A Low Complexity Communication Technique for Mobile-to-Mobile Communication Systems

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***Abstract*—Mobile-to-mobile communications are offering clear benefits including spectrum and energy efficiency and low latency. However, these systems have to deal with various constraints with the most notable being related to the power consumption as well as the various peculiarities of the time varying wireless medium. In order to improve these systems' performance, antenna selection (AS) techniques have been proposed as an efficient approach to satisfy the hardware/power limitations that exist. However, these systems' performance is directly affected by the fast varying wireless medium, since AS is frequently performed using outdated estimates of the signal-to-noise ratio. In this paper, we propose a transmit AS scheme, whose operation is based on the shadowing side information (SSI) that is acquired in every stationarity region. By adopting SSI as an AS criterion, the negative consequences of the outdated channel state information (CSI) can be alleviated, since large-scale fading varies more slowly as compared to small-scale fading. The performance of this scheme is analyzed using the measures of the outage probability and the average bit error probability. It is shown that the proposed scheme outperforms the corresponding one that is based on (outdated) CSI, especially in scenarios with good channel conditions.**

I. Introduction

Direct mobile-to-mobile (M2M) communication systems will be part of the next generation communication networks. These systems are expected to offer improved spectrum efficiency, system throughput, and energy efficiency, while they will also decrease the transmission delay [1]. M2M communications have been applied in various fields, ranging from vehicle-to-vehicle (V2V) communications [2], to unmanned aerial vehicles [3], and mobile base stations [4]. However, in these systems, the communication engineers should deal with the inherent characteristics of the M2M communications that are related with energy, processing, hardware complexity, and space limitation constraints, as well as the time-varying wireless channel and network topology. Therefore, the direct application of advanced cellular communication techniques is either not supportable by the mobile devices or will achieve poor results due to the peculiarities of the wireless medium in vehicular environments. For this reason, low complexity and energy efficient communication schemes have been considered as promising solutions, since they offer an excellent compromise regarding the tradeoff between satisfactory system's output signal-to-noise ratio (SNR) and low hardware and software processing capabilities [5]–[7]. For example, in [6], a new reconfigurable antenna selection (AS) scheme is proposed for V2V communications that aims to reduce the complexity of the traditional AS techniques.

In regard to low complexity communication schemes, AS has been considered as a quite attractive approach, since only one radio frequency (RF) chain is required at both the transmitter (Tx) and the receiver (Rx) sides. Depending on the examined diversity paths, several techniques have been proposed including the selection diversity (SD) and the switch-and-stay combining [8]. These techniques offer good performance in static scenarios, where channel behaviour is not time-varying. However, in M2M communications, due to the continuous motion of the Tx, Rx, and the surrounding scatterers, the channel conditions are expected to change fast. Thus, in these cases, the AS techniques, which are mainly based on the available channel state information (CSI), are often operating with outdated versions of the CSI. As a result, irreducible diversity gain losses are expected, as it is proved by many studies in the past, e.g., [9], [10]. The performance degradation due to the outdated CSI increases with the speed of the mobile device, since higher Doppler shifts are expected, which, in limiting scenarios, will result to performances similar to a single antenna (no diversity) communication system. A quite promising solution to improve this situation is proposed in [11]. In that paper, a transmit antenna selection (TAS) scheme based on shadowing side information (SSI) was proposed, in which the transmit antenna offering the highest shadowing coefficient between the Tx and the Rx was selected. It was shown that as the number of antennas increases, the shadowing effects on the transmitted signal can be eliminated. The same basic idea, regarding AS with SSI, was recently adopted in [12] in a cooperative relaying scenario. In that paper, it was also proved that SSI-based AS is a promising option for higher frequency communication systems.

Motivated by the aforesaid observations, in this paper, we propose and analytically investigate a threshold-based AS scheme that exploits the available SSI. The system operates in a composite fading environment, in which multipath fading and shadowing are modeled using the Nakagami and the inverse-Gamma (IG) distributions, respectively. The latter one was recently proposed as an alternative and simple distribution for modeling the shadowing coefficient [13]. In this context, important statistical characteristics for this composite model are derived in closed form. The analysis is extended to the scenario where multiple antennas exist at the Tx and the antenna offering an acceptable mean SNR is selected for the communication phase. For comparison purposes, an analytical framework has been also developed for investigating the performance of a CSI-based AS scheme, which operates in the same environment under the acquisition of outdated CSI. By comparing these two schemes, interesting results are extracted regarding the influence of the outdated CSI to the system's performance as well as the the improvement that can be achieved by exploiting the SSI.

The remainder of the paper is organized as follows. In Section II, the system and channel models are presented along with a stochastic analysis for the received SNR statistics. In Section III, an analytical framework for important statistical metrics of the proposed scheme output SNR are provided, while in Section IV, the derived statistics are employed for evaluating the performance of the scheme under consideration. In Section V, several numerical performance results are presented and discussed, while in Section VI, the concluding remarks are provided.

II. System and Channel Model

Let us consider a communication system in which the Tx is equipped with one RF chain and L antennas, while the Rx is equipped with one antenna. Such a low complexity system satisfies the space and hardware constraints that exist in mobile devices. The links between the Tx and the Rx are simultaneously affected by both small-and large-scale fading. The received SNR at the ith link is given by

$$\gamma_i = h_i^2 s_i^2 \frac{E_s}{N_0} = g_i p_i, \tag{1}$$

where h_i and s_i denote the fading and shadowing coefficients, respectively, $g_i = h_i^2$, $p_i = s_i^2 \frac{E_s}{N_0}$, E_s is the average energy per transmitted symbol, and N_0 is the power spectral density of the additive white Gaussian noise. In general, in the CSI-based AS schemes that operate in mobile communication environments, the channel estimation at the selection phase is very likely to be different to the corresponding one at the reception instance, due to the fast variations of the wireless medium. This is due to the fact that the feedback interval is usually larger than the channel's coherence time, i.e., the duration within the channel is approximately constant. Therefore, a delayed version of the CSI will be available. An alternative approach is to select antennas based on information that depends on the shadowing condition [11]. In particular, since the decorrelation distance of the shadow fading is two order of magnitude larger than the one of multipath fading, it is expected that the large-scale fading behaviour will not be modified so quickly as the small-scale fading ones. Therefore, in SSI-based AS, the criterion used for selecting the antenna is based on the averaged received power, i.e., shadowing coefficient. In particular, the proposed scheme selects the Tx antenna offering acceptable shadowing conditions over a predetermined time interval, which is related with the stationarity region, i.e., the duration in which signal power remains constant. Thus, given that the ith antenna is selected, the received SNR can be expressed as

$$\gamma_{\mathrm{out}} = g_i p_{\mathrm{td}}, \tag{2}$$

where g_i depends on the (multipath) fading and p_{td} depends on the shadowing coefficient and the adopted AS scheme.

A. Channel Model

In this paper, small-scale fading is modeled by the Nakagami-m distribution, while shadowing is modeled by the IG distribution. It is noteworthy that shadowing in mobile networks can be originated by large objects such as buildings and/or other vehicles [14]. The probability density function (PDF) of g_i is given by

$$f_{g_i}(x) = \frac{m^m x^{m-1}}{\Omega^m \Gamma(m)} \exp\left(-\frac{mx}{\Omega}\right), \tag{3}$$

where m is the Nakagami-m fading parameter, which is related to the severity of the fading and ranges from $1/2$ to ∞, $\Omega = \mathbb{E}\langle g_i \rangle$, with $\mathbb{E}\langle \cdot \rangle$ denoting expectation, and $\Gamma(\cdot)$ is the Gamma function [15, eq. (8.310/1)]. Moreover, the shadowing coefficients are assumed to follow the IG distribution, with PDF given by [13]

$$f_{p_i}(y) = \frac{\overline{\gamma}^k}{\Gamma(k) y^{k+1}} \exp\left(-\frac{\overline{\gamma}}{y}\right), \tag{4}$$

where $k > 1$ is the shaping parameter of the distribution related to the severity of the shadowing, and $\overline{\gamma}$ denotes the scaling parameter. It is noted that the IG PDF is closely related to the PDF of Gamma distribution since if $X \sim Gamma(\alpha, b)$, then $1/X \sim Inv-Gamma(\alpha, b^{-1})$ [13]. The corresponding cumulative distribution function (CDF) expression for p_i is given by

$$F_{p_i}(y) = \frac{\Gamma\left(k, \overline{\gamma}/y\right)}{\Gamma(k)}, \tag{5}$$

where $\Gamma(\cdot,\cdot)$ is the upper incomplete Gamma function defined in [15, eq. (8.350/2)]. In order to evaluate the composite fading PDF of the output SNR for the ith link, the total probability theorem will be applied as follows

$$f_{\gamma_i}(\gamma) = \int_0^\infty f_{g_i}(\gamma|y) f_{p_i}(y) dy. \tag{6}$$

Substituting (3) and (4) in (6) and using [15, eq. (8.310)], the following expression is derived

$$f_{\gamma_i}(\gamma) = \frac{m^m \Gamma(k+m) \overline{\gamma}^k}{\Gamma(m)\Gamma(k)} \frac{\gamma^{m-1}}{\left(\overline{\gamma} + m\gamma\right)^{m+k}}. \tag{7}$$

Based on (7) and using [16, eq. (1.2.4/3)], the corresponding CDF expression is given by

$$F_{\gamma_i}(\gamma) = \frac{m^{m-1}\Gamma(m+k)}{\Gamma(m)\Gamma(k)\overline{\gamma}^m} \gamma^m {}_2F_1\left(m, k+m, m+1, -\frac{m\gamma}{\overline{\gamma}}\right), \tag{8}$$

where ${}_2F_1(\cdot,\cdot,\cdot,\cdot)$ denotes the Gauss hypergeometric function [15, eq. (9.100)].

B. System Model

In this paper, an AS scheme is employed that aims to reduce complexity and feedback load processing as compared to the best (in terms of the received SNR) AS mechanism, which is based on the SD principle. In this scheme, the Rx monitors the available channels continuously and selects the one satisfying a predefined threshold that is related with the shadowing coefficient. In particular, the estimated shadowing coefficient of the previously selected antenna is compared with a predefined threshold $\gamma_{\rm th}$ and if it exceeds it, then this antenna is selected for the next communication phase and no further processing is required. Otherwise, the system identifies the shadowing coefficients of all active antennas and selects the antenna that offers the highest value. Then, the corresponding index is fed back to the Tx. Mathematically speaking and assuming independent and identically distributed (i.i.d.) fading/shadowing conditions, the CDF of the SSI-based selection criterion, $F_{p_{\rm td}}(x)$, can be expressed as [17]

$$F_{p_{\rm td}}(x)=\begin{cases} F_{p_i}(x)-F_{p_i}(\gamma_{\rm th}) \\ \quad +F_{p_i}(\gamma_{\rm th})F_{p_i}(x)^{L-1}, x\geq\gamma_{\rm th} \\ \quad F_{p_i}(x)^{L}, x<\gamma_{\rm th}. \end{cases} \tag{9}$$

The corresponding expression for the PDF is given by

$$f_{p_{\rm td}}(x)=\begin{cases} f_{\gamma_{p_i}}(x)+(L-1)F_{\gamma_{p_i}}(\gamma_{\rm th}) \\ \times f_{\gamma_{p_i}}(x)F_{\gamma_{p_i}}(x)^{L-2}, x\geq\gamma_{\rm th} \\ Lf_{\gamma_{p_i}}(x)F_{\gamma_{p_i}}(x)^{L-1}, x<\gamma_{\rm th}. \end{cases} \tag{10}$$

Using these two expressions, in Section III, important statistical characteristics of the proposed scheme's output SNR will be analytically evaluated.

III. System Output SNR

The PDF of the proposed scheme output SNR $\gamma_{\rm out}$ is given by

$$\begin{aligned} f_{\gamma_{\rm out}}(\gamma)=&\frac{m^m\gamma^{m-1}\overline{\gamma}^k}{\Gamma(m)\Gamma(k)}\Bigg\{\frac{\gamma\left(m+k,m\gamma+\overline{\gamma}\right)/\gamma_{\rm th}}{\left(m\gamma+\overline{\gamma}\right)^{m+k}} \\ &+(L-1)\frac{\Gamma\left(k,\overline{\gamma}/\gamma_{\rm th}\right)}{\Gamma(k)} \\ &\times\sum_{\substack{n_1,n_2,\ldots,n_k=0\\ n_1+\cdots+n_k=L-2}}^{L-2}\frac{\overline{\gamma}^{s_1}\gamma\left(s_1+k+m,\left(m\gamma+\overline{\gamma}(L-1)\right)/\gamma_{\rm th}\right)}{\left(m\gamma+(L-1)\overline{\gamma}\right)^{s_1+k+m}} \\ &+L\sum_{\substack{n_1,n_2,\ldots,n_k=0\\ n_1+\cdots+n_k=L-1}}^{L-1}\frac{\overline{\gamma}^{s_1}\Gamma\left(s_1+k+m,\left(m\gamma+\overline{\gamma}L\right)/\gamma_{\rm th}\right)}{\left(m\gamma+L\overline{\gamma}\right)^{s_1+k+m}}\Bigg\}, \end{aligned} \tag{11}$$

where

$$\sum_{\substack{n_1,n_2,\ldots,n_k=0\\ n_1+\cdots+n_k=L}}^{L}=\sum_{\substack{n_1=0}}^{L}\sum_{n_2=0}^{L}\cdots\sum_{\substack{n_k=0\\ n_1+n_2+\cdots+n_k=L}}^{L}\frac{L!/\left[n_1!n_2!\cdots n_L!\right]}{(0!)^{n_1}\cdots((k-1)!)^{n_k}},$$

$s_1=\sum_{j=2}^{k}(j-1)n_j$, and $\gamma(\cdot,\cdot)$ is the lower incomplete Gamma function defined in [15, eq. (8.350/2)]. The proof for the derivation (11) can be found in Appendix A. Based on the CDF of g_i, given in (B-5), and using a similar analytical framework as the one for deriving (11), the corresponding CDF expression of $\gamma_{\rm out}$ is given by

$$\begin{aligned} F_{\gamma_{\rm out}}(\gamma)=&\frac{\overline{\gamma}^k}{\Gamma(k)}\Bigg\{\frac{\gamma(k,\overline{\gamma}/\gamma_{\rm th})}{\overline{\gamma}^k}-\sum_{t=0}^{m-1}\frac{(m\gamma)^t}{t!} \\ &\times\frac{\gamma\left(k+t,(m\gamma+\overline{\gamma})/\gamma_{\rm th}\right)}{(\overline{\gamma}+m\gamma)^{k+t}}+\frac{\Gamma(k,\overline{\gamma}/\gamma_{\rm th})}{\Gamma(k)} \\ &\sum_{\substack{n_1,n_2,\ldots,n_k=0\\ n_1+\cdots+n_k=L-2}}^{L-2}\overline{\gamma}^{s_1}(L-1)\Bigg[\frac{\gamma\left(s_1+k,(L-1)\overline{\gamma}/\gamma_{\rm th}\right)}{\left((L-1)\overline{\gamma}\right)^{s_1+k}} \\ &-\sum_{t=0}^{m-1}\frac{(m\gamma)^t}{t!}\frac{\gamma\left(s_1+k+t,(m\gamma+(L-1)\overline{\gamma})/\gamma_{\rm th}\right)}{\left(m\gamma+(L-1)\overline{\gamma}\right)^{s_1+k+t}}\Bigg] \\ &+L\sum_{\substack{n_1,n_2,\ldots,n_k=0\\ n_1+\cdots+n_k=L-1}}^{L-1}\overline{\gamma}^{s_1}\Bigg[\frac{\gamma\left(s_1+k,L\overline{\gamma}/\gamma_{\rm th}\right)}{(L\overline{\gamma})^{s_1+k}} \\ &-\sum_{t=0}^{m-1}\frac{(m\gamma)^t}{t!}\frac{\gamma\left(s_1+k+t,(m\gamma+L\overline{\gamma})/\gamma_{\rm th}\right)}{\left(m\gamma+L\overline{\gamma}\right)^{s_1+k+t}}\Bigg]. \end{aligned} \tag{12}$$

IV. Performance Analysis

In this section, using the previously derived results, analytical expressions for the outage probability (OP) and the average bit error probability (BEP) are derived.

A. Outage Probability (OP)

OP is defined as the probability that the output SNR falls below a predetermined threshold $\gamma_{\rm T}$ and it can be evaluated as $P_{\rm out}=F_{\gamma_{\rm out}}(\gamma_{\rm T})$, in which $F_{\gamma_{\rm out}}(\gamma_{\rm T})$ is given by (12).

B. Average Bit Error Probability (BEP)

The BEP is a performance measure that provides a clear evidence of the system's reliability. It can be evaluated as

$$\overline{P}_{\rm se}=\int_0^\infty f_{\gamma_{\rm out}}(\gamma)P_{\rm se}(\gamma)d\gamma, \tag{13}$$

where $P_{\rm se}(\gamma)$ depends on the considered modulation scheme. For example, for binary differentially phase shift keying (BDPSK) $P_{\rm se}(\gamma)=\exp(-\gamma)/2$. Using this formula and (11) in (13), integrals of the following form appear

$$\begin{aligned} I_3=&\int_0^\infty\frac{\gamma^a}{(\gamma+A)^b}\exp\left(-B\gamma\right)d\gamma \\ =&\Gamma(a+1)A^{a+1-b}\Psi\left(a+1,a+2-b,AB\right), \end{aligned} \tag{14}$$

where $\Psi(\cdot,\cdot,\cdot)$ denotes the confluent hypergeometric function [15, eq. (9.210/2)]. It is noted that the second equality in (14) holds due to [16, eq. (2.3.6/9)]. Based on the solution provided in (14) and after some mathematical manipulations, the following closed-form expression for the BEP has been derived

$$\overline{P}_{\rm se} = \frac{\Gamma(m+k)}{2\Gamma(k)} \left[\Psi\left(m, 1-k, \frac{\overline{\gamma}}{m}\right) - \sum_{t=0}^{m+k-1} \frac{\exp\left(-\overline{\gamma}/\gamma_{\rm th}\right)}{t!} \right.$$
$$\left. \times \left(\frac{\overline{\gamma}}{\gamma_{\rm th}}\right)^t \Psi\left(m, 1+t-k, \frac{m+\gamma_{\rm th}}{m\gamma_{\rm th}}\overline{\gamma}\right)\right] + \frac{\Gamma(k, \overline{\gamma}/\gamma_{\rm th})}{\Gamma(k)}$$
$$\sum_{\substack{n_1, n_2, \ldots, n_k = 0 \\ n_1 + \cdots + n_k = L-2}}^{L-2} \frac{\Gamma(s_1+k+m)}{\Gamma(k)(L-1)^{s_1+k-1}} \Bigg[\Psi\left(m, 1-s_1-k, \frac{(L-1)\overline{\gamma}}{m}\right)$$
$$- \sum_{t=0}^{s_1+k+m-1} \frac{\exp\left(-(L-1)\overline{\gamma}/\gamma_{\rm th}\right)}{t!} \left(\frac{(L-1)\overline{\gamma}}{\gamma_{\rm th}}\right)^t$$
$$\times \Psi\left(m, 1-s_1-k+t, \frac{(m+\gamma_{\rm th})(L-1)\overline{\gamma}}{m\gamma_{\rm th}}\right)\Bigg]$$
$$+ \sum_{\substack{n_1, n_2, \ldots, n_k = 0 \\ n_1 + \cdots + n_k = L-1}}^{L-1} \frac{\Gamma(s_1+k+m)}{\Gamma(k)L^{s_1+k-1}} \sum_{t=0}^{s_1+k+m-1} \frac{\exp\left(-L\overline{\gamma}/\gamma_{\rm th}\right)}{t!}$$
$$\times \left(\frac{L\overline{\gamma}}{\gamma_{\rm th}}\right)^t \Psi\left(m, 1-s_1-k+t, \frac{(m+\gamma_{\rm th})L\overline{\gamma}}{m\gamma_{\rm th}}\right)\Bigg]. \quad (15)$$

V. Numerical Results

In this section, several numerically evaluated performance results are provided. In Fig. 1, assuming $L = 3, k = 3$, the OP is plotted as a function of the outage threshold γ_T, for different values of the (fading) shaping parameter m and the switching threshold $\gamma_{\rm th}$. It is shown that the performance improves with the increase of m, i.e., with the improvement of the fading conditions. Moreover, as $\gamma_{\rm th}$ increases, the OP decreases, since it is more likely that this threshold is not exceeded by the previously selected antenna and thus the best one in terms of shadowing coefficient will be selected in the current communication phase. It is interesting to note that the performance improvement due to the increase of $\gamma_{\rm th}$ is higher for greater values of m. In Fig. 2, assuming $m = 2, k = 2, \gamma_{\rm th} = 17.5$ dB, the BEP is plotted as a function of the average input SNR $\overline{\gamma}$ for different values of the number of antennas L. It is shown that the performance improves with the increase of L, with a decreased, however, rate. It is shown that a 3 dB gain is achieved with 4 antennas as compared to the single antenna communication scenario. In the same figure, the performance of a single-input single-output (SISO) system that operates in a non-shadowing environment is depicted. It is interesting to note that the proposed scheme may act as an effective shadowing countermeasure technique, since it provides better performance, in cases with $L \geq 4$, as compared to the non-shadowed SISO system.

Another important investigation that is also made concerns the performance comparison between SSI- and CSI-based AS schemes, with the latter one being affected by outdated versions of the channel estimates. In order to perform this comparison, the CDF of the output SNR of a CSI-based TAS scheme operating over Nakagami/IG composite fading environment is required to be evaluated. However, since an exact analytical expression for this CDF does not exist in the open technical literature, in Appendix B, we have provided an analytical expression for it. In Fig. 3, assuming $m = 1, \overline{\gamma} = -5dB, \gamma_T = 1$ dB, the OPs of the proposed scheme (with $\gamma_{\rm th} = 10$ dB) and the one that is based on (B-9) are plotted as a function of the temporal correlation coefficient ρ, which quantifies the correlation between the exact and the outdated versions of the received SNR. To obtain this figure, different scenarios regarding the number of antennas L and the shadowing severity, k, have been considered. It is shown that the performance of the CSI-based system improves as ρ increases as well as with the decrease of k. The most

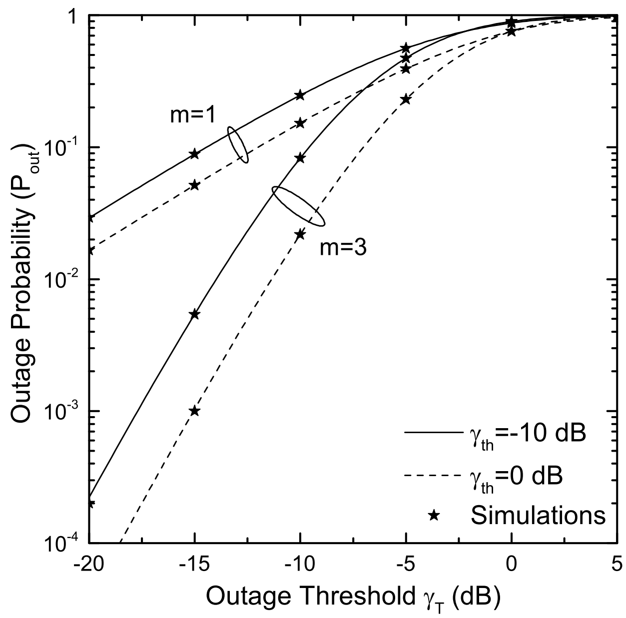

Fig. 1. Outage probability vs the outage threshold.

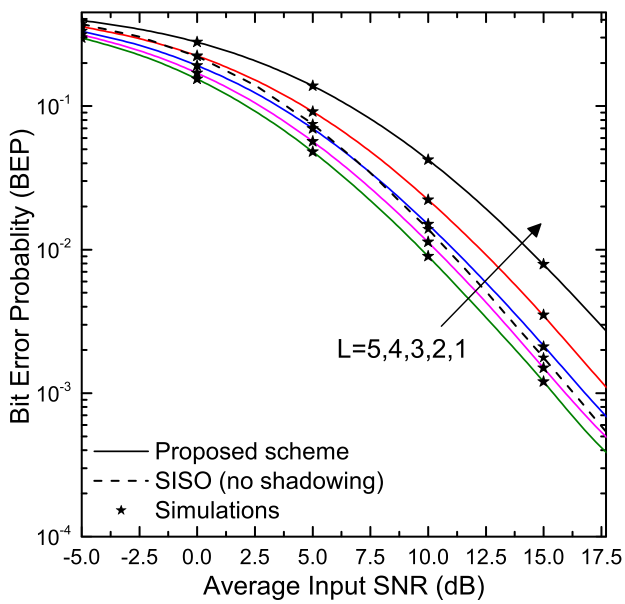

Fig. 2. Bit error probability vs the average input SNR.

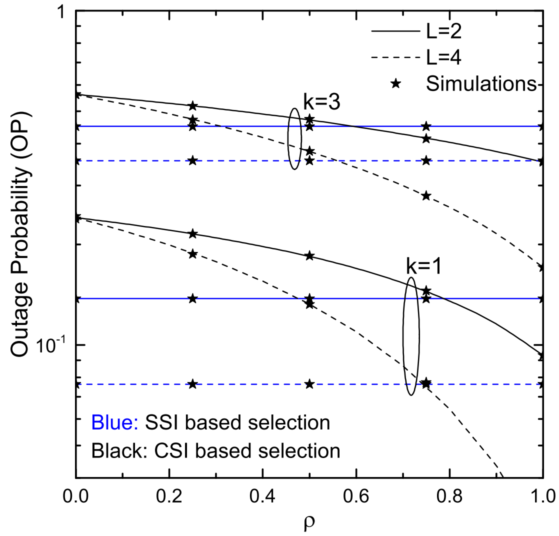

Fig. 3. Outage probability as a function of the correlation coefficient for SSI- and CSI-based antenna selection schemes.

interesting observation is that the proposed SSI-based scheme outperforms the one that is based on outdated CSI in all scenarios with lower values of ρ, i.e., in highly time varying situations. It is noteworthy that for good fading/shadowing conditions, i.e., $k = 1$, the proposed scheme provides better performance even when $\rho \approx 0.8$. These results reveal that the negative impact of outdated CSI on the system's performance can be alleviated by exploiting the shadowing information. Finally, the Monte Carlo simulations that have been included in all figures verify the validity of the theoretical framework.

VI. Conclusions

The performance of an antenna selection scheme operating in a M2M communication environment in the presence of composite fading has been analytically investigated. By adopting a threshold-based channel selection criterion and exploiting the available shadowing information, a new scheme has been proposed that offers improved performance with reduced complexity. Based on it and capitalizing on the slow variations of the shadowing coefficient, the negative consequences of the outdated CSI, that is frequently observed in M2M communications, can be effectively alleviated. The results reveal that the proposed approach outperforms the one that exploits CSI acquisition in various fading/shadowing conditions and can be considered as a promising solution in scenarios where power and processing constraints coexist with time varying communication conditions.

Appendix A
Proof for Equation (11)

In this Appendix, the proof for the derivation of (11) is provided. The PDF of γ_{out} can be evaluated by

$$f_{\gamma_{\text{out}}}(\gamma) = \int_0^\infty f_{g_i}(\gamma|y) f_{p_{\text{td}}}(y) dy. \tag{A-1}$$

In (A-1), $f_{g_i}(\gamma|y)$ is given by (3), while $f_{p_{\text{td}}}(y)$ is given by (10). In order to simplify the analysis and by employing the multinomial identity [18, eq. (24.1.2)], the following expression is deduced

$$F_{p_i}(y)^L = \exp\left(-\frac{L\overline{\gamma}}{y}\right) \sum_{\substack{n_1, n_2, \ldots, n_k = 0 \\ n_1 + \cdots + n_k = L}}^{L} \left(\frac{\overline{\gamma}}{y}\right)^{s_1}. \tag{A-2}$$

Substituting (3), (10), and (A-2) in (A-1), the following type of integrals appear

$$\begin{aligned} I_1 &= \int_0^{\gamma_{\text{th}}} y^a \exp(-By) dy \\ I_2 &= \int_{\gamma_{\text{th}}}^\infty y^a \exp(-By) dy. \end{aligned} \tag{A-3}$$

These two integrals can be solved in closed form by employing [15, eqs. (8.350/1) and (8.350/2)] and after some mathematical manipulations yields the expression shown in (11) and also completes the proof.

Appendix B
Antenna Selection Based on Outdated CSI

In this Appendix, the performance of a communication system with L Tx antennas and a single Rx antenna is studied. For this system, it is assumed that the AS is performed based on the SD rule, i.e., the antenna providing the highest instantaneous fading coefficient during the selection phase is selected. However, due to the fast time varying channel behaviour, the estimated version of the CSI is considered to be outdated. In this context, an exact expression for the CDF of the output SNR for the considered scheme is derived. Assuming Nakagami/IG composite fading and i.i.d. conditions, this CDF can be expressed as

$$F_{\gamma_{\text{out}}}(\gamma) = \int_0^\infty F_{\gamma_r}(\gamma|y) f_{p_i}(y) dy, \tag{B-1}$$

in which $F_{\gamma_r}(\gamma|y)$ denotes the CDF of SD scheme based on the fading coefficients. This CDF can be evaluated as

$$F_{\gamma_r}(\gamma) = \int_0^\gamma \int_0^\infty \frac{f_{x_1,x_2}(y,x)}{f_{x_1}(x)} f_{p_{\text{sd}}}(x) dx dy, \tag{B-2}$$

in which $f_{x_1,x_2}(y,x)$ denotes the bivariate Nakagami PDF and $f_{p_{\text{sd}}}(x)$ denotes the PDF of the output SNR of the SD scheme. By making a straight-forward change of variables in [8, eq. (6.1)], $f_{x_1,x_2}(y,x)$ can be evaluated as follows

$$\begin{aligned} f_{x_1,x_2}(y,x) &= \frac{m^{m+1}(xy)^{(m-1)/2}}{\Gamma(m)(1-\rho)\rho^{(m-1)/2}\Omega^{m+1}} \\ &\times \exp\left(-m\frac{x+y}{\Omega(1-\rho)}\right) I_{m-1}\left(\frac{2m\sqrt{\rho x y}}{\Omega(1-\rho)}\right). \end{aligned} \tag{B-3}$$

In (B-3), $I_v(\cdot)$ is the modified Bessel function of the first kind and order v [15, eq. (8.406/3)] and $0 \leq \rho < 1$ is a correlation coefficient related with the estimation accuracy. Higher values of ρ denote an estimation quite close to the exact value of the fading coefficient, while lower values denote a strong outdated estimation. Moreover, $f_{\mathrm{p_{sd}}}(x)$ is given by

$$f_{\mathrm{p_{sd}}}(x) = L f_{g_i}(x) F_{g_i}(x)^{L-1}, \tag{B-4}$$

where

$$F_{g_i}(x) = \frac{\gamma\left(m, x/\Omega\right)}{\Gamma(m)}. \tag{B-5}$$

Substituting (B-3), (B-4), and (B-5), in (B-2), employing [15, eq. (8.352)] and using [19, eq. (2.15.5/4)] the following expression is deduced

$$F_{\gamma_r}(\gamma) = \frac{L}{\Gamma(m)^2} \sum_{p=0}^{L-1} \sum_{\substack{n_1,n_2,\ldots,n_k=0 \\ n_1+\cdots+n_k=p}}^{p} \frac{(-1)^p (1-\rho)^{s_1} \Gamma\left(s_1+m\right)}{\Omega^m (1+(1-\rho)p)^{s_1+m}} \times \int_0^\gamma y^{m-1} \exp\left(-\frac{y}{\Omega(1-\rho)}\right) \times {}_1F_1\left(s_1+m, m, \frac{\rho y}{(1-\rho)\Omega(1+(1-\rho)p)}\right) dy, \tag{B-6}$$

in which ${}_1F_1(\cdot,\cdot,\cdot)$ denotes the confluent hypergeometric function [15, eq. (9.210/1)] and $(z)_n$ denotes the Pochhammer symbol [18, eq. (6.1.22)]. In order to evaluate the integral above, a simplified expression for the confluent hypergeometric function is used [20, eq. (07.20.03.0025.01)] as follows

$${}_1F_1\left(n, m, z\right) = \exp(z) \sum_{b=0}^{n-m} \frac{(m-n)_b (-z)^b}{b!(m)_b}. \tag{B-7}$$

Based on (B-7), using [15, eq. (8.350/1)], and after some mathematical analysis the following expression for $F_{\gamma_r}(\gamma)$ is derived

$$F_{\gamma_r}(\gamma) = \frac{L}{\Gamma(m)^2} \sum_{p=0}^{L-1} \sum_{\substack{n_1,n_2,\ldots,n_k=0 \\ n_1+\cdots+n_k=p}}^{p} \binom{L-1}{p} \Gamma\left(s_1+m\right) \times \sum_{b=0}^{s_1} (-s_1)_b \frac{(-1)^{p+b} \rho^b (1-\rho)^{s_1-b}}{(1+p)^{b+m}(1+(1-\rho)p)^{s_1} b!(m)_b} \times \gamma\left(m+b, \frac{\gamma(1+p)/\Omega}{1+(1-\rho)p}\right). \tag{B-8}$$

Finally, substituting (B-8) in (B-1), employing [15, eq. (6.455/2)], yields the closed-form expression for the CDF of the output SNR given below

$$F_{\gamma_{\mathrm{out}}}(\gamma) = \frac{L}{\Gamma(m)^2} \sum_{p=0}^{L-1} \sum_{\substack{n_1,n_2,\ldots,n_k=b \\ n_1+\cdots+n_k=p}}^{p} \binom{L-1}{p} \frac{\Gamma\left(s_1+m\right)}{\Gamma(k)} \times \sum_{b=0}^{s_1} (-s_1)_b \frac{(-1)^{p+b} \rho^b (1-\rho)^{s_1-b}}{(1+p)^{b+m}(1+(1-\rho)p)^{s_1-k} b!(m)_b} \times \frac{\overline{\gamma}^k \left(\gamma(1+p)\right)^{b+m} \Gamma(b+m+k)}{\left[\gamma(1+p)+\overline{\gamma}\left(1+p(1-\rho)\right)\right]^{b+m+k}(b+m)} \times {}_2F_1\left[1, b+m+k, b+m+1, \frac{\gamma(1+p)}{\gamma(1+p)+\overline{\gamma}(1+p(1-\rho))}\right]. \tag{B-9}$$

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