + \left[\frac{2K(1-C_{0,0})}{(1+K)^2} + 2\sigma^2 + \sigma^4\right]\delta(m) \end{aligned} \quad (12)$$

where σ^2 is the noise power, and $\omega_d = 2\pi f_d$.

Proof: Equation (10) can be proved by using (5) and (6). The proof of (11) needs to utilize the following two identities: $E\{v_1v_2v_3\} = 0$ and $E\{v_1v_2v_3v_4\} = E\{v_1v_2\}E\{v_3v_4\} + E\{v_1v_3\}E\{v_2v_4\} + E\{v_1v_4\}E\{v_2v_3\}$, where v_1, v_2, v_3 and v_4 are zero-mean Gaussian random variables. The proof of (11) is lengthy, details are omitted for brevity. The proof of (12) can be done by showing $V_{2,2}(m) = R_{2,2}(m) - R^2_{yy}(0)$.

Based on the derived statistics of received signal $y(n)$, we have five remarks as follows.

Remark 1: The autocorrelation of the received signal is zero when the time lag is non-zero, this is different from the autocorrelation of the fading channel coefficients. Therefore, those algorithms which rely on the autocorrelation (or autocovariance) of the fading channel coefficients will not work if they are applied to the received signal without knowing the fading channel coefficients. However, knowing the fading channel coefficients are computationally very expensive.

Remark 2: For both frequency flat and frequency selective Rayleigh fading channels, $K = 0$, thus the normalized autocorrelation and/or normalized auto-covariance of the received signal power (*i.e.*, $R_{2,2}(m)/R_{2,2}(0)$ and/or $V_{2,2}(m)/V_{2,2}(0)$) can be employed for estimating mobile speed as "slow" or "fast" as done in [13], [16].

Remark 3: For frequency flat Rician fading channel, $C_{0,0} = 1$, the normalized auto-covariance of the received signal power can still be employed for mobile speed estimation if the Rice factor K is small (*e.g.*, $K \leq 3$) and the SNR is high (*e.g.*, SNR $\geq$ 30 dB). However, for reasonable large Rice factor and/or practical SNR values, the speed estimation accuracy is generally unsatisfactory. That is why many existing algorithms only considered noise-free and small Rice factor scenarios.

Remark 4: For frequency selective Rician fading channel, the normalized auto-covariance $V_{2,2}(m)/V_{2,2}(0)$ may not provide satisfactory results for estimating mobile speed as "slow" or "fast". Because the normalized value $V_{2,2}(m)/V_{2,2}(0)$ can be small for both large Doppler and small Doppler due to realistic SNR, Rice factor K, and/or $C_{0,0}$, where $C_{0,0}$ is less than one for frequency selective fading channels.

Remark 5: To make use of the auto-covariance (12) for mobile speed estimation in realistic frequency selective Rician fading channels, we need to remove the effect of the delta function on the third term in (12). Therefore, we propose to utilize the modified auto-covariance given by (13), at the top of next page, for mobile speed estimation. This modified auto-covariance has two advantages. One is to avoid the noise influence which can be significant for large Rice factor. The other is to mitigate the frequency selectivity impact which can also be significant when the average power (*i.e.*, $C_{0,0}$) of the zero-delay fading tap (*i.e.*, $h_0(n)$) is only a fraction of the total average power of the channel.

IV. Mobile Speed Estimation Algorithm

In this section, we take EDGE [29] cellular networks as an example to present a practical algorithm for mobile speed estimation based on (13).

It is known that the maximum Doppler frequency is about 250Hz (528Hz) when the mobile is traveling at 300km/h in the 900MHz (1.9GHz) cellular cells. It is also known that an EDGE mobile is to send voice/data slot by slot, the duration of one slot is 576.9μs, the time from ith slot to $(i+1)$th slot of the same mobile is a frame of 4.615ms. This 4.615ms yields 217Hz in the frequency domain. We call this 217Hz "frame burst frequency". The frame burst frequency is a strong potential interference to our mobile speed estimation, because it is inside the Doppler frequency range. To eliminate this interference, we calculate the auto-covariance values by frame basis. Let $s_k(n)$ be the kth-frame nth-sample of the received signal power given by $s_k(n) = y_k(n)y_k^*(n)$, where $y_k(n)$ is the nth symbol in the kth frame. The auto-covariance values of N-frame signals $s_k(n)$ are given by

$$V_N(q)=\sum_{k=1}^{N-q}\sum_{n=1}^{M-1}\left[s_{k+q-1}(n+1)-\bar{s}\right]\left[s_k(n)-\bar{s}\right] \tag{14}$$

where M is the number of symbols per slot to be utilized, and $\bar{s}$ is given by

$$\bar{s}=\frac{1}{NM}\sum_{k=1}^{N}\sum_{n=1}^{M}s_k(n). \tag{15}$$

To minimize the power fluctuation factor, we normalize the auto-covariance values as $V_N(q)/V_N(1)$. Based on our extensive simulations, we find that the auto-covariance values $V_N(q=3)/V_N(q=1)$, which is $V_N(9.23ms)/V_N(3.7\mu s)$, provides very good performance for estimating mobile speed at different channel conditions.

After obtaining $\frac{V_N(9.23ms)}{V_N(3.7\mu s)}$, we set two thresholds T_L and T_H with $T_L \geq T_H$, and estimate the mobile speed as follows:

$$\frac{V_N(9.23ms)}{V_N(3.7\mu s)}\begin{cases} > T_L, & \text{slow speed}\\ < T_H, & \text{fast speed}\\ \text{otherwise}, & \text{moderate speed.}\end{cases} \tag{16}$$

We described our idea and algorithm for EDGE cellular systems as an example, however, it is noted that this method can be applied to other multiple access wireless protocols including CDMA radios. In the simulation results to follow we will however restrict our attention to the EDGE system with 8PSK modulation.

V. Simulation Results

In this section, we take two examples to show that our new algorithm can provide reliable speed estimation results for frequency selective Rician fading channels.

We choose $N = 200$ frames, $M = 156$, and SNR= 5dB for our simulations. We calculate the modified auto-covariance values for mobile speeds of 3, 5, 30, 50, and 200 kilometers per hour (km/h). Our first example is for the exponential decaying Rayleigh fading channel [25] plus LOS component. The inter-tap correlation coefficients are given in Table 1.

Table 1. The inter-tap correlation coefficients for the exponential delay power profile

C_{l_1,l_2}	$l_2=-1$	$l_2=0$	$l_2=1$	$l_2=2$
$l_1=-1$	0.0091	0.0426	0.0178	-0.0016
$l_1=0$	0.0426	0.3664	0.3407	0.0367
$l_1=1$	0.0178	0.3407	0.5583	0.1414
$l_1=2$	-0.0016	0.0367	0.1414	0.0602

We employ the Rician fading simulator presented in [30] to generate frequency selective Rician fading coefficients, we also generate the random 8PSK modulated signal $x(n)$ and the white Gaussian noise $v(n)$, then compose the received signal $y(n)$. We estimate the mobile speed by using the received signal $y(n)$ rather than the channel fading coefficients.

Based on our simulations and equation (16), we choose two different thresholds with $T_L = 0.70$ and $T_H = 0.48$. This means that if the modified auto-covariance value at $\tau = 9.23ms$ is larger than 0.70, then the mobile speed is estimated as slower than 5km/h; if the modified auto-covariance value at $\tau = 9.23ms$ is smaller than 0.48, then the mobile speed is estimated as faster than 30km/h; otherwise, the mobile speed is indeterminate. We now summarize the estimation accuracy for the exponential decaying power delay profile plus LOS component channel into Tables 2–4.

We emphasize here that when the original auto-covariance method fails to estimate mobile speeds, our modified auto-covariance method can still provide reliable estimation results. This can be seen from Fig. 1, where the LOS component has Rice factor $K = 10$ and angle of arrival $\theta_0 = \pi/2$, which

$$\frac{V_{2,2}(m)}{V_{2,2}(1)} = \frac{\sum_{l=-L_1}^{L_2}\sum_{q=-L_1}^{L_2}|C_{l,q}|^2 J_0^2(\omega_d m T_s) + 2KC_{0,0}J_0(\omega_d m T_s)\cos(\omega_d m T_s\cos\theta_0)}{\sum_{l=-L_1}^{L_2}\sum_{q=-L_1}^{L_2}|C_{l,q}|^2 J_0^2(\omega_d T_s) + 2KC_{0,0}J_0(\omega_d T_s)\cos(\omega_d T_s\cos\theta_0)}, \quad m > 1. \tag{13}$$

means that the mobile is moving perpendicularly around the base-station, the Doppler frequency of the LOS component is zero. Most existing algorithms will fail under this severe channel condition. But our new algorithm still perform very well as shown in Table 4 and Fig. 1.

Table 2: Estimation Accuracy for Exponential Profile plus LOS with $K = 10$, $\theta_0 = 0$, SNR= 5 dB

Actual speed (km/h)	Estimated speed		
	slow	indeterminate	fast
3	100%	0%	0%
5	100%	0%	0%
30	0%	0%	100%
50	0%	0%	100%
200	0%	0%	100%

Table 3: Estimation Accuracy for Exponential Profile plus LOS with $K = 10$, $\theta_0 = \pi/4$, SNR= 5 dB

Actual speed (km/h)	Estimated speed		
	slow	indeterminate	fast
3	100%	0%	0%
5	99.4%	0.6%	0%
30	0%	0%	100%
50	0%	0%	100%
200	0%	0%	100%

Table 4: Estimation Accuracy for Exponential Profile plus LOS with $K = 10$, $\theta_0 = \pi/2$, SNR= 5 dB

Actual speed (km/h)	Estimated speed		
	slow	indeterminate	fast
3	100%	0%	0%
5	99.1%	0.9%	0%
30	0%	0%	100%
50	0%	0%	100%
200	0%	0%	100%

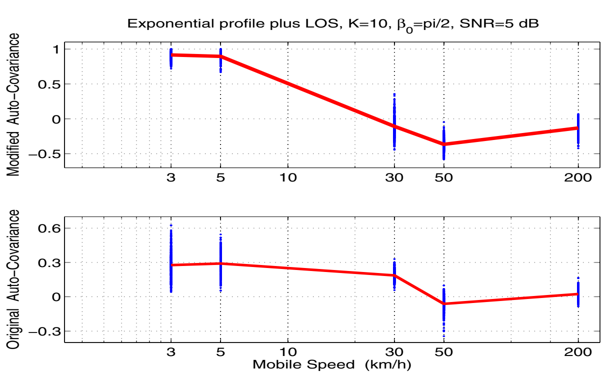

Fig. 1. Comparisons of the original auto-covariance $V_N(9.2ms)/V_N(0)$ and the modified auto-covariance $V_N(9.2ms)/V_N(3.7\mu s)$ for 5 sample speeds.

Our second example is for Typical Urban channel profile plus LOS component. The inter-tap correlation coefficients are listed in Table 5. The estimation accuracy is summarized in Tables 6–8.

Table 5. The inter-tap correlation coefficients for Typical Urban profile

C_{l_1,l_2}	$l_2 = -1$	$l_2 = 0$	$l_2 = 1$	$l_2 = 2$	$l_2 = 3$
$l_1 = -1$	0.0481	0.1799	0.0678	-0.0030	0.0029
$l_1 = 0$	0.1799	0.7401	0.3253	-0.0073	0.0121
$l_1 = 1$	0.0678	0.3253	0.1957	0.0168	0.0052
$l_1 = 2$	-0.0030	-0.0073	0.0168	0.0133	-0.0002
$l_1 = 3$	0.0029	0.0121	0.0052	-0.0002	0.0002

Table 6: Estimation Accuracy for TU Profile plus LOS with $K = 20$, $\theta_0 = 0$, SNR= 5 dB

Actual speed (km/h)	Estimated speed		
	slow	indeterminate	fast
3	100%	0%	0%
5	99.5%	0.5%	0%
30	0%	0%	100%
50	0%	0%	100%
200	0%	0%	100%

Table 7: Estimation Accuracy for TU Profile plus LOS with $K = 20$, $\theta_0 = \pi/4$, SNR= 5 dB

Actual speed (km/h)	Estimated speed		
	slow	indeterminate	fast
3	100%	0%	0%
5	99.2%	0.8%	0%
30	0%	0%	100%
50	0%	0%	100%
200	0%	0%	100%

Table 8: Estimation Accuracy for TU Profile plus LOS with $K = 20$, $\theta_0 = \pi/2$, SNR= 5 dB

Actual speed (km/h)	Estimated speed		
	slow	indeterminate	fast
3	100%	0%	0%
5	98.8%	1.2%	0%
30	0%	0%	100%
50	0%	0%	100%
200	0%	0%	100%

As can be seen from these two examples, our new algorithm provides very reliable results for estimating mobile speeds under frequency selective Rician fading channels. Actually, our algorithm provides even better estimation accuracy for Rayleigh fading channel than Rician fading channels.

It is noted that when we increase SNR, our algorithm will give better estimation results. If we increase the slot

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number N, our method will also give better estimation results. However, if we decrease the slot number N and/or SNR, then the estimation accuracy will decrease. The estimator starts to report mobile speed estimation results within one second after the communication is established.

It is also noted that the thresholds $T_L = 0.70$ and $T_H = 0.48$ are chosen for illustration purpose only, they can be chosen to other values to get better estimation accuracy in favor of high speed estimation or low speed estimation or a compromise for both.

VI. Conclusion

In this paper, we analyzed the statistical properties of the received signals which contain unknown transmitted data, unknown frequency selective Rician fading coefficients, and additive white Gaussian noise. Based on the received signal's statistics, we proposed a mobile speed estimation algorithm. The new algorithm employed modified auto-covariance to estimate "slow" and "fast" mobiles. Extensive simulations have shown that our new algorithm provides very reliable classification results for various fading channel conditions, which include Rician fading with large Rice factor, frequency selective channel with severe multipath spread, and low signal-to-noise ratio scenario, etc. This method is computationally efficient, and it only need simple arithmetic operations such as multiplications, additions and subtractions. As a by-product, our theoretical analysis explains why many existing algorithms fail on certain channel conditions including frequency selective Rician fading and/or realistic SNR values.

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