PAPR of Variable-Gain and Fixed-Gain Amplify and Forward Relaying

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***Abstract*—Most works on amplify and forward (AF) relaying assume that the relay obtains perfect channel state information (CSI) of the source-relay channel. This renders variable-gain relaying (VGR) an attractive technique, as the relay can ideally invert the channel at its input and thus ensure constant output power. What happens to the output power, however, if the CSI at the input is outdated? As an attempt to answer this question, we introduce a study of AF relaying under a novel perspective. This involves the use of the well-known peak-to-average-power-ratio (PAPR) for capturing the negative effects of imperfect channel inversion at the relay. The imperfect channel inversion, caused by imperfect CSI at the relay, results in using the power amplifier in its non-linear region, which induces signal distortion. In this regard, expressions for the complementary cumulative distribution function (CCDF) of the PAPR at the relay's output are derived. The analysis involves VGR with outdated CSI at its input, as well as its simpler counterpart which uses only statistical CSI, namely fixed-gain relaying (FGR). Our results manifest that there exists a threshold on the reliability of the CSI at the relay, below which VGR looses its advantage over FGR in being more efficient in terms of the potential signal distortion at the relay, caused by amplification in the non-linear region.**

I. Introduction

Amplify and forward (AF) is a widely studied relaying technique, which offers the benefits of wireless relaying at a low implementation cost. Its operation is based upon simply amplifying the signal sent from a source terminal using analog techniques, and then forward it to a destination terminal without using any further processing at the relay. Among the several variations of AF relaying, the two most common ones are so-called variable-gain relaying (VGR) (a.k.a. channel state information (CSI)-assisted relaying), and fixed-gain relaying (FGR).

In VGR, the gain employed at the relay can be dynamically adjusted so as to compensate for the instantaneous strength of the source-relay link, aiming at maintaining a constant relay transmit power. In FGR, the relay gain is based only on the statistical (i.e., long-term) CSI of the source-relay link, instead of the instantaneous CSI, rendering FGR a simpler alternative to VGR. In the literature, there exist a large variety of works that analyze the performance of VGR, see e.g. [2]-[7]. These works are evaluating the performance of AF relaying in terms of the common metrics of outage probability and bit error rate (BER), and are based on the assumption that the relay acquires perfect CSI of the source-relay link.

Nevertheless, the relay may not always acquire perfect CSI of the source-relay link in practice, affecting thus its ability to maintain constant transmit power. As a result, imperfect CSI acquisition at the relay causes fluctuations of its transmit power, which ultimately result in signal distortion (see e.g. [8]). Such distortion stems from the fact that the linear region of the amplifier at the relay is limited, hence occasionally underestimated channel gains result in using the amplifier in its non-linear region. This sensitivity of AF relaying to the accuracy of the estimation of the source-relay channel motivates us to investigate the performance of AF relaying in terms of an alternative metric, the peak-to-average-power-ratio (PAPR).

The PAPR is a metric that quantifies the fluctuations of the transmit power at the relay. For the case of perfect CSI acquisition at the relay, the PAPR for VGR is one[1]. This is perhaps the reason that the PAPR has not been used in the literature to characterize the performance of VGR. In the case of imperfect CSI acquisition at the relay, however, the PAPR occasionally becomes greater than one, affecting thus the overall performance. Of particular importance is the complementary cumulative distribution function (CCDF) of the PAPR, which reflects the probability that the amplifier at the relay operates in the non-linear region, where signal distortion occurs. In other words, the CCDF of the PAPR is a performance metric that takes into account the practical implementation aspects of AF relaying.

In this work, we study the CCDF of the PAPR for VGR and FGR for Nakagami-m fading, when the CSI at the relay is outdated. We note that the concept of outdated CSI has been considered in the literature in the context of relay schemes before (see, e.g., [10]-[12] and the references therein). However, in [10]-[12] it was assumed that the outdated channel estimation affects the relay selection process in multiple-relay setups, whereas in this work we consider the fundamental three node relaying setup, consisting of a single source, a single relay and a single destination terminal, and concentrate on the effect of outdated CSI at the relay on the CCDF of the PAPR. Furthermore, in [10]-[12] the relay gain was assumed to be based on perfect CSI, whereas we assume here that it is calculated based on outdated CSI. We show that, although for

[1] In fact, the instantaneous relay transmit power experiences an additional level of fluctuations even when the CSI is perfect. Such fluctuations are caused by noise at the relay input, as well as pulse-shaping filtering at the modulation level [9]. Nevertheless, in this work we relax this assumption and consider constant transmit power during the transmission period of each symbol.

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perfect CSI acquisition at the relay, VGR outperforms FGR in terms of the CCDF of the PAPR, for outdated CSI this may not always be the case. In other words, if the CSI of the source-relay channel is not reliably obtained by the relay, compared to FGR VGR can result in a higher probability of signal distortion due to saturation effects at the relay amplifier. This, in conjunction with the comparison between VGR and FGR in terms of BER and outage probability in outdated CSI scenarios [13], sheds some light onto the level of CSI confidence that renders VGR preferable to FGR, in practical applications.

The remainder of this work is organized as follows. The detailed operation of the two AF relaying schemes, namely VGR and FGR, is given in Section II, along with the considered channel model. An analysis of these schemes in terms of the PAPR is conducted in Section III, where discussions regarding the similarities of the two variations of FGR are also provided. Illustrative results on the PAPR of VGR and FGR are given in Section IV, while our concluding remarks are given in Section V.

II. System and Channel Model

We consider a dual-hop wireless communication system with an AF relay, consisting of a source S, a relay R, and a destination D. The relay operates in the AF mode, such that the signal at its input is amplified by a gain, G, and forwarded to D. We denote by α and β the fading amplitudes of the $S-R$ and the $R-D$ links, respectively, which are assumed to follow the Nakagami-m distribution with fading parameters m_X and m_Y, respectively, and $E\langle\alpha^2\rangle = \Omega_X$ and $E\langle\beta^2\rangle = \Omega_Y$ with $E\langle\cdot\rangle$ denoting expectation.

A fundamental assumption throughout this paper is that the relay obtains an estimate of α, which, as shown later, is used for determining the relay gain in VGR. The estimate of α is denoted by $\hat{\alpha}$. Let $X = \alpha^2$ and $\hat{X} = \hat{\alpha}^2$. Then, random variables X and $\hat{X}$ follow the Gamma distribution with shape parameters m_X and $m_{\hat{X}} = m_X$, respectively, and have mean values $E[X] = E[\hat{X}] = \Omega_X = \Omega_{\hat{X}}$. Their probability density function (PDF) and cumulative density function (CDF) are given by

$$f_U(x) = \left(\frac{m_U}{\Omega_U}\right)^{m_U} \frac{x^{m_U-1}}{\Gamma(m_U)} \exp\left(-\frac{m_U x}{\Omega_U}\right), \quad x \geq 0\,, \quad (1)$$

$$F_U(x) = 1 - \frac{1}{\Gamma(m_U)}\,\Gamma\left(m_U, \frac{m_U\, x}{\Omega_U}\right), \quad x \geq 0\,, \quad (2)$$

respectively, where $U \in \{X, \hat{X}\}$, $\Gamma(\cdot)$ denotes the Gamma function defined in [14, eq. (8.310.1)], and $\Gamma(\cdot,\cdot)$ is the incomplete Gamma function defined in [14, eq. (8.350.2)].

Let us denote the power correlation coefficient between α and $\hat{\alpha}$ (i.e., the correlation coefficient between X and $\hat{X}$) by ρ. Then, the joint PDF of X and $\hat{X}$ is given by [15, Eq. (126)]

$$f_{X\hat{X}}(x,\hat{x}) = \left(\frac{m_X}{\Omega_X}\right)^{m_X+1} \frac{1}{(1-\rho)\Gamma(m_X)} \left(\frac{x\hat{x}}{\rho}\right)^{\frac{m_X-1}{2}} \times \exp\left(-\frac{m_X(x+\hat{x})}{(1-\rho)\Omega_X}\right) I_{m_X-1}\left(\frac{2m_X\sqrt{\rho x\hat{x}}}{(1-\rho)\Omega_X}\right), \quad (3)$$

where $I_{m_X-1}(\cdot)$ represents the modified Bessel function defined in [14, eq. (8.406.1)], $x \geq 0$, $\hat{x} \geq 0$, and $\rho \in [0,1]$.

A. VGR

In VGR, the relay gain, G, is set as

$$G^2 = \frac{E_R}{E_S\hat{\alpha}^2 + N_0}\,. \quad (4)$$

where E_S is the power of the transmitted signal from S, N_0 is the power of the additive white Gaussian noise (AWGN) at the relay, and E_R is a constant that equals the relay transmit power when the CSI at the relay is perfect. It is noted that, as it is shown later in Section III, the relay's average transmit power for outdated CSI is generally different than E_R, and depends on the correlation coefficient ρ.

B. FGR

The principal idea of FGR is to employ a fixed value of relay gain, which alleviates the need for continuous channel monitoring as it depends only on the statistics of the S-R channel. In the literature, there are two common variations of FGR, which operate as follows.

1) Semi-Blind FGR: So-called semi-blind FGR (see, e.g., [16], [17] and references therein) employs a relay gain which equals the average of the gain employed by VGR. That is, the relay gain is given by

$$G^2 = E\left\langle \frac{E_R}{E_S\hat{\alpha}^2 + N_0} \right\rangle. \quad (5)$$

2) Average Power Scaling (APS) FGR: In so-called average power scaling (APS) FGR [18], the fixed gain is selected as in (4) with $\hat{\alpha}^2$ replaced by its average, Ω_X, yielding

$$G^2 = \frac{E_R}{E_S E\langle\hat{\alpha}^2\rangle + N_0}. \quad (6)$$

III. PAPR analysis

In the ideal case of perfect CSI, the main advantage of the AF relay gain shown in (4) is that it ensures a constant relay transmit power[2]. When the CSI at the relay is outdated, however, its ability to invert the attenuation caused by the S-R link is impaired, resulting in larger fluctuations of the relay transmit power. Below, we quantify these fluctuations of the relay transmit power through the well-known crest factor, which is also known as the PAPR [19], [20].

[2]In fact, the signal at the input of the relay experiences two types of fluctuations, caused by small-scale fading and noise. Here, by "constant" we refer to the absence of fluctuations caused by small-scale fading, since these fluctuations are compensated by the gain in (4).

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The PAPR, U, is defined as

$$U \triangleq \frac{P_R}{E\left\langle P_R\right\rangle} \tag{7}$$

where P_R is the relay's transmit power for given G, and $E\left\langle P_R\right\rangle$ is the mean transmit power of the relay. Hence, the relay's ability to maintain constant transmit power is reflected in the statistics of the PAPR.

Below, the cases of VGR and FGR are considered separately.

A. PAPR Analysis of VGR

It follows from (4) that the relay output power is given by

$$P_R = G^2\left(E_S\alpha^2+N_0\right) = E_R\frac{E_S\alpha^2+N_0}{E_S\hat{\alpha}^2+N_0} = E_R\frac{X+1/\Gamma_0}{\hat{X}+1/\Gamma_0}. \tag{8}$$

where Γ_0 denotes the transmit SNR, i.e., $\Gamma_0 = E_S/N_0$. Notice from (8) that the relay's average transmit power is not the same as that of VGR with perfect CSI, and is actually a function of ρ. Denoting the relay's average transmit power by $\overline{E}_R^{\,VGR}$, (8) in conjunction with (3) and [21, Eq. (2.15.3/2)] yields

$$\begin{aligned}\overline{E}_R^{\,VGR} &= E\left\langle P_R\right\rangle \\ &= E_R\int_0^\infty\int_0^\infty \frac{X+1/\Gamma_0}{\hat{X}+1/\Gamma_0} f_{X\hat{X}}\left(X,\hat{X}\right)dX d\hat{X} \\ &= E_R\,\Psi\,,\end{aligned} \tag{9}$$

where

$$\begin{aligned}\Psi &= 1+(1-\rho) \\ &\times\left[m_X e^{\frac{m_X}{\Gamma_0\Omega_X}}\epsilon_{m_X}\left(\frac{m_X}{\Gamma_0\Omega_X}\right)\left(1+\frac{1}{\Gamma_0\Omega_X}\right)-1\right]\end{aligned} \tag{10}$$

and $\epsilon_n(\cdot)$ denotes the exponential integral, defined as $\epsilon_n(z) = \int_1^\infty\left(e^{-zt}\right)/\left(t^n\right)dt$ [22, Eq. (5.1.4)].

Interestingly, we observe that $\overline{E}_R^{\,VGR} = E_R$ for $\rho = 1$; $\overline{E}_R^{\,VGR} > E_R$ for any $0 \le \rho < 1$. This implies that, when the relay gain in a VGR application with oudated CSI is set as if perfect CSI was available, the relay's average transmit power is higher than expected. This fact should be taken into account when the performance of VGR with outdated CSI is compared with that of other relevant schemes. The PAPR for VGR is obtained from (8) and (9) as

$$U_{VG} = \frac{1}{\Psi}\frac{X+1/\Gamma_0}{\hat{X}+1/\Gamma_0}\,. \tag{11}$$

A typical measure for quantifying the fluctuations in the relay transmit power is the CCDF of U_{VG} [19]; that is, the probability that U_{VG} exceeds a given value, denoted by ε. This is an important metric as it can be used to quantify the probability that a given power amplifier at the relay operates in its non-linear region, where signal distortion occurs [8]. From another perspective, schemes with high probability of PAPR exceeding a given ε would require an amplifier with an extended linear region, increasing its cost.

Although an exact study of the CCDF of U_{VG} is cumbersome, for sufficiently high SNR, the term $1/\Gamma_0$ can be neglected in both the numerator and denominator of (11), yielding a high SNR approximation of U_{VG}, which is denoted here by $U_{VG}^{'}$, and given by

$$U_{VG}^{'} = \frac{1}{\Psi}\frac{X}{\hat{X}}. \tag{12}$$

The PDF of $U_{VG}^{'}$ is derived as

$$\begin{aligned}f_{U_{VG}^{'}}(u) &= \int_0^\infty \Psi f_{U_{VG}^{'},\hat{X}}\left(\Psi u,\omega\right)d\omega \\ &= \Psi\int_0^\infty \omega f_{X,\hat{X}}\left(\Psi u\;\omega,\omega\right)d\omega.\end{aligned} \tag{13}$$

Plugging (3) into (13) and using [21, Eq. 2.15.3/2], yields

$$\begin{aligned}f_{U_{VG}^{'}}(u) &= \frac{2^{2m_X-1}(1-\rho)^{m_X}\,\Gamma\left(m_X+\frac{1}{2}\right)\Psi}{\sqrt{\pi}\Gamma\left(m_X\right)} \\ &\times\frac{(\Psi u)^{m_X-1}(\Psi u+1)}{\left[\Psi^2u^2+2\left(1-2\rho\right)\Psi u+1\right]^{m_X+\frac{1}{2}}}.\end{aligned} \tag{14}$$

The CCDF of $U_{VG}^{'}$ is obtained from (14) as

$$\Pr\left\{U_{VG}^{'} > \varepsilon\right\} = \int_\varepsilon^\infty f_{U_{VG}^{'}}(u)\,du. \tag{15}$$

It is noted that for the values of interest, i.e., $\varepsilon > 1$, (15) represents an upper bound on the CCDF of the exact PAPR, U_{VG}, since for any $\varepsilon > 1$, $X > \hat{X}$ holds, hence $U_{VG}^{'} > U_{VG}$ holds as well. Numerical examples of the performance of VGR with outdated CSI, in terms of the CCDF of the PAPR at the relay output, are provided in Section IV.

B. PAPR Analysis of FGR

The PAPR for the two variations of FGR discussed in Section II-B is studied below.

1) Semi-Blind FGR: In semi-blind FGR, using (5) the relay transmit power is expressed as

$$\begin{aligned}P_R &= G^2\left(E_S\alpha^2+N_0\right) \\ &= \left(E_S\alpha^2+N_0\right)E\left\langle\frac{E_R}{E_S\hat{\alpha}^2+N_0}\right\rangle \\ &= E_R\left(X+1/\Gamma_0\right)E\left\langle\frac{1}{\hat{X}+1/\Gamma_0}\right\rangle.\end{aligned} \tag{16}$$

By averaging over the distributions of $\hat{X}$ and X, given in (1), we obtain $E\left\langle P_R\right\rangle$ as

$$\begin{aligned}E\left\langle P_R\right\rangle =&E_R\;E\left\langle X+1/\Gamma_0\right\rangle \\ &\times\;\frac{m_X\exp\left(\frac{m_X}{\Gamma_0\Omega_X}\right)\epsilon_{m_X}\left(\frac{m_X}{\Gamma_0\Omega_X}\right)}{\Omega_X} \\ =&E_R m_X\exp\left(\frac{m_X}{\Gamma_0\Omega_X}\right)\epsilon_{m_X}\left(\frac{m_X}{\Gamma_0\Omega_X}\right) \\ &\times\left(1+\frac{1}{\Gamma_0\Omega_X}\right).\end{aligned} \tag{17}$$

We notice from (17) that $E\left\langle P_R\right\rangle > E_R$, implying that the parameter E_R set in the relay gain of the semi-blind FGR scenario does not correspond to the relay's average transmit

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power, but to an underestimate of it. This fact should be taken into account when semi-blind FGR is compared with other relevant schemes.

The PAPR for semi-blind FGR is obtained from (16) and (17) as

$$U_{FG_{SB}} = \frac{X + 1/\Gamma_0}{\Omega_X + 1/\Gamma_0}. \quad (18)$$

Considering the fact that X is Gamma distributed, the CCDF of $U_{FG_{SB}}$ is derived from (18) and (2) as

$$\Pr\{U_{FG_{SB}} > \varepsilon\} = \frac{\Gamma\left(m_X, \frac{m_X\left[\varepsilon\left(\Omega_X + \frac{1}{\Gamma_0}\right) - \frac{1}{\Gamma_0}\right]}{\Omega_X}\right)}{\Gamma(m_X)}. \quad (19)$$

2) APS FGR: For the case of APS FGR, the relay transmit power is obtained from (6) as

$$P_R = \frac{E_R}{E_S\Omega_X + N_0}\left(E_S\alpha^2 + N_0\right). \quad (20)$$

It is easy to notice from (20) that $E\langle P_R\rangle = E_R$, i.e., the relay's average transmit power equals E_R. Consequently, the PAPR for APS FGR is also given by (18).

C. On the FGR Variations

Motivated by the PAPR analysis, interesting observations can be made regarding the similarities between semi-blind and APS FGR.

First, we notice that the PAPR for APS FGR is exactly the same as that of semi-blind FGR. This result is in accordance with the intuition that, whichever fixed gain value the relay applies, the instantaneous and the average transmit power will be scaled by the same coefficient, hence the PAPR will be the same, irrespective of the gain. Second, semi-blind FGR results in a higher average transmit power at the relay than APS FGR, which leads to better performance, as noted in the literature (see e.g. [23]).

In fact, the gain in semi-blind FGR is normalized such that it equals the average gain of VGR; the gain in APS FGR is normalized such that the relay transmit power equals that of VGR. Hence if, for comparison purposes, the same relay transmit power is assumed for both cases, *semi-blind FGR and APS FGR represent two different viewpoints of the same technique*. For this reason, in the sequel we use the term FGR to refer to both semi-blind and APS FGR.

D. Average Relay Transmit Power

For the reader's convenience, a summary of the results regarding the average relay transmit power for VGR with outdated CSI, semi-blind FGR, and APS FGR is provided in Table I.

TABLE I
AVERAGE RELAY TRANSMIT POWER FOR VGR WITH OUDATED CSI, SEMI-BLIND FGR, AND APS FGR.

$$A = m_X \exp\left(\frac{m_X}{\Gamma_0\Omega_X}\right)\epsilon_{m_X}\left(\frac{m_X}{\Gamma_0\Omega_X}\right)\left(1 + \frac{1}{\Gamma_0\Omega_X}\right)$$

Relaying Scheme	Average Relay Transmit Power
VGR, Outdated CSI	$E_R\left[1 + (1-\rho)(A-1)\right]$
Semi-blind FGR	$E_R A$
APS FGR	E_R

IV. NUMERICAL EXAMPLES

Fig. 1 illustrates the CCDF of the PAPR of VGR with outdated CSI, and the CCDF of the PAPR of FGR. In particular, Fig. 1 plots the probability that the PAPR of VGR and FGR exceeds a given threshold value, ε, versus ε, for several values of ρ. The Nakagami-m parameter considered was $m_X = 3$. Solid lines correspond to the upper bound of the CCDF of VGR, and were generated from (15). Dotted lines correspond to FGR, and were generated from (19). The simulated CCDF of the PAPR for VGR is also depicted for Γ_0=15 dB and Γ_0=20 dB, showing convergence to the upper bound for high SNRs.

As expected, we notice a considerable increase in the CCDF of the PAPR for the VGR case, as ρ decreases. For interpreting this result, let us consider the following example. Suppose that the linear region of the relay amplifier extends up to $\varepsilon = 4$ dB units higher than the ideal operation point. For perfect CSI, the probability of exceeding the linear region tends to zero, as the PAPR tends ideally to one. However, for outdated CSI (i.e. for $\rho < 1$), the probability of exceeding the linear region and thus distorting the output signal becomes non-zero, such that, for ρ =0.8 there exists 2% probability of exceeding the linear region, while for ρ =0.2 this probability is about 8%. The latter fact implies that the reliability of the CSI at the relay is crucial for ensuring that the amplified signal is not distorted. From another viewpoint, if the CSI at the AF relay is not reliable enough, an amplifier with extended linear region is required for ensuring no signal distortion, increasing thus the implementation cost.

Fig. 2 sheds light onto the correlation coefficient, ρ, that results in VGR being more efficient than FGR, in terms of PAPR. Specifically, the CCDF of the PAPR is plotted for VGR and FGR versus ρ. We notice that there exists a correlation coefficient threshold, ρ_0, such that for $\rho < \rho_0$ the CCDF of the PAPR is higher for VGR than FGR. The higher the ε value of interest (equivalently, the larger the linear region of the power amplifier at the relay), the higher ρ_0. One could argue that Fig. 2, in conjunction with [13, Fig. 3], sheds some light on the required reliability of the CSI at the relay such that VGR is preferable over FGR.

V. CONCLUSION

Outdated CSI at the input of an AF relay results not only in a performance degradation in terms of outage probability and BER (as shown in [13]), but also increases the potential signal distortion caused by operation of the power amplifier in its non-linear region. This was the main conclusion drawn from this work, where an analysis of the PAPR of variable-gain relaying and fixed-gain relaying was conducted. It was particularly shown that the probability of exceeding the amplifier's

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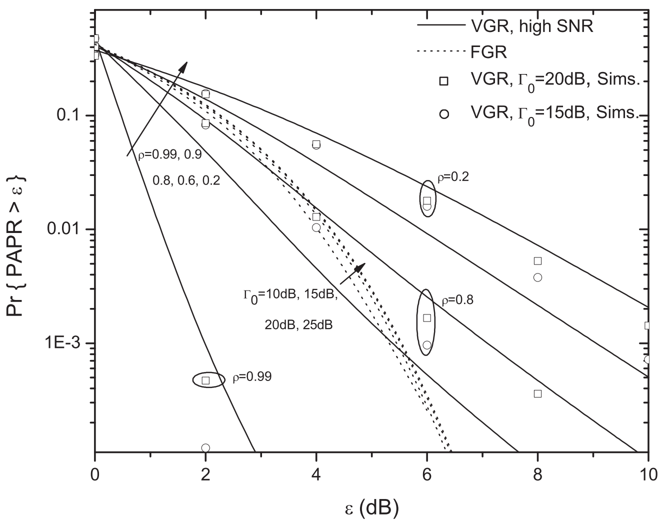

Fig. 1. CCDFs of the PAPR for VGR with outdated CSI and FGR, for $m_X = 3$, and $\Omega_X = 1$.

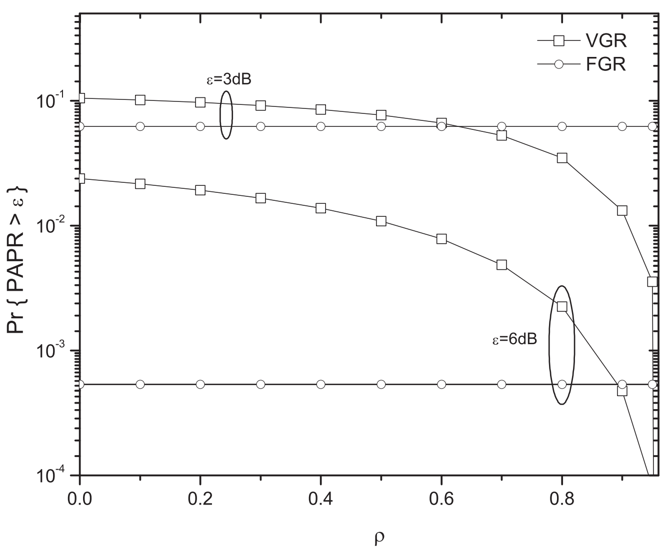

Fig. 2. CCDFs of PAPR for VGR with outdated CSI and FGR vs. the correlation coefficient ρ, for $\varepsilon = 3$dB and $\varepsilon =$6dB, assuming $m_X = 3$, and transmit SNR $E_S/N_0 = 25$ dB.

linear region (and thus causing signal distortion) increases as the reliability of the CSI at the relay input decreases, and if such reliability is too low, variable-gain relaying becomes even worse than fixed-gain relaying in this respect. It was further observed that the average relay transmit power is also affected when the CSI at the input is outdated, a fact which should be taken into account when variable-gain relaying is compared with other relevant schemes.

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