Improving Achievable Rates in MPSK Amplify-and-Forward Relay Networks via Clipping

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***Abstract*—Companding techniques, which are conventionally considered to reduce the peak-to-average power ratio (PAPR) for orthogonal frequency-division-multiplexing (OFDM) systems, decrease the achievable rate. However, we propose to employ clipping, one of the companding techniques, to improve the achievable rates for M-ary phase-shift-keying (MPSK) amplify-and-forward (AF) cooperative communications in this paper. The improved achievable rate of the system is shown through numerical results. It is also found that among the conventional companding techniques, the clipping technique may achieve the highest transmission rate.**

***Index Terms*—Achievable rate, amplify-and-forward (AF), clipping, companding, cooperative communication.**

I. Introduction

Cooperative communication, i.e., a technology to exploit the spatial diversity in a distributed manner, has motivated a surge of research activities that produced a series of research results [1]–[10]. The basic idea of cooperative communication is that a node, which is denoted as "relaying node," in the wireless communication network is able to act as a cooperative transceiver for the source. Because of the shared antennas on one or more relaying nodes and the source, the antennas form a virtual multiple-input–single-output antenna array [1], [2]. Through cooperation between the nodes, the relay communication network can achieve more spatial diversity and higher transmission rate.

In cooperative communications, various relaying protocols, such as amplify-and-forward (AF), decode-and-forward (DF), and compress-and-forward, have been proposed [1]–[3]. Among them, although its handling of the analog signal may impose implementation issues, the AF protocol is widely employed in situations where the relaying nodes have limited ability of signal processing.

In the AF protocol, the source broadcasts the signal to the relaying nodes and the destination. The signals arriving at the relaying nodes are attenuated by the wireless fading channel and corrupted by the additive white Gaussian noise (AWGN). The relaying nodes simply scale the received signals and retransmit them to the destination. When the channel state information (CSI) is known at the destination, the received signals from the source and relaying nodes can optimally be combined and demodulated at the destination. Through cooperative communication, the relayed signals mixed with the scaled AWGN provide soft information, which can be exploited to increase the spatial diversity and to improve the SNR at the destination.

The AF protocol achieves the capacity of the relay channel when the number of relaying nodes in the network is large [4]. Whereas when there is a single relaying node, the AF protocol is not necessarily the optimal choice. Under the aforementioned condition, sawtooth relaying was proposed to improve the achievable rates of relay networks [8]. In [8], when the amplitude of the transmitted signal from the source is assumed to be Gaussian distributed, the received signal at the relaying node is mapped to another signal that is relayed to the destination. The proposed mapping function is a "modulo" or "triangular" function with sawtooth-like shape. It has been shown that the achievable rates can be improved when the received signals from the source and relaying nodes are jointly decoded. However, sawtooth relaying, which is designed for signals with different amplitudes, may not be suitable for signals with the same amplitude, such as M-ary phase-shift keying (MPSK) signals.

In this paper, we propose to improve the achievable rates of MPSK AF relay networks via clipping. Clipping is a well-documented technique [11]–[14]. As a companding technique, clipping was conventionally considered to reduce high peak-to-average power ratio (PAPR) of orthogonal frequency-division-multiplexing (OFDM) systems [15]–[19]. Similar to OFDM signals, which are complex Gaussian distributed over a complex signal space, the relayed signals of MPSK AF relay networks are the superposition of M complex Gaussian distributed signals. The relayed signals with high (low) amplitudes have relatively low (high) entropy per unit power. The companding technique reduces (increases) the amplitudes of relayed signals with high (low) amplitudes. Therefore, we consider to apply the companding technique such as clipping to improve the system achievable rates of MPSK AF relay networks. In [10], simulation results of a clipped AF relay network have been provided. However, to the best of our knowledge, work on employing clipping to improve the system achievable rate has not been reported. It will be shown that compared with the superb companding techniques in the literature, clipping is the most suitable technique for MPSK AF relay communication networks.

The rest of this paper is organized as follows: Section II describes the system model. In Section III, the optimization of the clipping factor is provided. Numerical results are shown and discussed in Section IV. We conclude and summarize this paper in Section V.

II. System Model

In a cooperative communication network, the wireless channels from source to destination, from source to each relaying node, and from each relaying node to destination are usually considered to be mutually independent [1], [5]–[7]. This is realistic because the physical distances between any two nodes in the network are much larger than the carrier wavelength with probability close to 1. Since we focus on the cooperative transmission problem at each relaying node, the system model employed in this paper consists of a source, a destination, and only one relaying node.

We consider an MPSK-modulated AF cooperative communication network in Rayleigh flat-fading channels. The network adopts half-duplex mode, where one transmission unit is divided into two transmission slots. In the first slot, the source broadcasts the signal x_s to the destination and the relaying node. The received signals at the relaying node and the destination are denoted as y_{sr} and y_{sd}, respectively. In the second slot, the relaying node amplifies the received signal y_{sr} and retransmits the amplified signal x_r to the destination resulting in

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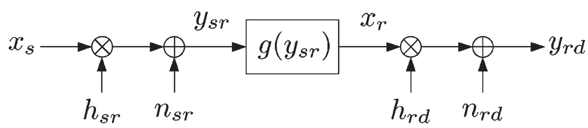

Fig. 1. System model of the clipped AF relay network.

the received signal y_{rd} at the destination. The received signals at the relaying node and the destination can be written, respectively, as

$$y_{sr} = \sqrt{E_s} h_{sr} x_s + n_{sr} \tag{1}$$

$$y_{rd} = \sqrt{E_r} h_{rd} x_r + n_{rd} \tag{2}$$

$$y_{sd} = \sqrt{E_s} h_{sd} x_s + n_{sd} \tag{3}$$

where E_s and E_r denote the transmitting energies per symbol at the source and the relaying node, respectively; n_{sr}, n_{rd}, and n_{sd} are complex AWGNs with zero mean and variance N_o; and h_{sr}, h_{rd}, and h_{sd} represent the Rayleigh flat-fading channel coefficients from the source to the relaying node, from the relaying node to the destination, and from the source to the destination, respectively. The channel coefficients h_{sr}, h_{rd}, and h_{sd} are assumed to be mutually uncorrelated in this paper.

From [8], we know that the achievable rate of the aforementioned cooperative communication network can be written as

$$R = I(x_s y_{sd}|h_{sd}) + H(y_{rd}|y_{sd}, h_{sr}, h_{rd}, h_{sd}) - H(y_{rd}|x_s, h_{sr}, h_{rd}) \tag{4}$$

where $I(p; q|l)$ denotes the conditional mutual information between p and q given l, and $H(p|l)$ denotes the conditional entropy of p given l. Different from [8], where the amplitudes of the transmitted signals are assumed to be Gaussian distributed, the amplitudes of the MPSK-modulated signals are the same. Since the AF protocol and companding techniques only modify the amplitudes of relayed signals, the conditional entropies $H(y_{rd}|y_{sd}, h_{sr}, h_{rd}, h_{sd})$ and $H(y_{rd}|h_{sr}, h_{rd})$ remain the same, i.e.,

$$H(y_{rd}|y_{sd}, h_{sd}, h_{sr}, h_{rd}) = H(y_{rd}|h_{sr}, h_{rd}). \tag{5}$$

The aforementioned conditional entropies are not equal only when DF or the quantize-and-forward protocol [10] is employed.

Therefore, the achievable rate of the AF cooperative communication network R can be rewritten as

$$R = I(x_s; y_{sd}|h_{sd}) + I(x_s; y_{rd}|h_{sr}, h_{rd}) \tag{6}$$

which means that in the proposed MPSK AF relay network, the direct transmission from source to destination is uncorrelated with the relaying transmission. Thus, in this paper, we employ the system model, as illustrated in Fig. 1, which omits direct transmission and only includes the relaying transmission. Although the system model turns out to be a multihop relay network, the proposed scheme is applicable to cooperative communication networks.

In conventional AF cooperative communications, the transmitted signal x_r and the received signal y_{sr} at the relaying node have a simple linear relationship [2], i.e.,

$$x_r = K_1 y_{sr} \tag{7}$$

where

$$K_1 = \sqrt{\frac{1}{E_s|h_{sr}|^2 + N_o}} \tag{8}$$

is the amplification factor. In (8), it should be noted that by assuming that the relaying node has no knowledge on the CSI h_{sr}, some papers (such as [9]) employ the expected value of $|h_{sr}|^2$ instead of $|h_{sr}|^2$. The resulting AF protocol is very simple, particularly when compared with the DF protocol, as only statistics of the channel are required to be known at the relaying node. In this paper, the relaying node is assumed to have perfect instantaneous CSI; thus, $|h_{sr}|^2$ is used in (8).

In the proposed clipped AF relay network, the relationship of the transmitted signal x_r and the received signal y_{sr} at the relaying node is shown as follows:

$$x_r = g(y_{sr}) = \begin{cases} K_2 y_{sr}; & |y_{sr}| < \xi \\ \frac{\xi K_2 y_{sr}}{|y_{sr}|}; & |y_{sr}| \geq \xi \end{cases} \tag{9}$$

where

$$\xi = \sqrt{E_s}|h_{sr}| + \alpha\sqrt{N_o} \tag{10}$$

K_2 is the amplification factor for the clipped AF relay network, and α denotes the clipping factor. From (1), we know that y_{sr} is a complex Gaussian distributed random variable (RV) with mean $\sqrt{E_s} h_{sr} x_s$. Thus, the amplitude of y_{sr} is a Rician distributed RV, whose probability density function (pdf) is

$$f_{|y_{sr}|}(\zeta) = \frac{\zeta}{N_o} \exp\left(-\frac{\zeta^2 + E_s|h_{sr}|^2}{2N_o}\right) \times I_0\left(\frac{\zeta\sqrt{E_s}|h_{sr}|}{N_o}\right) \tag{11}$$

where $f_\bullet(\zeta)$ denotes the pdf of $(\bullet)$, and $I_0(\bullet)$ is the modified Bessel function of the first kind with order zero. Therefore, to satisfy the power constraint for the relaying node, the amplification factor K_2 is the solution of the following equation:

$$K_2^2 \int_0^\xi \zeta^2 f_{|y_{sr}|}(\zeta) d\zeta + K_2^2 \xi^2 Q_1\left(\frac{\sqrt{E_s}|h_{sr}|}{\sqrt{N_o}}, \frac{\xi}{\sqrt{N_o}}\right) = 1 \tag{12}$$

where $Q_1(p, q)$ is the first-order Marcum Q-function [20].

III. Optimization of Clipping Factor

In the proposed clipped MPSK AF relay network, it is important to obtain the optimal clipping factor that maximizes the achievable rate from the source to the destination.

The achievable rate of the AF relay network, as illustrated in Fig. 1, which is denoted as R_{srd}, can be expressed as

$$\begin{aligned} R_{srd} &= I(x_s; y_{rd}|h_{sr}, h_{rd}) \\ &= H(y_{rd}|h_{sr}, h_{rd}) - H(y_{rd}|x_s, h_{sr}, h_{rd}). \end{aligned} \tag{13}$$

In (13), $H(y_{rd}|h_{sr}, h_{rd})$ and $H(y_{rd}|x_s, h_{sr}, h_{rd})$ can be obtained when the conditional pdfs $f_{y_{rd}}(z|h_{sr}, h_{rd})$ and $f_{y_{rd}}(z|x_s, h_{sr}, h_{rd})$ are known.

When x_s is transmitted, the conditional pdf of y_{sr} given h_{sr} is

$$f_{y_{sr}}(z|x_s, h_{sr}) = \frac{1}{\pi N_o} \exp\left[-\frac{(z - x_s h_{sr})^2}{N_o}\right]. \tag{14}$$

After clipping and scaling, the conditional pdf of x_r given x_s and h_{sr}, which is restricted into a circle centered at 0 with radius of ξK_2, is expressed as that in (15), shown at the bottom of the page, where $i = \sqrt{-1}$, and $\angle\bullet$ denotes the angle of $(\bullet)$.

The conditional pdf of x_r is then scaled and rotated according to h_{rd} and convoluted with the pdf of the complex AWGN n_{rd} to obtain the conditional pdf of y_{rd} given $\{x_s, h_{sr}, h_{rd}\}$, i.e.,

$$f_{y_{rd}}(z|x_s, h_{sr}, h_{rd}) = f_{x_r}\left(\left.\frac{z}{h_{rd}}\right| x_s, h_{sr}\right) \otimes f_{n_{rd}}(z). \tag{16}$$

The conditional pdf of y_{rd} given $\{h_{sr}, h_{rd}\}$ is simply

$$f_{y_{rd}}(z|h_{sr}, h_{rd}) = \frac{1}{M}\sum_{x_s} f_{y_{rd}}(z|x_s, h_{sr}, h_{rd}). \tag{17}$$

The optimal clipping factor is the clipping factor that maximizes the achievable rate R_{srd} as

$$\alpha_{\text{opt}} = \arg\max_{\alpha} R_{srd} \tag{18}$$

where

$$\begin{aligned} R_{srd} = &-\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f_{y_{rd}}(z|h_{sr}, h_{rd}) \\ &\times \log f_{y_{rd}}(z|h_{sr}, h_{rd}) d\beta d\zeta \\ &+\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f_{y_{rd}}(z|x_s, h_{sr}, h_{rd}) \\ &\times \log f_{y_{rd}}(z|x_s, h_{sr}, h_{rd}) d\beta d\zeta \end{aligned} \tag{19}$$

in which

$$z = \zeta + i\beta. \tag{20}$$

The closed-form expression for the optimal clipping factor α_{opt} is complicated. The key difficulties are to obtain the close-form expression of K_2, the convolution of $f_{y_{rd}}(z|x_s, h_{sr}, h_{rd})$ with $f_{n_{rd}}(z)$, and to solve the optimization problem. For special cases, such as the very high or very low SNR case, the closed-form expression α_{opt} may be obtained with some approximations. However, the obtained α_{opt} is not instructive. This is because when the SNR is very high or low, the improvement of achievable rate via clipping is negligible. The approximated α_{opt} and the actual α_{opt}, with almost the same achievable rate, may differ a lot. In this paper, we employ numerical calculation to obtain the achievable rate R_{srd} and the optimal clipping factor α_{opt}.

IV. Numerical and Simulation Results

In this section, we present the numerical and simulation results to validate our designs. In Fig. 2, we show the achievable rate R_{srd} with respect to the different values of the clipping factor α for binary phase-shift keying (PSK) cooperative communications. In Fig. 2, the SNR at the relaying node $E_s|h_{sr}|^2/N_o$ is set to be the same as that at the destination $E_r|h_{rd}|^2/N_o$. It is noted that the clipping factor α cannot be less than a certain value because from (9) and (10) we have

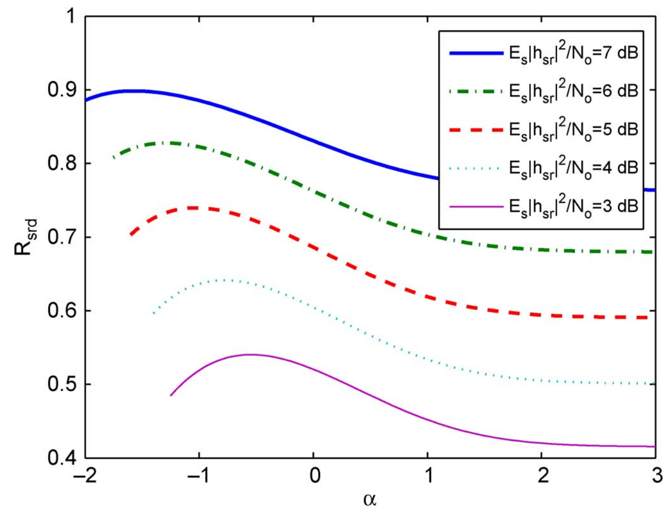

Fig. 2. Achievable rate R_{srd} versus the clipping factor α; binary PSK-modulated AF relay network.

$$\alpha > -\sqrt{\frac{E_s}{N_o}}|h_{sr}|. \tag{21}$$

From Fig. 2, we know that when the conventional AF relay network is employed, i.e., $\alpha \gg 1$, the achievable rate is not optimal. Furthermore, the optimal clipping factor varies with the SNR at the relaying node $E_s|h_{sr}|^2/N_o$. It is also noticed that the achievable rates of the proposed clipped AF relay network are about 18%–30% higher than the conventional AF relay network.

In Fig. 3, the achievable rates R_{srd} with respect to the different values of the clipping factor α for 8-ary PSK-modulated relay network are shown. It is found that the achievable rates of the proposed clipped AF relay network are about 10%–12% higher than the conventional AF relay network. The results in Figs. 2 and 3 prove that the clipping technique is able to improve the achievable rates for MPSK AF relay network.

In Fig. 4, we show the optimal clipping factor α_{opt} with respect to different SNRs at the relaying node and the destination (i.e., $E_s|h_{sr}|^2/N_o$ and $E_r|h_{rd}|^2/N_o$) for the binary PSK-modulated relay network. It is found from Fig. 4 that the optimal clipping factor monotonically decreases with the SNR at the relaying node $E_s|h_{sr}|^2/N_o$. The SNR at the destination $E_r|h_{rd}|^2/N_o$ has limited effect on the optimal clipping factor. Therefore, when the forward channel knowledge at the relaying node h_{rd} is not available, we may employ the clipping factor, which is optimal under the condition that $E_r|h_{rd}|^2/(E_s|h_{sr}|^2) = 1$ as a suboptimal choice.

The employment of the suboptimal clipping factor has negligible effect on the achievable rate, which is illustrated in Fig. 5. When $E_r|h_{rd}|^2/(E_s|h_{sr}|^2) = 1/8$ and 8, we compare the achievable rates R_{srd} of the binary PSK relay networks when the optimal and

$$f_{x_r}(z|x_s, h_{sr}) = \begin{cases} \frac{1}{\pi N_o K_2^2}\exp\left[-\frac{(z - x_s h_{sr} K_2)^2}{N_o K_2^2}\right] & |z| < \xi K_2 \\ \int_{\xi K_2}^{\infty} \frac{1}{\pi N_o K_2^2}\exp\left[-\frac{(\rho\exp(i\angle z) - x_s h_{sr} K_2)^2}{N_o K_2^2}\right]\rho d\rho & |z| = \xi K_2 \\ 0 & |z| > \xi K_2 \end{cases} \tag{15}$$

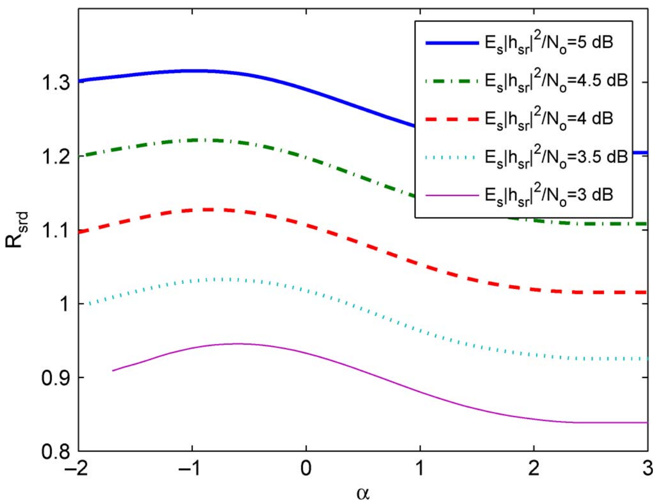

Fig. 3. Achievable rate R_{srd} versus the clipping factor α; 8-ary PSK-modulated AF relay network.

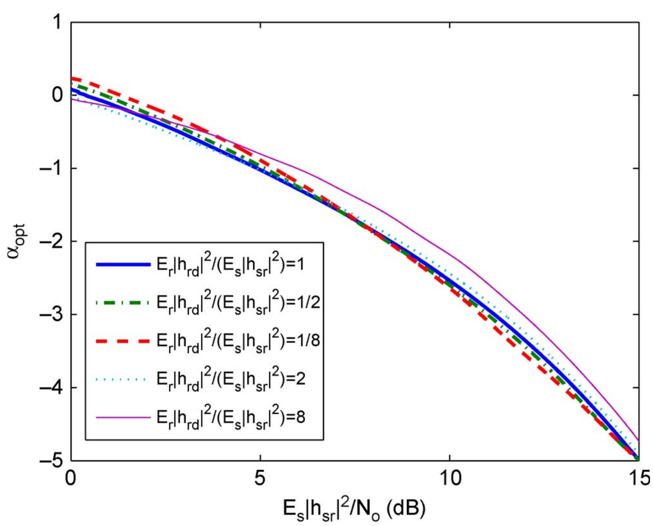

Fig. 4. Optimal clipping factor $\alpha_{\rm opt}$ versus SNR at the relay $E_s|h_{sr}|^2/N_o$; binary PSK-modulated AF relay network.

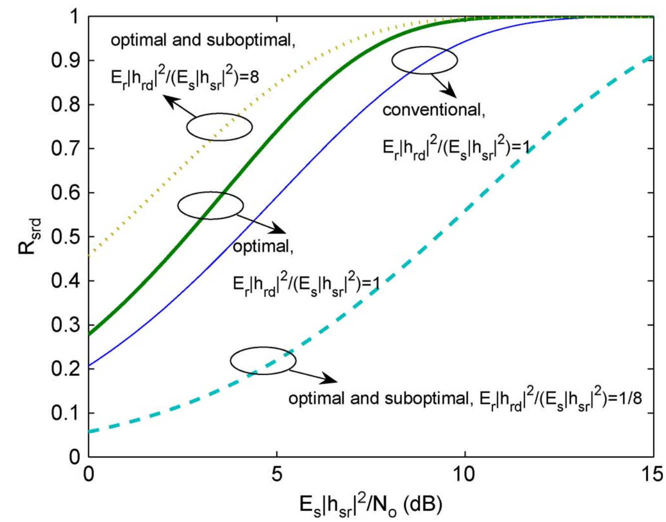

Fig. 5. Achievable rate R_{srd} versus SNR at the relay $E_s|h_{sr}|^2/N_o$; optimal and suboptimal receiver comparison.

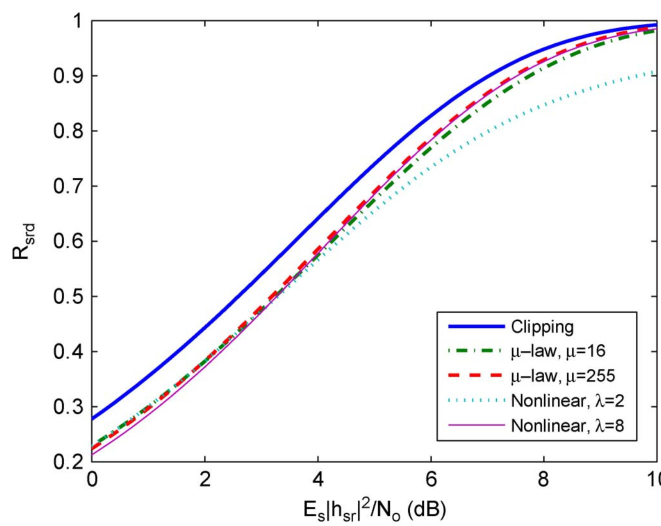

Fig. 6. Achievable rate R_{srd} versus SNR at the relay $E_s|h_{sr}|^2/N_o$; companding technique comparison.

suboptimal clipping factors (denoted as "optimal" and "suboptimal" in the marker, respectively) are employed. It is shown in Fig. 5 that there is no obvious performance degradation. In Fig. 5, we also compare the achievable rates R_{srd} in the conventional AF (denoted as "conventional" in the marker) and the optimal clipped AF relay networks. It is shown in Fig. 5 that the optimal clipped AF protocol has about 1- to 2-dB performance gain over the conventional AF protocol.

In Fig. 6, we compare the different companding techniques with our proposed clipping technique for the binary PSK-modulated relay network. The μ-law companding technique is the same as in [15]. In Fig. 6, we show the achievable rates when the μ-law companding with the parameter $\mu = 16$ and $\mu = 255$. The nonlinear companding technique is the same as in [16]. The idea in [16] is to make the λth power of the amplitude of the companded signal have a uniform distribution. In [19], Jiang and Wu showed that the aforementioned nonlinear companding is the technique that approaches the performance bound of the OFDM system employing PAPR reduction schemes. In Fig. 6, we show the achievable rates when the nonlinear companding schemes with the parameter $\lambda = 2$ and $\mu = 8$ are employed. It is observed from Fig. 6 that the proposed clipping technique outperforms all the other companding techniques. This may be explained by the fact that unlike MPSK signals, which have the same entropy and same amplitude, the relayed signals have different entropies and different amplitudes. When E_r is the same, maximizing the achievable rate is equivalent to maximizing the signal entropy per unit power. For the received signals at the relaying nodes, which are the scaled MPSK signals mixed with AWGN, the signals with high (low) amplitudes have relatively low (high) entropies per unit power. The clipping technique clips the amplitudes of the relayed signals with high amplitudes while keeping the other signals invariant. For μ-law companding and nonlinear companding techniques, the relayed signals with high amplitudes and low entropies, although reduced, still exist with probabilities, and the signals with low amplitudes, after processing, may have less entropies.

It is noted that the results in Figs. 2–6 are obtained when the SNRs at the relaying node and the destination (i.e., $E_s|h_{sr}|^2/N_o$ and $E_r|h_{rd}|^2/N_o$) are considered. Under this condition, the channel model is equivalent to an AWGN channel model. To make sure that the proposed clipped technique increases the achievable rate in Rayleigh fading channels, we compare the bit-error-rate (BER) performance of capacity-approaching channel-coded clipped binary PSK-modulated AF and conventional AF relay networks in Fig. 7. This is because the

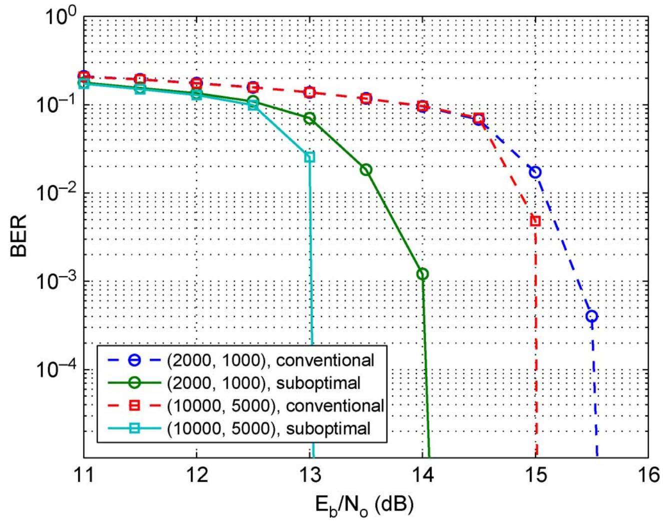

Fig. 7. BER versus E_b/N_o; performance comparison of (2000, 1000) and (10 000, 5000) LDPC-coded clipped and conventional binary PSK-modulated AF relay networks.

uncoded system performance comparison may not show the difference of achievable rates in Rayleigh fading channels. Here, we employ the (2000, 1000) and (10 000, 5000) low-density-parity-check (LDPC) regular codes with column weight of 3 for channel coding [21]. In LDPC-coded systems, an interleaver is usually employed to further improve the system performance in a Rayleigh fading environment [22]. Therefore, we assume that the channel coefficients are uncorrelated for each transmitted symbol, as in [22]. The transmitting energy at the source E_s is set to be the same as that at the relaying node E_r; thus, the energy per bit, which is denoted as E_b, is

$$E_b = 2(E_s + E_r) = 4E_s = 4E_r \tag{22}$$

since the rate half codes are employed. We also assume that the forward channel knowledge at the relaying node h_{rd} is not available, and the suboptimal clipping factor is employed. In Fig. 7, it is found that the (2000, 1000) and (10 000, 5000) LDPC-coded clipped AF relay networks have about 0.6- and 1.0-dB performance improvements over their conventional counterparts, respectively.

V. Conclusion

In this paper, we have proposed to employ a clipping technique to improve the achievable rate of MPSK-modulated AF relay networks. It is shown through numerical results that, different from the clipping technique for OFDM systems that decreases the end-to-end achievable rate, the clipped AF protocol increases the achievable rate from the source to the destination. It is also found that compared with other companding techniques in the literature, clipping may be the best technique that is able to achieve the maximal achievable rate. When the relaying node has no information about the forwarding channel h_{rd}, it is found that we may employ the suboptimal clipping factor, which is actually the optimal clipping factor under the condition that $E_r|h_{rd}|^2/(E_s|h_{sr}|^2) = 1$. The employment of suboptimal clipping factor has negligible effect on the achievable rate from the source to the destination. In this paper, the optimal clipping factor is found through numerical calculation. The closed-form expression of the optimal clipping factor requires further research.

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