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AVERAGE SPECTRAL EFFICIENCY OF CSI-ASSISTED MULTI-RELAY AMPLIFY-AND-FORWARD COOPERATIVE COMMUNICATION SCHEME

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ABSTRACT

This paper studies the multiple relays amplify-and-forward (AF) cooperative communication system with adaptive continuous (ACR) and discrete rate (ADR) M-QAM modulation in Rayleigh fading channel. The average spectral efficiency of the fixed ACR, ADR M-QAM schemes with various number of relays are researched and analyzed. We first obtain quantitative spectral efficiency loss for the fixed rate M-QAM scheme resulting from the increasing number of the relay nodes. It is verified that under certain BER level, the adaptive M-QAM scheme achieves significant efficiency gains over the non-adaptive one. And, the more constellation size is available in ADR M-QAM, the closer the BER approaches to the target level and the more potentialities of the spectral efficiency can be realized.

Keywords: *Amplify-and-Forward Cooperative Communication System, Adaptive Modulation, Average Spectral Efficiency*

1. INTRODUCTION

Modern wireless communication is required to improve the performances of reliability, data rate at a relatively low cost. Cooperative communication, as a newly born advanced technique, could meet that demands in a large extent. Unlike the traditional MIMO (Multiple-Input Multiple-Output) system, it can dramatically improve the BER performance by using the antennas available of the other nodes without laying any additional practical antennas or increasing the cost of hardware. And the cooperative techniques are gaining an increasing popularity among several new emerging IEEE 802.X standards such as 802.11n and 802.11j. Although an relay node in a cooperative wireless network may either amplify what it receives (in case of amplify-and-forward relaying mode) [1] or digitally decodes, and re-encodes the source message (in case of decode-and-forward relaying mode) [2] or decoding the signals followed by employing error detection to avoid error propagation (in case of coded cooperation mode) [3, 4] before retransmitting them to the destination node, we shall concentrate on the amplify-and-forward relaying scheme because of its ease of implementation and the simplicity of protocol in practical systems especially for those who have critical real-time requirement. While this protocol can achieve full diversity using a virtual antenna array, there exists loss of spectral efficiency due to the fact that relays repeat the received bits resulting in insufficient utilization of the channel capacity. This could be compensated by utilizing efficient high efficiency modulation style or a link adaptation mechanism where the power level or other transmission parameters are adapted to the instantaneous regular or irregular channel fluctuations. There exist prior theoretical studies in regarding to the performance analysis of fixed rate as well as ACR and ADR M-QAM cooperative communication. In [5-7], the optimal adaptive transmission scheme which can achieve the Shannon capacity employing the optimal power allocation was derived. Paper [8] and [9] derive bounds for the Shannon capacity of link adaptive cooperative networks with channel-side-information (CSI). Although variable power, variable-rate adaptive schemes are shown to be optimum, approaching the capacity of the channel, they have high implementation complexity. Thus, constant power with optimal rate adaptation modulation is a potential candidate for improving spectral efficiency. Paper [10] examines the discrete adaptive M-QAM for a single incremental relay in Nakagami-m channel. The throughput performance and the achievable signal-to-noise ratio gain in constant-power adaptive-modulation schemes employing various diversity schemes are detailed in [11]. An adaptive M-QAM scheme for orthogonal space time block codes is proposed and analyzed in paper [12].

The main objective of this work is as follows: Quantitatively analyze the average spectral efficiency loss lead to by the increasing of the number of the relay nodes in non-adaptive M-QAM scheme. Afterwards, we investigate the performance gains introduced respectively by ACR and ADR schemes where the BER is restricted to a prescribed level. Further, for the ADR scheme, we will research how the constellation size-selection scheme affects the average spectral efficiency.

This paper is organized as follows. In section II, we present the channel and system model. Simulation and performance analysis of adaptive and non-adaptive M-QAM modulation in cooperative communication is conducted in Section III. Conclusions are given in Section IV.

2. SYSTEM AND CHANNEL MODEL

The cooperative diversity scheme under consideration is composed of 3 components: one source, m relay nodes and one destination as presented in Figure 1.

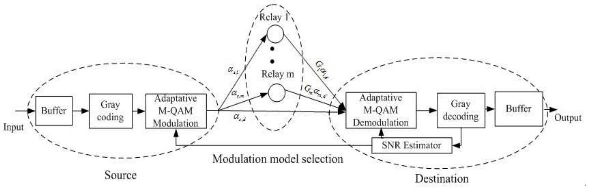

Figure 1: AF Multiple relays system with adaptive M-QAM

An error-free channel lies between the source node and the destination node. The destination node provides the real time uplink channels quality to the source node, judging from which the nodes can self-adaptively adjust itself to the varying channel; meanwhile the BER keeps lowering than a certain level. The received signals can be represented as

$$r_{d,s(t)} = \alpha_{s,d}s(t) + n_{s,d}(t) + \sum\nolimits_{i=1}^{m}(\alpha_{s,i}\alpha_{i,d}G_i s(t) + \alpha_{i,d}G_i n_{s,i}(t) + n_{i,d}(t)) \quad (1)$$

where $s(t)$ is the transmitted signal from source, G_i is the amplifying power gain at the i th($i=1,2,\cdots m$) relay node, $\alpha_{s,i}$, $\alpha_{i,d}$ and $\alpha_{s,d}$ are separately fading coefficients of the source - i th relay, the i th relay – destination and the source- destination, and $n_{s,d}(t)$, $n_{s,i}(t)$, $n_{i,d}(t)$ are AWGN with a variance of N_0 between the source-destination, source- i th relay, the i th relay – destination, respectively.

Assuming that each relay uses $1/m$ times signal power and the average symbol energy is E_s , then the relay gain G_i is set to $\sqrt{E_s/m(\alpha^2{}_{s,i}E_s + N_0)}$ due to the output power constraint at the relays. Thus, with maximum ratio combining (MRC) the total SNR at the destination node is

$$\gamma_{total} = \gamma_{s,d} + (\sum_{i=1}^{m}\sqrt{\frac{\gamma_{s,i}\gamma_{i,d}}{\gamma_{s,i}+1}})^2 \Big/ (1 + \sum_{i=1}^{m}\frac{\gamma_{i,d}}{\gamma_{s,i}+1}) \quad (2)$$

where $r_{s,i} = \alpha^2{}_{s,i}E_s/N_0$, $r_{s,d} = \alpha^2{}_{s,d}E_s/N_0$, $r_{i,d} = \alpha^2{}_{i,d}E_s/N_0$ are the instantaneous SNRs between source-destination, source- i th relay and i th relay-destination, respectively. The total SNR can be approximates as

$$\gamma_{total} \le \gamma_{up} = \gamma_{s,d} + \sum_{i=1}^{m}\min(\gamma_{s,i}, \gamma_{i,d}) \quad (3)$$

To start with, the source node transmits a short frame for channel testing. When the received SNR is estimated and retransmitted to the source node, the corresponding modulation scheme is only certainty, i.e., the number of bits per symbol is varied depending on the instantaneous SNR. The BER for a received SNR under AWGN with Gray coding is bounded by

$$BER(\gamma) \le 0.2\exp(-1.5\gamma/(M-1)) . \quad (4)$$

Thus, the $M(\gamma)$ can be represented as

$$M(\gamma) = 1 - 1.5\gamma/\ln(5BER) . \quad (5)$$

Given that BER is restricted to 10^{-3}, the constellation size relative to the received SNR are exhibited in Figure 2. We first consider the continuous rate adaptive M-QAM in our model and the subsequent simulations due to its ease of implementation and analysis.

In practical system, however, the constellation size is limited to some discrete values. Thus, there is great need to concentrate on adaptive discrete rate (ADR) where the range of the received SNR is divided into $N+1$ regions. In other words, when the received SNR falls into the nth region (n=0,1,2, ⋯ ⋯ N), the corresponding readily available discrete constellation size is employed for transmission.

The region boundaries γ_n to meet a specific target BER, say BER_0, can be represented as:

$$\gamma_n = -\ln(5BER_0)\square 2(2^n - 1)/3 \quad n = 0,1,\cdots N \tag{6}$$

Here, the total SNR are separately divided into 9 or 5 regions. The corresponding region boundaries γ_n are given by:

$$\gamma_{9,n} = -\ln(5BER_0)\square 2(2^n - 1)/3 \quad n = 0,1,\cdots 8 \tag{7}$$

$$\gamma_{5,n} = -\ln(5BER_0)\square 2(2^{2n} - 1)/3 \quad n = 0,1,\cdots 4 \tag{8}$$

Where $n = \log_2(M_n)$ corresponds to the constellation size in the nth regions.

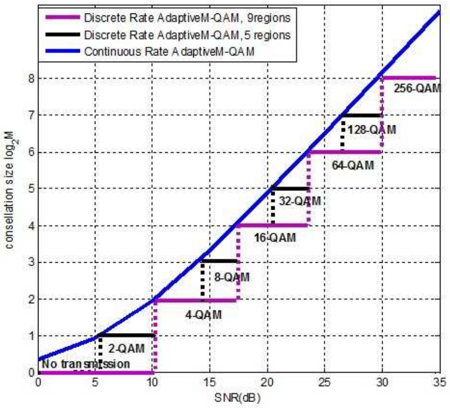

Figure 2: Constellation size relative to the received SNR for both ACR and ADR

A. The average spectral efficiency

The average spectral efficiency for ACR is found by integrating (5) over the PDF of the received SNR.

$$\eta = \frac{1}{m+1}\int_0^\infty \log_2 M(r)\ f_{r_{ub}(\gamma)} d_\gamma \ . \tag{9}$$

For the case of ADR the spectral efficiency can be given by the sum of the data rates weighted by the probability that the received SNR falls in some certain portioned region, i.e.,

$$\eta_{adr} = \frac{1}{m+1}\sum_{n=0}^{N} np_n \ . \tag{10}$$

Where n is the constellation size and the probability is definite as:

$$p_n = \int_{\gamma_n}^{\gamma_{n+1}} f_{\gamma_{ub}} d\gamma \ . \tag{11}$$

B. Bit Error Rate

The BER for cooperative communication with ACR M-QAM modulation has been detailed above in (4).

And the BER for ACR M-QAM modulation can be given by [5].

$$BER_{adr} = \frac{\sum_{n=0}^{N} n\overline{BER_n}}{\sum_{n=0}^{N} np_n} = \frac{\sum_{n=0}^{N} n\overline{BER_n}}{(m+1)\ \eta_{adr}}, \tag{12}$$

Where $\overline{BER_n}$ is the average BER in the nth region

$$\overline{BER_n} = \int_{\gamma_n}^{\gamma_{n+1}} BER_n f_{\gamma_{ub}} d\gamma \tag{13}$$

Where, corresponding to (4), $BER_n = 0.2e^{-1.5\gamma/(M_n - 1)}$.

3. SIMULATION AND PERFORMANCE ANALYSIS

Both the rate-adaptive and fixed rate M-QAM cooperative systems with various m ($m = 0,1,2,3, m = 0$ means no cooperation) relays over Rayleigh channel are simulated here respectively. The performances of average spectral efficiency are comprehensively analyzed.

The unbalancedness of direct and relay channels is characterized with the parameter k, which is defined as the ratio of the average relay link SNR over the average direct link SNR, i.e. , $k = \overline{\gamma}_{s,i} / \overline{\gamma}_{s,d}$. We plot the average spectral efficiency of various schemes as the function of the ratio k. The average SNR of the links are chosen arbitrarily such that they represent a realistic model of a practical cooperative communication system. The amplitude of fading in all links is set to 5.

We simulate the average spectral efficiency of fixed rate M-QAM cooperative systems with 1, 2 and 3 relays, separately. We can conclude from Figure 3: (1) the average spectral efficiency of 128-QAM or 16-QAM closely approaches to that of the theoretical analysis value especially when the SNR is higher than 2.5dB. Actually, the conclusions are applicable to all fixed M-QAM schemes illustrated in Figure 1. (2) The spectral efficiency increases as M increases which can be concluded by comparing the cases of 16-QAM and 128-QAM schemes with 3 relays. (3) Quantitative analysis shows that this scheme suffers from $m+1$ times spectral efficiency loss when m increases, which is also demonstrated in (9). Since for the fixed modulation rate M, spectral efficiency can be given by

$$\begin{aligned}\eta_M &= \frac{1}{(m+1)}\int_0^\infty \log_2 M f_{\gamma(up)} d\gamma \\ &= \frac{1}{(m+1)}\log_2 M \int_0^\infty f_{\gamma(up)} d\gamma\end{aligned} \tag{14}$$

where $\int_0^\infty f_{\gamma(up)} d\gamma$ is a constant value one over Rayleigh fading channel. Then (9) can be simplified as

$$\eta_M = \frac{1}{(m+1)}\log_2 M \tag{15}$$

Consequently, for the fixed rate M-QAM scheme η_M is inversely proportional to $(m+1)$ while proportional to the constellation size $\log_2 M$.

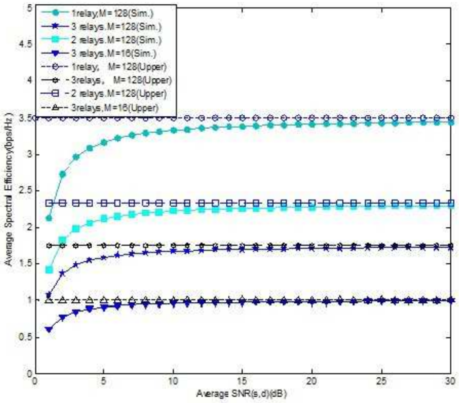

Figure 3: k=0.5, $BER_0=10^{-3}$ .Comparison of the simulated results and upper bound values of the average spectral efficiency for the fixed M-QAM modulation

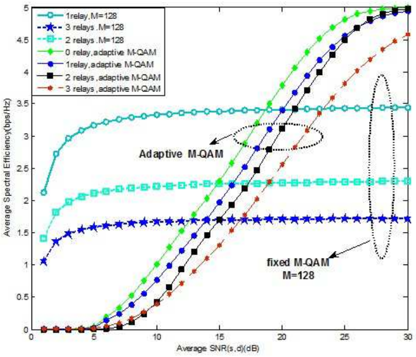

Figure 4: k=0.5, $BER_0=10^{-3}$.Comparison of the average spectral efficiency of ACR M-QAM

The comparison of the average spectral efficiency between the fixed and adaptive rate M-QAM scheme is shown in Figure 4. Clearly, non-adaptive transmission suffers a large spectral efficiency loss in exchange for its simplicity. By comparing the performance over certain SNR region, say m=3 and SNR>20 dB, We can see that even though the fixed rate M-QAM scheme adopts the 128-QAM which can provide 7 times data rate as shown in Figure 1, it fails to achieve higher average spectral efficiency than that of the ADR M-QAM modulation scheme. Specifically, the adaptive M-QAM achieves 0.8-2.8 bps/Hz efficiency gain over the non-adaptive one. Likewise, the similar conclusion can be concluded in the system with 2 relays or one relay.

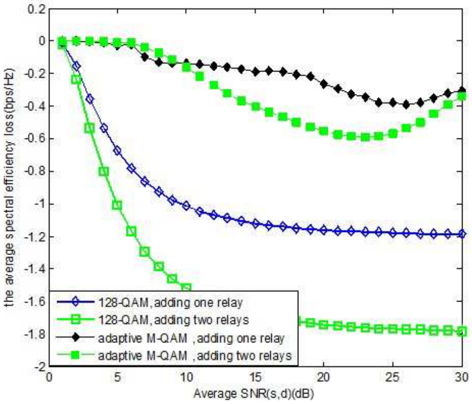

Figure 5: The analysis of average spectral efficiency loss as m increases

We characterize the average spectral efficiency loss lead to by the increasing of the number of the relay nodes in Figure 5. It can be observed that with one relay added to the AF cooperative communication system, the average spectral efficiency loss caused for the adaptive M-QAM and the fixed 128-QAM system are separately about 0.2 bps/Hz and 1.2bps/Hz when SNR is higher than 10 dB. And in the case of another relay added into the systems, the loss is increased to 0.4 bps/Hz and 1.8 bps/Hz respectively.

Hence, the adaptive M-QAM scheme enjoys significant advantages since it decreases the gaps of the average spectral efficiency of fixed rate AF communication systems induced by the increase of the amount of the relay. In effect, relays in AF cooperative system with fixed 128-QAM modulation simply works in the mode mentioned in Section, i.e., repeat the received signal which fails to adapt to the instantaneous channel fluctuations. Nevertheless, without sacrificing bit-error rate, the adaptive M-QAM scheme increases average spectral efficiency by transmitting at high speeds and reduces spectral efficiency as the channel undergoes degradation.

4. CONCLUSIONS

In this paper, we study and analyze the performance of average spectral efficiency for an adaptive variable-rate M-QAM modulation technique in AF cooperative communication systems. We have verified that there is a considerable efficiency loss as the number of relays increases for the fixed M-QAM scheme. And the adaptive M-QAM scheme achieves significant efficiency gains over the non-adaptive one and can thus in a large extent compensate for the spectral efficiency loss. Specifically, when SNR is higher than 10dB, the average spectral efficiency loss caused by one additional relay is reduced by 1 bps/Hz. For the case of two additional relays, likewise, 1.4 bps/Hz efficiency losses are eliminated.

5. ACKNOWLEDGEMENT

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