The Diversity Potential of Relay Selection with Practical Channel Estimation

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Abstract—We investigate the diversity order of decode-and-forward relay selection in Nakagami-m fading, in cases where practical channel estimation techniques are applied. In this respect, we introduce a unified model for the imperfect channel estimates, where the effects of noise, time-varying channels, and feedback delays are jointly considered. Based on this model, the correlation between the actual and the estimated channel values, ρ, is expressed as a function of the signal-to-noise ratio (SNR), yielding closed-form expressions for the overall outage probability as a function of ρ. The resulting diversity order and power gain reveal a high dependence of the performance of relay selection on the high SNR behavior of ρ, thus shedding light onto the effect of channel estimation on the overall performance. It is shown that when the channel estimates are not frequently updated in applications involving time-varying channels, or when the amount of power allocated for channel estimation is not sufficiently high, the diversity potential of relay selection is severely degraded.

In short, the main contribution of this paper lies in answering the following question: How fast should ρ tend to one, as the SNR tends to infinity, so that relay selection does not experience any diversity loss?

Index Terms—Relay selection, imperfect channel estimation, Nakagami-m fading model.

I. INTRODUCTION

WIRELESS relaying technology has been recently proposed as a method that promises significant performance improvement in wireless communications without any power increase [1], [2]. Among the most common relaying techniques is so-called relay selection which has been extensively analyzed in the literature [3]–[11], and is conceptually related to antenna selection in multi-antenna schemes (see, e.g., [12]- [32][1]). In relay selection, the system is able to select a single relay out of the set of available relays, in order to take advantage of the multiple paths available and thus

achieve spatial diversity. It has been shown that activating only the relay with the strongest instantaneous end-to-end channel represents a bandwidth-efficient alternative to all-participate relaying, since, on the one hand, the same diversity order is achieved, yet on the other hand, the excessive bandwidth usage that the activation of multiple relays entails is avoided [5].

Most of the literature dealing with relay selection in fading channels has assumed that perfect channel state information (CSI) is available at the terminal where the decision on which relay to activate is made. This assumption, however, may not be true in practical scenarios where the channel changes rapidly enough, so that the CSI available at the selecting terminal is outdated. In addition, if the power allocated to the pilot symbols is not sufficiently high, the noisy channel estimates may lead to suboptimal relay selection. The above two cases reveal the vulnerability of relay selection to imperfect channel estimation, and constitute the main rationale for conducting a thorough outage and diversity analysis of relay selection in scenarios with imperfect CSI. For antenna selection, the effect of imperfect CSI was studied in [17], [18], [25]–[29], [31].

The case of relay selection under outdated CSI and Rayleigh fading has been recently studied in [33]–[40], where interesting results on the outage probability and diversity order were derived. Nonetheless, these works consider only a special case, since they assume that the CSI imperfection stems only from delayed feedback. This may not always be the case in practice, since channel estimates may also be impaired by time-varying fading and channel noise. In the recent works [41], [42], the effect of noisy channel estimates is also included in the performance analysis. However, these works assume that the training symbols' power is independent from the power used for data transmission, leading to zero diversity order. As this assumption may not always be practical, we investigate here the diversity loss due to imperfect CSI in the versatile case where the powers allocated for training and data transmission are not necessarily independent from one another.

In summary, the contributions of this paper are as follows.

- We conduct an outage analysis of relay selection with imperfect CSI, which is general enough so as to account for both the effects of noisy and outdated channel estimates, integrated into a unified model. In particular, a closed-form expression for the outage probability is derived, which incorporates all effects that can cause imperfect channel estimates in practical applications. The considered channel estimation techniques include the cases of estimation in noisy static channels; estimation in

[1]We thank the anonymous reviewers for bringing the works [12]- [32] to our attention.

noiseless time-varying channels, and estimation in noisy time-varying channel with the aid of finite impulse response (FIR) and infinite impulse response (IIR) channel prediction.

- The amount of CSI imperfection is reflected by the correlation coefficient between the actual and the estimated channel values, ρ, which is modeled as a non-decreasing function of the signal-to-noise ratio (SNR). As a result, the asymptotic outage behavior of relay selection is determined by the speed of convergence of the correlation coefficient to unity, as the SNR approaches infinity. The diversity order of relay selection with imperfect CSI is thereby derived, shedding light onto the diversity loss caused by imperfect CSI, with implications for the design of channel estimation techniques.

- In contrast to other relevant works in the literature, where Rayleigh fading channels were assumed, the versatile scenario of Nakagami-m fading is studied. It is shown that the resulting diversity order is directly proportional to the fading shape parameter, m.

Overall, the general conclusion of this paper is that the level of CSI imperfection plays an important role in the performance of relay selection, considerably affecting its diversity potential. A detailed discussion on the diversity order of relay selection for several practical channel estimation techniques is presented in Section VI-C, and corresponding numerical examples are given in Section VII. These results are based on the exact outage analysis conducted in Section IV for Rayleigh fading and certain channel estimation techniques, and are extended to Nakagami-m fading in Section V. Prior to the outage analysis, the unified model that incorporates the effects of noisy and outdated channel estimates is presented in Section III. The system model of decode-and-forward (DF) relay selection with imperfect CSI is given in the ensuing, Section II.

II. SYSTEM MODEL

Let us consider a cooperative relaying system which consists of a single source terminal, S, N DF relays which are denoted by R_i, $i = 1, ..., N$, and operate in the half-duplex mode [1], and a single destination terminal, D.

Channel Model: Let h_{AB} denote the complex channel between nodes A and B, where $A, B \in \{S, D, R_i : i = 1, ..., N\}$. Moreover, Rayleigh distributed fading in each of the participating links is assumed, implying that h_{AB} is a complex Gaussian random variable (RV). The versatile scenario of Nakagami-m distributed fading is considered in Section V. In addition, since in this work we focus on the asymptotic properties of relay selection under imperfect CSI, we assume independent and identically distributed (i.i.d.) fading in each of the links involved. Moreover, the fading is considered slow enough such that h_{AB} remains constant during the transmission of one frame.

Let γ_{AB} represent the instantaneous SNR of the link between terminals A and B, i.e., $\gamma_{AB} = |h_{AB}|^2 / N_0$, where N_0 is the additive white Gaussian noise (AWGN) power. Due to the i.i.d. fading assumption, the average SNR is identical for all involved links, and denoted by $\bar{\gamma}$. Moreover, we use the notation $f_X(\cdot)$ and $F_X(\cdot)$ to refer to the probability density

function (pdf) and the cumulative distribution function (cdf) of RV X, respectively.

Relay Selection Process: Among the available relays, only a single relay is activated in each transmission session, based on the selection cooperation protocol [4]. In particular, the relay selection procedure is completed in two phases, as follows. In the first phase, the relays that can successfully decode the message form the so-called decoding set, denoted by $\mathcal{S}$.

Mathematically speaking, the decoding set $\mathcal{S}$ is defined as $\mathcal{S} = \{R_i : \gamma_{SR_i} > T\}$, where T denotes the outage threshold SNR, defined as the minimum SNR value that allows decoding; T is related to the target data rate, r, through $T = 2^{2r} - 1$. In the second phase, the destination collects the estimated CSI of the R_i-D links with $i : R_i \in \mathcal{S}$, and activates the relay with the strongest R_i-D channel.

A fundamental principle throughout this paper is that relay selection is based not on the actual channel values but on their estimates, which are not necessarily equal to the actual channel values. In this respect, let $\hat{h}_{AB}$ denote the estimate of channel h_{AB}, so that $\hat{\gamma}_{AB}$ represents the estimated value of γ_{AB}, as seen by the destination. Hence, denoting the selected relay by R_κ, we have

$$\kappa = \arg \max_{i : R_i \in \mathcal{S}} \hat{\gamma}_{R_i D}. \qquad (1)$$

The CSI imperfection is assumed to affect the relay selection process, but not the symbol detection at the destination. The reason behind this assumption is two-fold: First, a perfect relay selection process requires a higher number of pilot symbols than the detection process in each communication frame, since for detection only the active channel is estimated, whereas for relay selection the channels associated with all the potential relays need to be estimated and compared. For example, in a system with N relays the number of pilot symbols required for perfect relay selection is N-times the number of symbols required for symbol detection. As a result, the number of pilots used for relay selection is typically smaller than that which ensures optimal selection, especially for high N. Second, the update frequency of the pilots used for relay selection is typically smaller than the update frequency of the pilots used for detection. This is because the pilots for detection are usually incorporated in every transmitted packet, yet the selected relay remains active for several packets since, otherwise, frequent relay switchings would incur an excessively high overhead.

In view of the above, the outage analysis presented in Sections IV and V yields in fact lower bounds for the actual outage probability, as the channel estimation used for symbol detection at the destination is assumed to be perfect. A detailed description of the considered imperfect CSI model, used for relay selection, follows next.

III. IMPERFECT CSI MODEL

The physical causes of the considered CSI degradation are the time-varying nature of fading channels, as well as the finite pilot symbol power. In this work, both of these causes of imperfect CSI are integrated into a unified model, as shown below.

The level of CSI imperfection is quantified by the correlation coefficient between the actual squared channel envelope value, $|h_{AB}|^2$, and its corresponding estimate, $|\hat{h}_{AB}|^2$, where A and B can be any terminals of the set $\{S, D, R_i : i = 1, ..., N\}$. This coefficient is defined as (in the sequel, all channel indices are dropped due to the i.i.d. fading assumption)

$$\rho = \frac{E \left\langle \left(|h|^2 - \Omega_h \right) \left(|\hat{h}|^2 - \Omega_{\hat{h}} \right) \right\rangle}{\sigma_{|h|^2} \sigma_{|\hat{h}|^2}} \quad (2)$$

where $\Omega_h = E \left\langle |h|^2 \right\rangle$, $\Omega_{\hat{h}} = E \left\langle |\hat{h}|^2 \right\rangle$ with $E \left\langle \cdot \right\rangle$ denoting expectation, and σ_X denotes the standard deviation of RV X.

Note that ρ reflects the effect of imperfect CSI on the SNR of the selected relay and hence on the overall performance of relay selection with imperfect CSI. For this reason, the subsequent analysis focuses on expressing the performance degradation as a function of ρ, so that all physical phenomena that cause CSI degradation are, in fact, incorporated into ρ.

A. Versatile Imperfect CSI Case

Capitalizing on the fact that channel estimation is performed in noisy environments, let us consider the versatile scenario where ρ is a function of the SNR. That is,

$$1 - \rho = g(\bar{\gamma}) \quad (3)$$

where $g(\cdot)$ is generally a non-increasing function of its argument, with $0 \le g(\bar{\gamma}) \le 1$. In order to obtain insight into the asymptotic dependence of the CSI error on the SNR, we expand $g(\bar{\gamma})$ into a Puiseux series [43], so that for high SNR we have

$$g(\bar{\gamma}) = b\bar{\gamma}^{-a} + o(\bar{\gamma}^{-a}) \quad (4)$$

where a and b are positive constants with $0 < b \le 1$, and $o(\bar{\gamma}^{-a})$ is defined such that $\lim_{\bar{\gamma} \to \infty} o(\gamma^{-a}) / (\bar{\gamma}^{-a}) = 0$.

It is emphasized that the versatile imperfect CSI model considered in (3) and (4) is general enough to accommodate the cases of imperfect CSI due to noise impairment and the time-varying nature of the underlying channels. Next, we study the scenarios of CSI imperfection in static and time-varying Rayleigh fading channels, separately.

B. Static Channels, Noisy CSI

Let us assume the case of static channels, where channel estimation is implemented via averaging over L noisy pilot symbols. As a result, $g(\bar{\gamma})$ in (3) is a decreasing function of $\bar{\gamma}$, for which $\lim_{\bar{\gamma} \to \infty} g(\bar{\gamma}) = 0$ holds. Moreover, let us consider the scenario where the power allocated to pilot symbols, $\mathcal{E}_p$, is not necessarily equal to the power allocated to data transmission, $\mathcal{E}_d$. We allow the ratio of $\mathcal{E}_p$ over $\mathcal{E}_d$ to be SNR-dependent, so that

$$\mathcal{E}_p = \beta \bar{\gamma}^\alpha \mathcal{E}_d \quad (5)$$

where β is a positive constant and α is a constant, the sign of which determines whether $\mathcal{E}_p$ increases or decreases with SNR. The estimated channel values are expressed as $\hat{h} = h + n_p$, where h and n_p denote the true channel

component and the remaining noise component, respectively. Given that the channel estimates are derived by averaging over L pilot symbols, the noise variance of the estimation process equals $\sigma_{n_p}^2 = N_0 / (\mathcal{E}_p L)$.

Lemma 1: The correlation coefficient, ρ, between $|h|^2$ and $|\hat{h}|^2$, is given by

$$\rho = \frac{\Omega_h}{\Omega_{\hat{h}}} = \frac{\Omega_h}{\Omega_h + \sigma_{n_p}^2} = \frac{L\beta\bar{\gamma}^{\alpha+1}}{L\beta\bar{\gamma}^{\alpha+1} + 1}. \quad (6)$$

Proof: Since $\hat{h}$ equals a linear combination of complex Gaussian RVs, $|\hat{h}|^2$ is exponentially distributed. Hence, it follows from the theory of the moments of exponential RVs that $E \left\langle |h|^4 \right\rangle = 2\Omega_h^2$; $E \left\langle |\hat{h}|^4 \right\rangle = 2\Omega_{\hat{h}}^2$. Using this result, the proof follows from (2) after algebraic manipulations, in conjunction with (5) and the fact that $\bar{\gamma} = \mathcal{E}_d \Omega_h / N_0$. ∎

Expanding (6) in a Taylor series for $\bar{\gamma} \to \infty$ and using (3), we obtain for $\alpha > -1$ [2]

$$g(\bar{\gamma}) = 1 - \rho = \frac{1}{\beta L}\bar{\gamma}^{-(\alpha+1)} + o\left(\bar{\gamma}^{-(\alpha+1)}\right). \quad (7)$$

Therefore, using (4), from (7) we have $a = \alpha+1$; $b = 1/(\beta L)$.

C. Time-Varying Channels

Next, the case of time-varying Rayleigh fading is studied, where the maximum Doppler frequency on each of the participating links is assumed identical, and denoted by f_d. Moreover, the autocorrelation function of the complex channel h is denoted by $\rho_h(T_d)$; based on the Jakes' model [44], $\rho_h(T_d)$ is given as $\rho_h(T_d) = \Omega_h J_0(2\pi f_d T_d)$, where $J_0(\cdot)$ denotes the zeroth order Bessel function of the first kind [45, Eq. (8.411)].

1) FIR Channel Prediction: In time-varying environments, the channel estimation can be improved by utilizing the CSI available from previous time instances, so that the channel estimates are derived through a *channel prediction* process [46]. Let us consider an FIR channel prediction filter of length L, and denote the time interval between consecutive CSI acquisitions by T_d. In such case, following the analysis in [46], the predictor coefficients can be optimized so as to yield the minimum squared error between the actual and the predicted channel values, σ_e^2, resulting in

$$\sigma_e^2 = \Omega_h - \underline{u}_h^H \underline{R}^{-1} \underline{u}_h. \quad (8)$$

In (8), $\underline{u}_h$ denotes the L-dimensional autocorrelation vector, i.e., $\underline{u}_h = [\rho_h(-T_d), ..., \rho_h(-LT_d)]^T$, $\underline{R}$ denotes an $L \times L$ symmetric Toeplitz matrix, the first row of which given by $[\rho_h(0) + N_0/\mathcal{E}_p, \rho_h(-T_d), ..., \rho_h(-LT_d + T_d)]$, and $(\cdot)^H$ denotes the Hermitian operator. Hence, ρ is derived by combining (2) and (8), as

$$\rho = \underline{u}_h^H \underline{R}^{-1} \underline{u}_h / \Omega_h. \quad (9)$$

It follows from (3) that the CSI error can be expressed as a function of the SNR as $g(\bar{\gamma}) = 1 - \rho = 1 - \underline{u}_h^H \underline{R}^{-1} \underline{u}_h / \Omega_h$.

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[2]The case of $\alpha < -1$ yields $\rho = 0$ for $\bar{\gamma} \to \infty$, and is out of the scope of this paper.

Interestingly, it is noted that in the high-SNR regime and for $f_d > 0$, $g(\bar{\gamma})$ converges to a finite non-zero constant, i.e.,

$$\lim_{\bar{\gamma} \to \infty} g(\bar{\gamma}) = 1 - \underline{u}_h^H \underline{R}^{-1}\big|_{N_0=0} \underline{u}_h / \Omega_h = b > 0 \qquad (10)$$

implying that the CSI error is independent of the SNR. Hence, considering (4), it follows that for the case where the channel estimates are obtained through FIR channel prediction, $a = 0$ holds.

Ideal but Outdated CSI: This special case of channel estimation was considered in [33]–[39]. It is dubbed "outdated CSI" here, and in fact corresponds to noiseless FIR channel prediction with a one-tap predictor ($L = 1$). This case implies that the CSI based on which the "best" relay is selected is noise-free, yet the selection of the "best" relay is not based on the current time instant but on a previous one, because of, e.g., a feedback delay. Based on (9), it can be shown that the correlation coefficient, ρ, for the outdated CSI case equals $\rho = \rho_h^2(-T_d)/\Omega_h^2$, a result which is in accordance with [33], [34]. Moreover, $g(\bar{\gamma})$ is a constant in this case, and thus (4) yields $a = 0$; $b = 1 - \rho_h^2(-T_d)/\Omega_h^2$.

2) IIR Channel Prediction: Let us now extend the channel prediction case to the scenario where the number of pilot symbols participating in the prediction process are infinitely large. As shown in Appendix A, this scenario leads to a correlation coefficient of

$$\rho = 1 - \exp\left(T_d \int_{-f_d}^{f_d} \ln\left[\mathcal{S}_{hh}\left(e^{j2\pi f T_d}\right) + \left(\beta\bar{\gamma}^{\alpha+1}\right)^{-1}\right] df\right)$$
$$\times \left(\beta\bar{\gamma}^{\alpha+1}\right)^{-(1-2f_d T_d)} + \left(\beta\bar{\gamma}^{\alpha+1}\right)^{-1} \qquad (11)$$

where $\mathcal{S}_{hh}(\cdot)$ represents the Fourier transform of $\rho_h(\cdot)$. Hence, combining (3) and (11), we obtain for high SNR

$$g(\bar{\gamma}) = \underbrace{\exp\left(T_d \int_{-f_d}^{f_d} \ln\left[\mathcal{S}_{hh}\left(e^{j2\pi f T_d}\right)\right] df\right) \beta^{-(1-2f_d T_d)}}_{b}$$
$$\times \bar{\gamma}^{\underbrace{-(\alpha+1)(1-2f_d T_d)}_{a}}. \qquad (12)$$

Consequently, it is concluded that the parameters a and b of the asymptotic dependence of the CSI error on the SNR are given by $a = (\alpha+1)(1-2f_d T_d)$ and $b = \exp\left(T_d \int_{-f_d}^{f_d} \ln\left[\mathcal{S}_{hh}\left(e^{j2\pi f T_d}\right)\right] df\right) \beta^{-(1-2f_d T_d)}$.

The reader is referred to Table I for an overview of how the parameters a and b are derived for the practical channel estimation scenarios considered in this paper. An asymptotic performance analysis of suboptimal relay selection follows.

IV. OUTAGE ANALYSIS OF RELAY SELECTION WITH IMPERFECT CSI IN RAYLEIGH FADING

The outage probability is defined as the probability that the overall SNR lies below a given threshold, which is denoted here by T. That is, $P_{out} = \Pr\{\gamma_\kappa < T\}$, where κ denotes the index of the selected relay and γ_κ is the corresponding end-to-end SNR. Observing that for all channel estimation scenarios considered in Section III, $\hat{h}$ is obtained as a linear combination of complex Gaussian RVs, it follows that $\hat{h}$ is also a complex Gaussian RV. Hence, $\hat{\gamma}$ is exponentially

distributed. Consequently, the conditional pdf of the actual SNR, γ, conditioned on its estimate, $\hat{\gamma}$, is obtained from [47, Eq. (2.11)] as

$$f_{\gamma|\hat{\gamma}}(x|y) = \frac{\exp\left(-\frac{x}{\bar{\gamma}(1-\rho)} - \frac{y\rho}{\bar{\hat{\gamma}}(1-\rho)}\right)}{\bar{\gamma}(1-\rho)} I_0\left(2\frac{\sqrt{\rho xy}}{(1-\rho)\sqrt{\bar{\gamma}\bar{\hat{\gamma}}}}\right) \qquad (13)$$

where $\bar{\hat{\gamma}}$ denotes the average estimated SNR and $I_0(\cdot)$ denotes the zeroth order modified Bessel function of the first kind [45, Eq. (8.447.1)]. It is emphasized that since the parameters $\bar{\gamma}$ and $\bar{\hat{\gamma}}$ are not necessarily equal to each other (in contrast to the outdated CSI case treated in [33], [34]), the diversity investigation of relay selection with imperfect CSI under the general imperfect CSI assumption requires that we conduct a new outage analysis for our scheme. This outage analysis is similar to that in [33], yet the corresponding expression for the $f_{\gamma|\hat{\gamma}}(x|y)$ used in [33] is substituted by (13) .

In particular, based upon the mode of operation of selection cooperation [4] the outage probability is expressed as

$$P_{out} = \Pr\{\mathcal{S} = \emptyset\} + \sum_{l=1}^{N} F_{\gamma_{R_\kappa D}}(T\,||\mathcal{S}| = l)\Pr\{|\mathcal{S}| = l\} \qquad (14)$$

where $|\mathcal{S}|$ denotes the cardinality of $\mathcal{S}$ and $\emptyset$ is the empty set. Because of the i.i.d. assumption for the fading in the S-R_i links, the second term within the sum in (14) is given by [33, Eq. (7)]

$$\Pr\{|\mathcal{S}| = l\} = \binom{N}{l}\left[1 - \exp\left(-\frac{T}{\bar{\gamma}}\right)\right]^{N-l}\exp\left(-\frac{lT}{\bar{\gamma}}\right). \qquad (15)$$

Furthermore, by defining A_i as the event that the ith relay out of l relays is selected, i.e., $A_i : i = \kappa$, $F_{\gamma_{R_\kappa D}}(T\,||\mathcal{S}| = l)$ is expressed as

$$F_{\gamma_{R_\kappa D}}(T\,||\mathcal{S}| = l) = \sum_{i=1}^{l} F_{\gamma_{R_\kappa D}}(T\,||\mathcal{S}| = l,\ A_i)\Pr\{A_i\}$$
$$= \int_0^T \int_0^\infty f_{\gamma_{R_i D}|\hat{\gamma}_{R_i D}}(x_1|x_2)f_{\hat{\gamma}_{R_i D}|A_i}(x_2|A_i)\,dx_2 dx_1 \qquad (16)$$

where we used the fact that $\Pr\{A_i\} = 1/l$, because of symmetry. The conditional density of $\hat{\gamma}_{R_i D}$ conditioned on A_i is derived as

$$f_{\hat{\gamma}_{R_i D}|A_i}(x_2|A_i) = \frac{f_{\hat{\gamma}_{R_i D}|A_i}(x_2 \cap A_i)}{\Pr\{A_i\}} \qquad (17)$$
$$= \frac{f_{\hat{\gamma}_{R_i D}}(x_2)}{\Pr\{A_i\}}\prod_{\substack{j=1 \\ j \neq i}}^{l} F_{\hat{\gamma}_{R_j D}}(x_2) = lf_{\hat{\gamma}_{R_i D}}(x_2)F_{\hat{\gamma}_{R_i D}}^{l-1}(x_2).$$

Consequently, substituting (13) and (17) in (16) we obtain an expression for $F_{\gamma_{R_\kappa D}}(T\,||\mathcal{S}| = l)$ which coincides with [33, Eq. (8)], where the case of outdated CSI was considered. This leads to an interesting observation which is summarized below.

Under i.i.d. Rayleigh fading and assuming correlation coefficient ρ between the actual and the estimated SNR in each intermediate link, *the outage probability of relay selection with imperfect CSI, P_{out}, expressed as a function of ρ, is given by the same formula, irrespective of the channel*

TABLE I
PARAMETERS a AND b FOR THE CONSIDERED IMPERFECT CSI SCENARIOS.

Case	a	b
Outdated CSI	0	$1 - \rho$
Noisy CSI	$\alpha + 1$	$m/(\beta L)$
FIR Chan. Pred.	0	$1 - \underline{u}_h^H \, \underline{R}^{-1} \big|_{N_0=0} \, \underline{u}_h$
IIR Chan. Pred.	$(\alpha + 1)$ $\times (1 - 2 f_d T_d)$	$\exp(T_d \mathcal{I}) \beta^{-(1 - 2 f_d T_d)},$ where $\mathcal{I} = \int_{-f_d}^{f_d} \ln\left[S_{hh}\left(e^{j2\pi f T_d} \right) \right] df$

estimation technique used. Equivalently, P_{out} is independent of $\overline{\gamma}$, a fact which can be explained by noting that only the relative values of $\hat{\gamma}_i$ are relevant for relay selection, not their absolute values. Hence, scaling all the estimated SNRs by the same factor does not affect the relay selection process. Therefore, the outage probability of suboptimal DF relay selection for any channel estimation technique is as shown in [33, Eq. (2)]. It is emphasized, however, that *different channel estimation techniques lead to different dependencies of ρ on the SNR, resulting ultimately in different diversity behaviors.* The diversity order of relay selection with imperfect CSI is studied in detail in Section VI.

V. OUTAGE ANALYSIS IN NAKAGAMI-m FADING

Let us now consider the case where the fading in all channels follows the Nakagami-m distribution [48]. In this case, since the distribution of $\hat{h}$ is unknown for the unified imperfect CSI model, we confine ourselves to investigating the performance of relay selection with imperfect CSI for the three special cases presented below.

A. Time-Varying Channels: Outdated CSI

Recall from Section III-C1 that this case corresponds to noiseless FIR channel prediction with one tap. Consequently, $\hat{h}$ represents a delayed version of h, and $\hat{h}$ follows the same distribution as h. Therefore, the joint pdf of γ and $\hat{\gamma}$ is obtained from the bivariate Gamma distribution [49], which is simplified using [45, Eq. (9.210/1)] to

$$f_{\hat{\gamma},\gamma}(x_1, x_2) = \sum_{j=0}^{\infty} \frac{(m)_j \, m^{2m+2j} \rho^j}{j! \, (1-\rho)^{m+2j}} \prod_{i=1}^{2} \frac{x_i^{m+j-1} e^{-\frac{m x_i}{(1-\rho)\overline{\gamma}}}}{\Gamma(m+j) \, \overline{\gamma}^{m+j}} \tag{18}$$

where $(x)_y$ denotes the Pochhamer symbol defined in [45, pp.xliii].

Following the same steps as in (14)-(17), and using the fact that the pdf and cdf of the SNR for the Nakagami-m fading model are given by $f_\gamma(\gamma) = m^m \gamma^{m-1} / [\overline{\gamma}^m \Gamma(m)] \exp(-m\gamma/\overline{\gamma})$ and $F_\gamma(\gamma) = 1 - \Gamma\left(m, \frac{m}{\overline{\gamma}} y\right) / \Gamma(m)$, respectively, in conjunction with the binomial expansion [45, Eq. (1.110)], we obtain the equivalent expression for (16), pertaining to Nakagami-m fading, as

$$F_{\gamma_{R_\kappa D}}(T \,\|\, \mathcal{S} = l) = l \int_0^T \sum_{j=0}^{\infty} \frac{\rho^j m^{2m+2j}}{j! (1-\rho)^{m+2j}}$$

$$\times \frac{x_1^{m+j-1} e^{-\frac{m x_1}{(1-\rho)\overline{\gamma}}}}{\Gamma(m) \, \Gamma(m+j) \, \overline{\gamma}^{2(m+j)}} \sum_{i=0}^{l-1} \binom{l-1}{i} \left(\frac{-1}{\Gamma(m)} \right)^i$$

$$\times \left(\int_0^{\infty} x_2^{m+j-1} e^{-\frac{m x_2}{\overline{\gamma}(1-\rho)}} \Gamma\left(m, \frac{m}{\overline{\gamma}} x_2 \right)^i dx_2 \right) dx_1. \tag{19}$$

It is observed from (19) that in order to derive a closed-form expression for $F_{\gamma_{R_\kappa D}}(T \,\|\, \mathcal{S} = l)$, the following integral needs to be solved

$$I(\mu, \alpha, m, \beta, j) = \int_0^{\infty} x^\mu \exp(-\alpha x) \, \Gamma^j(m, \beta x) \, dx. \tag{20}$$

For the case of $m \in \mathbb{Z}$, the integral in (20) is evaluated as illustrated in Appendix B. Hence, $F_{\gamma_{R_\kappa D}}(T \,\|\, \mathcal{S} = l)$ can be derived, using (37), [45, Eq. (3.351/1)], and [45, Eq. (8.352/6)] as

$$F_{\gamma_{R_\kappa D}}(T \,\|\, \mathcal{S} = l) = l \sum_{j=0}^{\infty} \frac{\Gamma(m+j) - \Gamma\left(m+j, \frac{mT}{(1-\rho)\overline{\gamma}}\right)}{\rho^{-j} j! (1-\rho)^j \Gamma(m) \Gamma(m+j)}$$

$$\times \sum_{i=0}^{l-1} \binom{l-1}{i} (-1)^i \, \psi(m+j, \rho, i) \tag{21}$$

where we have set

$$\psi(x, \rho, i) = \frac{\Gamma(i+1)}{\left(\frac{1}{(1-\rho)} + i \right)^x} \sum_{\substack{\xi_0, \xi_1, \ldots, \xi_{m-1}=0 \\ \xi_0 + \xi_1 + \ldots + \xi_{m-1} = i}}^{i}$$

$$\times \left(\prod_{k=0}^{m-1} \frac{\left(\frac{1}{k! \left(\frac{1}{(1-\rho)} + j \right)^i} \right)^{\xi_k}}{\Gamma(\xi_k + 1)} \right) \left(x - 1 + \sum_{q=0}^{m-1} q \xi_q \right)!. \tag{22}$$

Consequently, a closed-form expression for the outage probability is obtained by combining (14), (15), and (21), yielding

$$P_{out} = \left(1 - \frac{\Gamma\left(m, \frac{m}{\overline{\gamma}} T \right)}{\Gamma(m)} \right)^N + \sum_{j=0}^{\infty} \sum_{l=1}^{N} \sum_{i=0}^{l-1} l \binom{N}{l} \binom{l-1}{i}$$

$$\times (-1)^i \frac{\left(1 - \frac{\Gamma\left(m, \frac{m}{\overline{\gamma}} T \right)}{\Gamma(m)} \right)^{N-l} \left(\frac{\Gamma\left(m, \frac{m}{\overline{\gamma}} T \right)}{\Gamma(m)} \right)^l \rho^j}{j! (1-\rho)^j \Gamma(m) \Gamma(m+j)}$$

$$\times \left(\Gamma(m+j) - \Gamma\left(m+j, \frac{mT}{(1-\rho)\overline{\gamma}} \right) \right) \psi(m+j, \rho, i). \tag{23}$$

It is noted that, for practical SNR values, i.e., $\overline{\gamma} \leq 40\text{dB}$, the infinite series in (23) converges after a finite number of terms, not greater than 100.

B. Time-Varying Channels: FIR Channel Prediction with Large L and IIR Channel Prediction

In this case, the channel estimate $\hat{h}$ is obtained as the weighted sum of a large number of observations in time-varying fading scenarios ($f_d > 0$) [46]. Hence, it follows from the central limit theorem that $\hat{h}$ is a complex Gaussian RV, therefore $|\hat{h}|^2$ is exponentially distributed with average value denoted by $\overline{\hat{\gamma}}$.

The joint pdf of γ and $\hat{\gamma}$ is obtained from [49, Eq. (10)] by setting $m_1 = m$ and $m_2 = 1$, leading to

$$
f_{\hat{\gamma},\gamma}(x_1, x_2) = (1-\rho)^m \sum_{j=0}^{\infty} \frac{\Gamma(j+1)\rho^j \left(\frac{m}{\overline{\gamma}(1-\rho)}\right)^{m+j}}{\left[\overline{\hat{\gamma}}(1-\rho)\right]^{j+1} j!}
$$
$$
\times \frac{x_2^j x_1^{j+m-1} \; {}_1F_1\left(m-1; m+j; \frac{\rho m x_1}{\overline{\gamma}(1-\rho)}\right)}{\Gamma(j+1)\Gamma(j+m)\exp\left(\frac{1}{1-\rho}\left(\frac{x_2}{\overline{\hat{\gamma}}} + \frac{m x_1}{\overline{\gamma}}\right)\right)} \quad (24)
$$

where ${}_1F_1(\cdot;\cdot;\cdot)$ is the confluent Hypergeometric function defined in [45, Eq. (9.210/1)]. Following the same procedure as in (14)-(17), we obtain the conditional cdf of $\gamma_{R_\kappa D}$ as

$$
F_{\gamma_{R_\kappa D}}(T\,\|\mathcal{S}| = l) = l \sum_{j=0}^{\infty} \sum_{i=0}^{l-1} \frac{\binom{l-1}{i}(-1)^i \left(\frac{m}{\overline{\gamma}}\right)^{m+j}\left(\frac{\rho}{1-\rho}\right)^j}{[1+i(1-\rho)]^{j+1}\Gamma(m+j)}
$$
$$
\times \int_0^T x_1^{m+j-1} e^{-\frac{m x_1}{(1-\rho)\overline{\gamma}}} \; {}_1F_1\left(m-1; m+j; \frac{\rho m x_1}{\overline{\gamma}(1-\rho)}\right) dx_1 \quad (25)
$$

where ρ is given in (9) and (11). It is observed that, for the same reasons addressed in Section IV, $F_{\gamma_{R_\kappa D}}(T\,\|\mathcal{S}| = l)$ is independent of $\overline{\hat{\gamma}}$.

In case of $m = 1$, using [45, Eq. (3.351/1)], [45, Eq. (8.352/2)] and the fact that ${}_1F_1(0; b; z) = 1$, (25) reduces after some algebraic manipulations to

$$
F_{\gamma_{R_\kappa D}}(T\,\|\mathcal{S}| = l) = l \sum_{i=0}^{l-1} \frac{\binom{l-1}{i}(-1)^i (1-\rho)}{[1+i(1-\rho)]} \quad (26)
$$
$$
\times \sum_{j=0}^{\infty} \left(\frac{\rho}{1+i(1-\rho)}\right)^j \left[1 - \sum_{t=0}^{\infty} \frac{\left(\frac{T}{(1-\rho)\overline{\gamma}}\frac{\rho}{1+i(1-\rho)}\right)^t}{t!\; e^{\frac{T}{(1-\rho)\overline{\gamma}}}}\right].
$$

As a cross check, it follows from [45, Eq. (0.231)] and the infinite series representation of the exponential function [45, Eq. (1.211/1)], that (26) is equivalent to [33, Eq. (8)]. In case of $m > 1$, (25) in conjunction with [45, Eq. (3.351/1)] yields

$$
F_{\gamma_{R_\kappa D}}(T\,\|\mathcal{S}| = l) = \sum_{j=0}^{\infty}\sum_{i=0}^{l-1}\sum_{k=0}^{\infty} \frac{l\binom{l-1}{i}(-1)^i(1-\rho)^m \rho^{i+j}}{[1+i(1-\rho)]^{j+1}\Gamma(m-1)}
$$
$$
\times \frac{\Gamma(m-1+k)\left[\Gamma(m+j+k) - \Gamma\left(m+j+k, \frac{mT}{(1-\rho)\overline{\gamma}}\right)\right]}{\Gamma(m+j+k)\,k!}. \quad (27)
$$

The overall outage probability follows then from (27) (or (26), if $m = 1$) and (14).

C. Static Channels: Noisy CSI in the high SNR Regime

Under the high SNR assumption, it is valid to assume that $\hat{h} = h + n_p$ is also Nakagami-m distributed, with $\overline{\hat{\gamma}} = \overline{\gamma}$. Consequently, the outage probability for this scenario is given by (23), where ρ is given in the ensuing Lemma.

Lemma 2: The correlation coefficient between $|h|$ and $|\hat{h}|$ for Nakagami-m fading is given by

$$
\rho = \frac{\sqrt{\frac{1}{m}\Omega_h^2}}{\sqrt{\frac{1}{m}\Omega_h^2 + \sigma_{n_p}^4 + 2\Omega_h \sigma_{n_p}^2}} = \frac{L}{\sqrt{L^2 + \frac{2mL}{\beta\overline{\gamma}^{\alpha+1}} + \frac{m}{\beta^2\overline{\gamma}^{2(\alpha+1)}}}}. \quad (28)
$$

Proof: The proof is similar to that for *Lemma* 1 by using the fourth moment of a Nakagami-m distributed RV, $E\left\langle |h|^4 \right\rangle = \frac{m+1}{m}\Omega_h^2$. ∎

It is noted that (28) reduces to (6) for $m = 1$. Expanding (28) in a Taylor series for $\overline{\gamma} \to \infty$ and using (3), we obtain for $\alpha > -1$

$$
g(\overline{\gamma}) = 1 - \rho \approx \frac{m}{\beta L}\overline{\gamma}^{-(\alpha+1)} + o\left(\overline{\gamma}^{-(\alpha+1)}\right). \quad (29)
$$

Next, we shed light onto the asymptotic behavior of relay selection with imperfect CSI in Nakagami-m fading.

VI. DIVERSITY ANALYSIS

A. High-SNR Analysis

Here, we present a high SNR outage expression, which is used as a stepping stone for deriving the diversity order of relay selection with imperfect CSI in Nakagami-m fading. For simplicity of exposition, this expression pertains to the cases of outdated CSI and noisy CSI for Nakagami-m fading, as well as FIR and IIR channel prediction in Rayleigh fading; an expression for FIR and IIR channel prediction in Nakagami-m fading follows, likewise, from (27).

For sufficiently high values of $\overline{\gamma}$, we have

$$
\frac{\Gamma\left(m, \frac{m}{\overline{\gamma}}y\right)}{\Gamma(m)} = \frac{\Gamma(m) - \gamma\left(m, \frac{m}{\overline{\gamma}}y\right)}{\Gamma(m)}
$$
$$
\approx \frac{\Gamma(m) - \frac{\left(\frac{my}{\overline{\gamma}}\right)^m}{m}}{\Gamma(m)} = 1 - \frac{m^{m-1}y^m}{\Gamma(m)\overline{\gamma}^m}. \quad (30)
$$

The above expression was obtained using the series representation of the lower incomplete Gamma function, $\gamma(s, x)$ [45, Eq. (8.354/1)], in conjunction with the fact that as $x \to 0$, $\gamma(s, x) \approx x^s/s$. Therefore, by substituting (30) in (23) and setting $\rho = 1 - b\overline{\gamma}^{-a}$, as implied by (4), we obtain an alternative expression for the outage probability as a function of parameters a and b for high SNR as follows

$$
P_{out} \approx \left(\frac{m^{m-1}y^m}{\Gamma(m)\overline{\gamma}^m}\right)^N + \sum_{j=0}^{\infty}\sum_{l=1}^{N}\binom{N}{l}\left(1 - \frac{m^{m-1}T^m}{\Gamma(m)\overline{\gamma}^m}\right)^l
$$
$$
\times \frac{l\left(\Gamma(m+j) - \Gamma\left(m+j, \frac{mT}{b\overline{\gamma}^{1-a}}\right)\right)G(m+j, a, b, l)}{j!\Gamma(m)\Gamma(m+j)\left(\frac{b\overline{\gamma}^{-a}}{1-b\overline{\gamma}^{-a}}\right)^n \left(\frac{\Gamma(m)\overline{\gamma}^m}{m^{m-1}T^m}\right)^{N-l}} \quad (31)
$$

where we have set

$$
G(m+j, a, b, l) = \sum_{i=0}^{l-1}\frac{\binom{l-1}{i}}{(-1)^i}\psi\left(m+j, 1-b\overline{\gamma}^{-a}, i\right). \quad (32)
$$

B. Diversity Order

An important result derived from the high SNR analysis of Section VI-A is the diversity gain of the scheme under consideration, which is summarized in the ensuing theorem.

Theorem 1: The diversity gain of relay selection with imperfect CSI with practical channel estimation and Nakagami-m fading is given by

$$
G_d = \begin{cases} m[a(N-1)+1], & \text{if } a < 1 \\ mN, & \text{if } a \geq 1 \end{cases} \quad (33)
$$

Proof: The proof is given in Appendix C. ∎

C. On The Diversity Potential of Relay Selection

Based on the high SNR analysis of the previous section, interesting results regarding the diversity order of relay selection can be obtained. These results are presented below, for different types of channels and different channel estimation techniques.

1) Channel Estimation over Static Channels: Let us first focus on the scenario where the channel estimates are obtained via training in static channels. In this case, as can be seen from Table I the exponent a can take any positive value, depending on how fast the training power increases with SNR, with respect to the data transmission power. In particular, it follows from Theorem 1 that full diversity is achieved by using a training power which increases with SNR at least as fast as the data transmission power, i.e., $\alpha \geq 0$. A slower increase with SNR results in a decreased diversity order. Further details regarding the latter argument are provided in Section VII, via numerical examples.

2) FIR Channel Prediction in Time-Varying Channels: Here, we concentrate our attention on the case of FIR channel prediction; note that the special case of outdated channel estimates is also included in this scenario, by setting the number of predictor taps equal to one. As shown in Table I, this case results in $a = 0$. Interestingly, it follows from (33) that the diversity order equals the fading shape parameter, m, regardless of the number of available relays. In other words, *when the estimates of time-varying channels are obtained via an FIR predictor, the diversity order of relay selection reduces to that of the scheme where only a single relay is available.* From another viewpoint, *when relay selection is performed over time-varying channels, its full diversity potential is completely lost, unless a predictor with an infinitely large length is employed.* A study of the latter case follows.

3) IIR Channel Prediction in Time-Varying Channels: As implied by Table I and Theorem 1, the diversity loss of relay selection incurred by the time-varying nature of the underlying channels can be recovered via IIR channel prediction. Nevertheless, given that the full diversity order is recovered for $a \geq 1$, it follows that if the power of the channel estimation pilot symbols grows with SNR as fast as the data transmission power, i.e., $\alpha = 0$, the resulting diversity order is still lower than the maximum value. As a result, it is concluded that *in order to achieve full diversity in relay selection over time-varying channels, IIR channel prediction is required, in conjunction with a training power which increases faster than the data transmission power, i.e., $\alpha > 0$.* The amount of training power required to achieve full diversity is determined by the Doppler spread of the channel and the time difference between the consecutive noisy channel observations.

VII. Numerical Results and Discussions

Figs. 1 and 2 consider the case of static channels, and illustrate the effect of noisy channel estimates on the outage probability of relay selection over Rayleigh fading (m=1). Specifically, Fig. 1 depicts results for $N = 3$ available relays and $\beta = 1$, showing a significant dependence of the outage probability on the parameter α. Recall from (5) that the parameters α and β reflect the relation between the
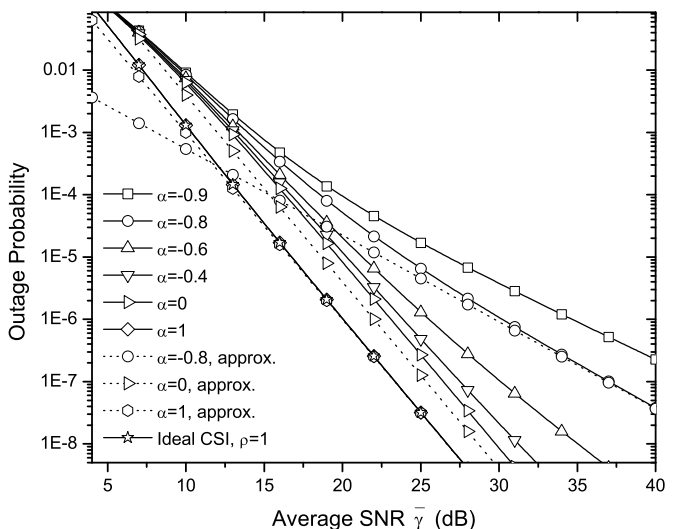

Fig. 1. Case of static channels: Outage probability of relay selection with noise-impaired channel estimates in Rayleigh fading ($m = 1$) versus average SNR, assuming $N = 3$ available relays, $T = 1$, $\beta = 1$, and several different values of α.

power allocated to pilot symbols and the power used for data transmission. It is observed that full diversity is achieved for any $\alpha \geq 0$, yet there exists a power gain loss compared to the perfect CSI case; this power gain loss is recovered for higher values of α, i.e., for $\alpha \geq 1$. In Fig. 1, we also observe the accuracy of the high SNR approximations in (48), (55), and (50) for $a < 1$ ($\alpha < 0$), $a \approx 1$ ($\alpha \approx 0$), and $a > 1$ ($\alpha > 0$), respectively.

The dependence of the outage probability on the ratio of the pilot power and data transmission power, β, is depicted in Fig. 2, for the case of static channels. Similarly as in Fig. 1, $N = 3$ available relays and Rayleigh fading ($m = 1$) are assumed, while the α parameter is set to $\alpha = 0$. We notice a slight dependence of the outage probability on β for a given α, which becomes negligible as β grows large. Consequently, it is concluded that when the ratio of $\mathcal{E}_p$ and $\mathcal{E}_d$ is constant in the whole SNR region, relay selection maintains its full diversity characteristics when operating over noisy static channels; the corresponding loss in power gain is noticeable only for small values of the ratio of $\mathcal{E}_p$ and $\mathcal{E}_d$.

Figs. 3 and 4 refer to the case of ideal but outdated CSI, where the channel estimation is assumed noise-free yet it suffers from feedback delay. Specifically, in Fig. 3 we assume the typical scenario of a vehicle moving at 50 km/h and receiving at a frequency of 2.4 GHz, which corresponds to a maximum Doppler frequency of approximately $f_d = 100$ Hz. Under this assumption, we illustrate the dependence of the corresponding outage probability on the time interval between estimation updates, T_d, for Rayleigh fading ($m = 1$), $T = 1$ and $N = 5$.

We notice from Fig. 3 that the rate of estimation update significantly affects the outage performance of relay selection, in the sense that low update rates result in severe diversity and power gain losses. This is in agreement with (33) where, given that for outdated channel estimates $a = 0$ holds, the diversity order equals m regardless of T_d. Nonetheless, it should be
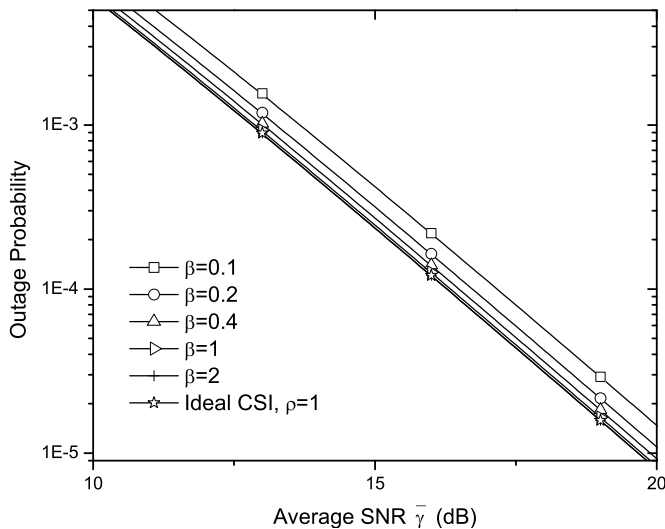
Fig. 2. Case of static channels: Outage probability of relay selection with noise-impaired channel estimates in Rayleigh fading versus average SNR, assuming $N = 3$ available relays, $T = 1$, $\alpha = 0$, and several different values of β.
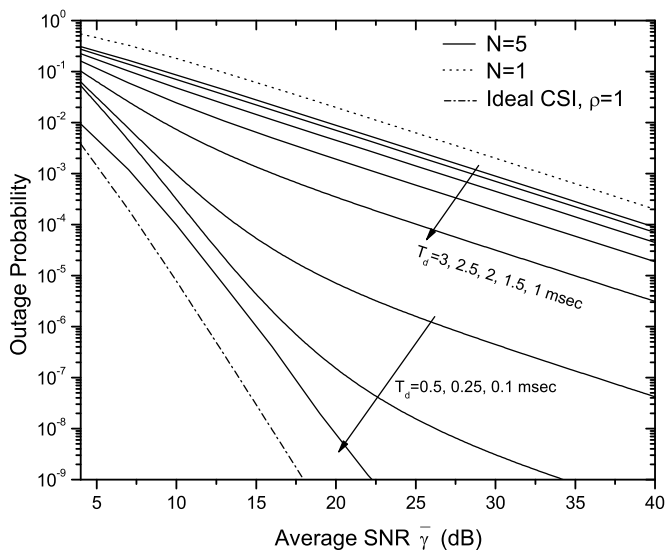

Fig. 4. Case of outdated CSI: Outage probability versus average SNR for $\rho = 0.5$, $N = 5$, $T = 3$, and several values of the Nakagami-m shape distribution parameter, m.

Fig. 3. Case of outdated CSI: Outage probability of relay selection in Rayleigh fading versus average SNR, assuming $N = 5$ relays, $T = 1$, maximum Doppler frequency $f_d = 100$ Hz, and several different values of T_d.

Fig. 5. Time-varying channels with FIR channel prediction: Outage probability of relay selection in Rayleigh ($m = 1$) fading versus average SNR, assuming $N = 5$ available relays, $T = 1$, $T_d = 3$ msec, $f_d = 100$ Hz, $\alpha = 0$, $\beta = 1$, and several values of the channel predictor length, L.

pointed out that for low values of T_d the slope of the outage curves retains its full diversity characteristics in the practical SNR range, and approaches m only for infinitely high SNRs. This observation sheds light onto the diversity potential of relay selection with outdated channel estimates since, *although it is impossible to achieve full diversity from a theoretical perspective (i.e., when $\bar{\gamma} \to \infty$), it is still possible to achieve full diversity in the practical SNR range, by decreasing T_d*. Fig. 3 also demonstrates that for relatively low channel estimation update rates (e.g., for $T_d = 3$ msec), relay selection cannot take advantage of the large number of available relays, since the case of $N = 5$ yields approximately the same performance as that of no selection, i.e., $N = 1$. Furthermore, it is worth
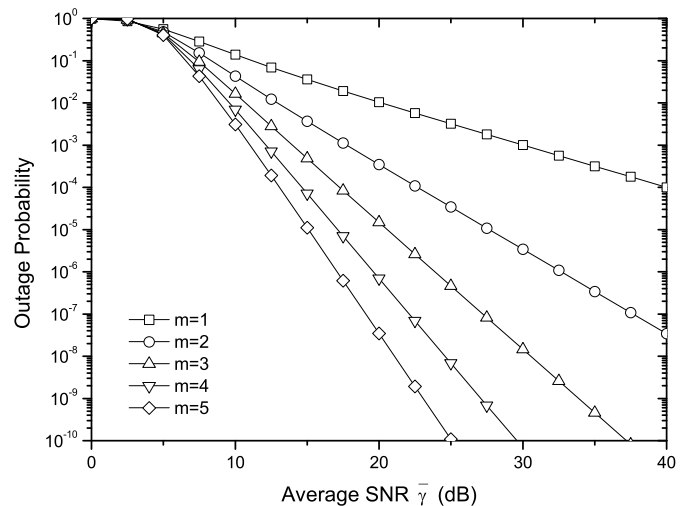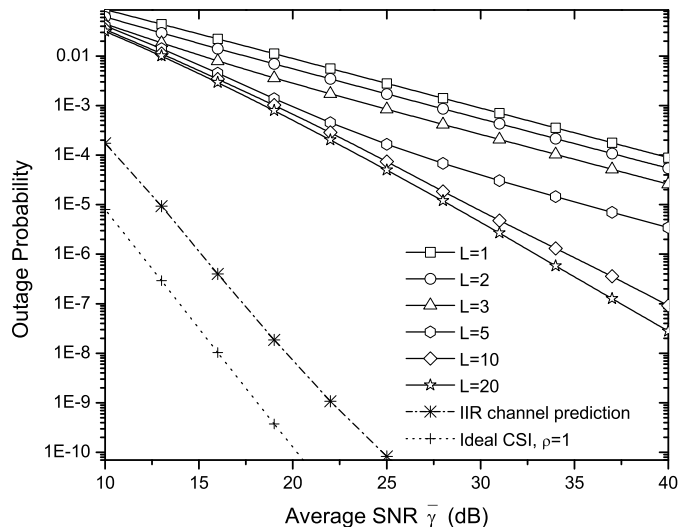
mentioning that the outage probability for the case where the mobile terminals are moving at the walking speed of 5 km/h can be also extracted from Fig. 3, by tenfolding the corresponding values of T_d (i.e., $T_d = 30, 25, ..., 1$ msec).

The outage probability dependence of relay selection with outdated CSI on the Nakagami-m parameter is depicted in Fig. 4. We assume five participating relays ($N = 5$) and an outage threshold SNR of $T = 3$, while the relation between f_d and T_d is set such that $\rho = 0.5$. As expected from (33), it is seen that increasing m results in a considerable outage probability decrease, accompanied by a shift of the slope of the outage curves at high SNR. Note that in all cases the diversity order equals m, as also corroborated by (33).

On the basis of the moving-vehicle scenario considered above, which corresponds to $f_d = 100$ Hz, the case of channel
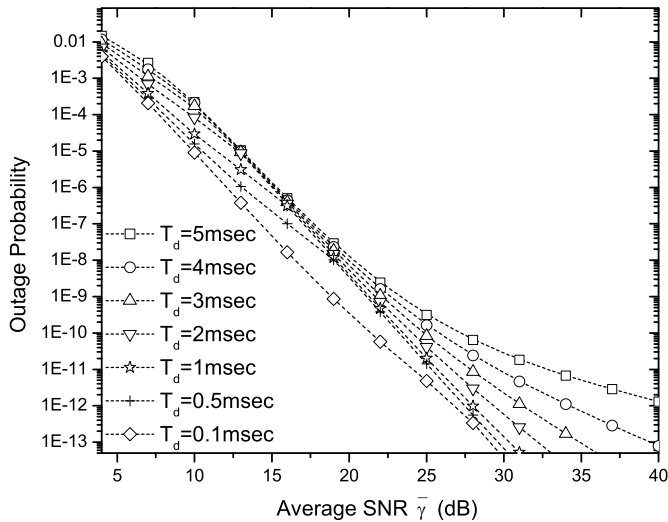
Fig. 6. Time-varying channels with IIR channel prediction: Outage probability of relay selection in Rayleigh ($m = 1$) fading versus average SNR, assuming $N = 5$ available relays, $T = 1$, $\alpha = 0$, $\beta = 1$, and several values of T_d.
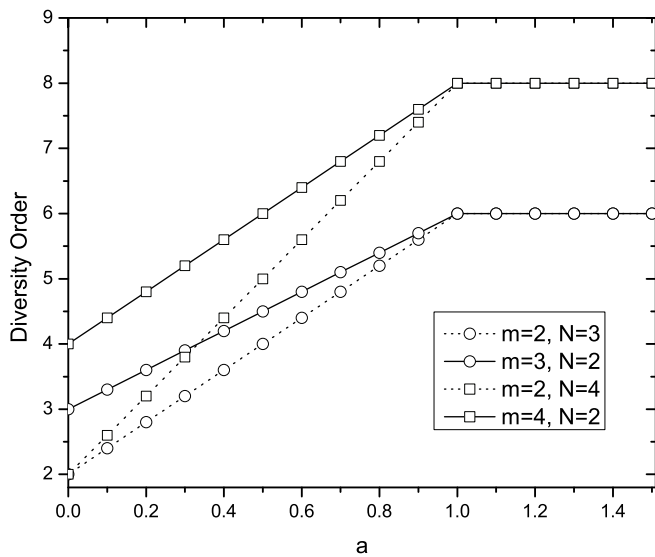

Fig. 7. Diversity order of relay selection with imperfect CSI in Nakagami-m fading as a function of the exponent parameter a, for several combinations of the number of available relays, N, and the fading shape parameter, m. Applies to all the considered imperfect CSI scenarios.

prediction in time-varying channels is treated in Figs. 5 and 6. In particular, Fig. 5 depicts the outage probability of relay selection in Rayleigh fading ($m = 1$) for several values of the channel predictor length, L, including the case of $L \to \infty$ which corresponds to IIR channel prediction and serves here as benchmark. As demonstrated in Fig. 5, by increasing the number of predictor coefficients in FIR channel prediction the outage probability experiences a power gain increase, yet no diversity gain increase is seen for low values of L. On the contrary, an increase in the diversity gain is attained through IIR channel prediction, as shown in the ensuing Fig. 6.

Fig. 6 illustrates the outage probability of relay selection for IIR channel prediction, when operating over Rayleigh fading.

We notice a high dependence of the outage probability on the value of T_d, which corresponds to the time difference between the consecutive time instances in the infinite-length channel predictor. In particular, we notice that full diversity is achieved for small values of T_d, while for larger values of T_d the diversity characteristics of relay selection are lost, as expected from (33) and Table I.

Finally, the achievable diversity order versus a for the unified imperfect CSI model, where the cases of noisy channel estimation and CSI imperfection due to time-varying channels are incorporated, is plotted in Fig. 7. As expected, we notice a linear increase of the diversity order for $0 \leq a \leq 1$ and constant diversity order for $a \geq 1$, which equals mN.

In fact, Fig. 7 sheds an interesting light onto our general assessment regarding the diversity order of relay selection in Nakagami-m fading, which is as follows. The Nakagami-m fading model assumes multiple scatterers in each link, causing an "*internal diversity*" phenomenon of order m, which is independent of the channel estimation quality. On the other hand, the presence of multiple available relays offers the potential for additional, "*external diversity*", yet this additional diversity strongly depends on the quality of channel estimation, as reflected by a. Consequently, we notice from Fig. 7 that for any non-prime diversity order of mN, the value of m is more important than N for the overall diversity order if $a < 1$; if $a \geq 1$, m and N affect the diversity order in exactly the same way.

VIII. CONCLUSIONS

We presented an assessment of the diversity potential of relay selection with practical channel estimation techniques in Nakagami-m fading. The considered channel estimation techniques include the cases of estimation in noisy static channels, estimation in noiseless time-varying channels, and estimation in noisy time-varying channel with the aid of FIR and IIR channel prediction. A closed-form expression for the outage probability of relay selection with imperfect CSI was provided, as a function of the correlation coefficient, ρ, between the actual and the estimated channel values. Capitalizing on this outage expression, our principal inference was that the diversity order of relay selection is determined by the relative speed of convergence of ρ to one, compared to the speed that the SNR approaches infinity.

APPENDIX A
IIR CHANNEL PREDICTION

Let us consider the process $y_l = h_l + n_l$, where h_l and n_l denote the channel value and the corresponding noise

component at time instance l, respectively, with $l = 1, ..., \infty$. The variance of the prediction error is derived as [50]

$$\sigma_e^2 = \exp\left(T_d \int_{-1/(2T_d)}^{1/(2T_d)} \ln\left[\mathcal{S}_{hh}\left(e^{j2\pi fT_d}\right) + \frac{N_0}{\mathcal{E}_p}\right] df\right) - \frac{N_0}{\mathcal{E}_p} \tag{34}$$

where $N_0/\mathcal{E}_p$ is the variance of the noise component and $\mathcal{S}_{hh}(f)$ is the Fourier transform of $\rho_h(\tau)$. Therefore, given that the spectrum of $\mathcal{S}_{hh}(f)$ is band-limited by f_d, (34) yields

$$\sigma_e^2 = \exp\left(T_d \int_{-f_d}^{f_d} \ln\left[\mathcal{S}_{hh}\left(e^{j2\pi fT_d}\right) + \frac{N_0}{\mathcal{E}_p}\right] df\right)$$
$$\times \left(\frac{N_0}{\mathcal{E}_p}\right)^{1-2f_dT_d} - \frac{N_0}{\mathcal{E}_p}. \tag{35}$$

Assuming $f_d > 0$, (11) is obtained from (35), (2), and (5).

APPENDIX B
DERIVATION OF THE AUXILIARY FUNCTION $I(\cdot, \cdot, \cdot, \cdot, \cdot)$

Using the alternative representation of the incomplete Gamma function shown in [45, Eq. (8.352/4)], and applying the multinomial theorem, we obtain

$$\Gamma^j(m, \beta x) = ((m-1)!)^j \exp(-j\beta x) \left(\sum_{i=0}^{m-1} \frac{\beta^i x^i}{i!}\right)^j$$
$$= \Gamma^j(m) \Gamma(j+1) e^{-j\beta x} \sum_{\substack{n_0,n_1,...,n_{m-1}=0 \\ n_0+n_1+...+n_{m-1}=j}}^{j} \prod_{i=0}^{m-1} \frac{\left(\frac{\beta^i}{i!}x^i\right)^{n_i}}{\Gamma(n_i+1)}. \tag{36}$$

Therefore, (20) yields

$$I(\mu, \alpha, m, \beta, j) = \sum_{\substack{n_0,n_1,...,n_{m-1}=0 \\ n_0+n_1+...+n_{m-1}=j}}^{j} \Gamma^j(m)\Gamma(j+1)$$
$$\times \left(\prod_{i=0}^{m-1} \frac{\left(\frac{\beta^i}{i!}\right)^{n_i}}{\Gamma(n_i+1)}\right) \int_0^\infty x^{\mu + \sum_{i=0}^{m-1} in_i} e^{-(a+j\beta)x} dx$$
$$= \frac{\Gamma^j(m)\Gamma(j+1)}{(a+j\beta)^{\mu+1}} \sum_{\substack{n_0,n_1,...,n_{m-1}=0 \\ n_0+n_1+...+n_{m-1}=j}}^{j}$$
$$\left(\prod_{i=0}^{m-1} \frac{\left(\frac{\beta^i}{i!(a+j\beta)^i}\right)^{n_i}}{\Gamma(n_i+1)}\right)\left(\mu + \sum_{i=0}^{m-1} in_i\right)!. \tag{37}$$

APPENDIX C
DIVERSITY ANALYSIS IN NAKAGAMI-m FADING

The following Lemma provides a high-SNR investigation of function $G(m+j, a, b, l)$, allowing for a simplification of (31).

Lemma 3: For sufficiently high $\bar{\gamma}$, the function $G(m+j, a, b, l)$, defined in (32), decays proportionally to $\bar{\gamma}^{-(alm+aj)}$, i.e.,

$$\lim_{\bar{\gamma}\to\infty} G(m+j, a, b, l) \sim \bar{\gamma}^{-(alm+aj)}. \tag{38}$$

Proof: It follows from (22) that the function $\psi(m+j, 1-b\bar{\gamma}^{-a}, i)$ takes the following form

$$\psi(m+j, 1-b\bar{\gamma}^{-a}, i) = \left(\frac{\bar{\gamma}^a}{b}+i\right)^{-j}\psi(m, 1-b\bar{\gamma}^{-a}, i). \tag{39}$$

Therefore, for deriving the decay exponent of $G(m+j, a, b, l)$ it suffices to evaluate the decay exponent of $G(m, a, b, l)$. After substituting (22) into (32) and algebraic manipulations, the function $G(m, a, b, l)$ can be expressed as

$$G(m, a, b, l) = \mu_0 \bar{\gamma}^{-am} \tag{40}$$

$$\times \frac{1 + \mu_1 \bar{\gamma}^a + \mu_2 \bar{\gamma}^{2a} + ... + \mu_{\binom{l-1}{\sum_{i=1}^{l-1} i}(m-1)} \bar{\gamma}^{\left(\sum_{i=1}^{l-1} i\right)(m-1)a}}{(1+\bar{\gamma}^a)^{2m-1}(2+\bar{\gamma}^a)^{3m-2} \times ... \times (l-1+\bar{\gamma}^a)^{lm-(l-1)}}$$

where μ_ζ, $\zeta \in \left\{0, ..., \frac{l}{2}(l-1)(m-1)\right\}$, are constants. It is observed from (40) that the dominant term of $G(m, a, b, l)$ in the high SNR regime decays in proportion to $\bar{\gamma}^{-d_G}$, where d_G is given by

$$d_G = am - \left(\sum_{i=1}^{l-1} i\right)(m-1)a + a\sum_{i=2}^{l}[im-(i-1)] = alm. \tag{41}$$

The proof then follows from (41) and (39), by applying the binomial expansion to the first term of the right hand side of (39). ∎

For the derivation of the diversity order, we simplify (31) for different values of a, as shown below.

1) Case of $a < 1$: In this case, the second argument of $\Gamma\left(m+n, mT/\left(b\bar{\gamma}^{1-a}\right)\right)$ in (31) tends to zero as $\bar{\gamma} \to \infty$. Hence, simplifying the incomplete Gamma function similarly as in (30), we obtain

$$\Gamma(m+j) - \Gamma\left(m+j, \frac{mT}{b\bar{\gamma}^{1-a}}\right) \approx \frac{m^{m+j}y^{m+j}}{(m+j)b^{m+j}\bar{\gamma}^{(1-a)(m+j)}}. \tag{42}$$

Therefore, from (31) and (42) we obtain an expression for the outage probability in the form of

$$P_{out}(y) \approx \left(\frac{m^{m-1}T^m}{\Gamma(m)\bar{\gamma}^m}\right)^N + \mathcal{C} \tag{43}$$

where

$$\mathcal{C} = \sum_{j=0}^{\infty}\sum_{l=1}^{N} \frac{l\binom{N}{l}\left(\frac{1-b\bar{\gamma}^{-a}}{b\bar{\gamma}^{-a}}\right)^n \left(\frac{m^{m-1}T^m}{\Gamma(m)\bar{\gamma}^m}\right)^{N-l}}{j!\Gamma(m)\Gamma(m+j)}$$
$$\times \frac{\left(1-\frac{m^{m-1}y^m}{\Gamma(m)\bar{\gamma}^m}\right)^l m^{m+j}T^{m+j}}{(m+j)b^{m+j}\bar{\gamma}^{(1-a)(m+j)}}G(m+j, a, b, l). \tag{44}$$

The following lemma investigates the high SNR behavior of $\mathcal{C}$.

Lemma 4: For sufficiently high $\bar{\gamma}$ and $a < 1$, the quantity $\mathcal{C}$ defined in (44) is approximated by reducing the sums to single terms corresponding to $j = 0$ and $l = N$, respectively, and decays in proportion to $\bar{\gamma}^{-m[a(N-1)+1]}$, i.e.,

$$\lim_{\bar{\gamma}\to\infty} \mathcal{C} \sim \bar{\gamma}^{-m[a(N-1)+1]}. \tag{45}$$

Proof: It follows from *Lemma* 3 that in the high SNR region the quantity inside the summation of (44) is analogous to $\bar{\gamma}^{d_{\mathcal{C}}}$, where $d_{\mathcal{C}}$ is given by

$$
\begin{aligned}
d_{\mathcal{C}} &= an - m(N-l) - (1-a)(m+n) - (alm+an) \\
&= (1-a)(ml - m - n) - mN.
\end{aligned}
\tag{46}
$$

Since $a < 1$, (46) is maximized over the set of non-negative integers j for $j = 0$, regardless of l; this value of j corresponds thus to the dominant term in the outer sum of (44). Consequently, (46) reduces to

$$
d_{\mathcal{C}} = m[(1-a)(l-1) - N].
\tag{47}
$$

Since $a < 1$ and $1 \le l \le N$, it follows from (47) that the dominant term in the inner sum of (44) corresponds to $l = N$. Hence, setting $l = N$ to (47) completes the proof. ∎

Therefore, considering the fact that the first term in (43) decays in proportion to $\bar{\gamma}^{-mN}$, it follows from *Lemma* 4 that for $a < 1$ and $N > 1$, the dominant term in (43) is $\mathcal{C}$, where only the term with $j = 0$ and $l = N$ is relevant, so that (43) reduces to

$$
P_{out} \approx N \frac{m^{m-1} T^m}{\Gamma^2(m) b^m \bar{\gamma}^{(1-a)m}} G(m, a, b, N).
\tag{48}
$$

Eq. (48) represents a high SNR expression for the outage probability for $a < 1$.

2) Case of $a > 1$: Let us now assume that a is larger than one, and does not lie in the proximity of one. The case where a approaches unity will be considered separately in Section C-3. For $a > 1$, we have

$$
\lim_{\bar{\gamma} \to \infty} \left[\Gamma(m+j) - \Gamma\left(m+j, \frac{mT}{b\bar{\gamma}^{1-a}}\right) \right] = \Gamma(m+j).
\tag{49}
$$

Hence, following the same procedure as for proving *Lemma* 4, it is concluded that the lth-order term within the double summation in (31) decays proportionally to $\bar{\gamma}^{-m[N+l(a-1)]}$, irrespective of j. Consequently, since $a > 1$ the negative decay exponent of the second term of (31) is higher than mN for any $l \ge 1$. This implies that the dominant term in (31) is the first term for high SNRs, yielding

$$
P_{out} \approx \left(\frac{m^{m-1}}{\Gamma(m)} \right)^N \left(\frac{T}{\bar{\gamma}} \right)^{mN}.
\tag{50}
$$

Eq. (50) represents the asymptotic outage expression in high SNR for $a > 1$.

3) Case of $a \approx 1$: The scenario where a lies in the proximity of one is treated separately, since in this case the second argument of $\Gamma\left(m+j, mT/(b\bar{\gamma}^{1-a})\right)$ converges very slowly (to either zero or infinity) as $\bar{\gamma} \to \infty$, hence the approximations in (42) and (49) do not hold for practical SNR values. As a result, the transition from the $a < 1$ case to the $a > 1$ case experiences a discontinuity in terms of the (practical) high SNR approximation of the outage probability, as a approaches unity. This discontinuity is bridged through the outage expression presented below. Recall from Section III-B that the case of $a = 1$ corresponds to the common scenario of channel estimation in noisy static channels, where the power allocated to pilot symbols equals the power allocated to data transmission.

Since $a \approx 1$, let us assume that $\bar{\gamma}^{1-a}$ approaches a non-zero finite constant as $\bar{\gamma} \to \infty$, i.e.,

$$
\lim_{\substack{a \to 1 \\ \bar{\gamma} \to \infty}} \bar{\gamma}^{1-a} = \lambda, \quad 0 < \lambda < \infty.
\tag{51}
$$

This allows us to evaluate the integral $I\left(m+j-1, m/(b\bar{\gamma}^{1-a}), m, m/\bar{\gamma}, i\right)$, shown in (20), as follows.

• Let us assume $0 < x < \infty$. Then, using [45, Eq. (8.352/7)] we have for high SNR

$$
\Gamma^i\left(m, \frac{m}{\bar{\gamma}} x\right) \approx \Gamma^i(m).
\tag{52}
$$

• Let $x \to \infty$. In this case, (52) does not hold. However, it follows from L'Hospital's rule, as well as from the fact that $b\lambda$ is finite, that

$$
\lim_{x \to \infty} \left[x^{m+j-1} \exp\left(-\frac{m}{b\lambda} x\right) \Gamma^i\left(m, \frac{m}{\bar{\gamma}} x\right) \right] = 0.
\tag{53}
$$

Therefore, it follows from (52) and (53) that for high SNRs

$$
\begin{aligned}
I\left(m+j-1, \frac{m}{b\bar{\gamma}^{1-a}}, m, \frac{m}{\bar{\gamma}}, i\right) &\approx \int_0^\infty \frac{x^{m+j-1}}{e^{\frac{mx}{b\lambda}}} \Gamma^i(m)\, dx \\
&= \Gamma^i(m) \Gamma(m+j) \left(\frac{b\lambda}{m} \right)^{m+j}.
\end{aligned}
\tag{54}
$$

By combining (31), (22), (37), (51), (54), [45, Eq. (0.15.4)], [45, Eq. (8.310/1)], [45, Eq. (8.350/2)], and the infinite series representation of the exponential function, we arrive after some manipulations at

$$
P_{out} \approx (N+1) \left(\frac{m^{m-1}}{\Gamma(m)} \right)^N \left(\frac{T}{\bar{\gamma}} \right)^{mN}.
\tag{55}
$$

Eq. (55) represents a high SNR approximation of the outage probability for the case where a lies in the neighborhood of one. *Theorem* 1 follows then directly from (48), (55), and (50).

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