CAPACITY ENHANCEMENTS IN IEEE 802.16J SYSTEMS USING MIMO-RELAY MULTIPLEXING

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ABSTRACT

This paper presents the analysis of relay multiplexing configuration for IEEE 802.16j systems employing MIMO antennas. The availability of multiple relay paths in IEEE 802.16j motivates two relay configurations: relay diversity and relay multiplexing. Existing works have focused on the relay diversity method. In this paper, we explore the relay multiplexing alternative. Using the concept of code-division multiple relay access (CDMRA), where relay stations (RS) are assigned unique access codes for parallel relaying of independent data streams from source to destination, we derive the capacity of the relay multiplexing system in comparison with the relay diversity methods. We show that while the capacity of the diversity methods grows with the log of the system SNR, the capacity of the relay multiplexing approach grows linearly with the number of parallel relay paths created in the system for iid channel case. Relay multiplexing thus provides affordable means of realizing high-speed multihop communications.

Index Terms— MIMO-Relay, Multihop cellular, IEEE 802.16j, Code-division multiple relay access.

1. INTRODUCTION

Fourth generation (4G) cellular systems are required to support high-quality broadband services, supporting voice and video applications in addition to data services. To meet the increasing demand for high data rate services, novel capacity enhancement techniques are currently being explored for the 4G cellular systems. WiMAX as one of the early 4G systems has recently defined the IEEE 802.16j mobile multihop relay extension to the WiMAX standard, which promises capacity or throughput enhancements through the use of relay stations (RS) inserted in the transmission path between the base station (BS) and the mobile station (MS).

In the last decade, MIMO multiplexing (or antenna multiplexing) has been widely embraced as effective method to enhance the capacity of wireless system, while operating on the same bandwidth compared to the single antenna (or SISO) systems. The capacity demands of the 4G cellular systems cannot easily be satisfied by the use of MIMO multiplexing or RSs individually, because of the unpredictable nature of the wireless environment. A combination of these two techniques is somewhat indispensable. Several works have thus recently intensified efforts on the development of workable MIMO relay configurations for future cellular systems. In [1], it is shown that the capacity of a multi-hop MIMO relaying system decreases as the source data traverses one or more relay hops. In [2], a wireless relay network is analyzed where the source and the destination nodes are equipped with multiple antennas and each relay has a single antenna employing distributed space time code (DSTC). In [3], a multi-hop relay network where each node is equipped with a single antenna and the relays employed distributed linear dispersion (LD) code is considered. In [4], distributed GABBA space-time codes are introduced for single antenna relay network, while in [5], the idea of random sequential relaying is introduced and shown to achieve the maximum antenna diversity gain in a multi-antenna network.

All these works, and numerous others in the literature, can however be categorized under the relay diversity method, where the relayed data from all the RS at any time instant belong to the same stream. In this paper, we explore the relay multiplexing alternative, where multiple RS are employed for parallel relaying of independent data streams from source to the destination. The capacity enhancement provided by the proposed method is analyzed and discussed in comparison with the relay diversity method.

2. IEEE 802.16j MULTIHOP RELAYING SYSTEM

The physics of wireless communication naturally favors multihop relaying systems. If the transmission path from BS to MS in a cellular system is divided into R equal hops, then the effect on path loss is such that the throughput will be enhanced R^2 times. Thus the IEEE 802.16j standard has proposed a two-hop relay configuration for cellular system as shown in Fig 1, where each cell BS, located at the center of the cell, is surrounded by six RSs, each equidistant from the BS and located at the center of each side of the cell hexagon. In this paper, we examine the IEEE 802.16j system with the objective of enhancing its capacity further using novel MIMO relaying configurations.

3. CAPACITY ENHANCEMENT IN MULTIHOP MIMO RELAYING SYSTEM

Fig 2 displays the general block diagram we employed for various relay configurations considered in this work, where data transfer from BS to MS is effected via two or more relay paths. The availability of multiple relay paths naturally motivates two possible relay configurations: relay diversity and relay multiplexing methods. Existing works in the literature, e.g. [2-5] can be classified under the relay diversity methods, where multiple RSs are employed for

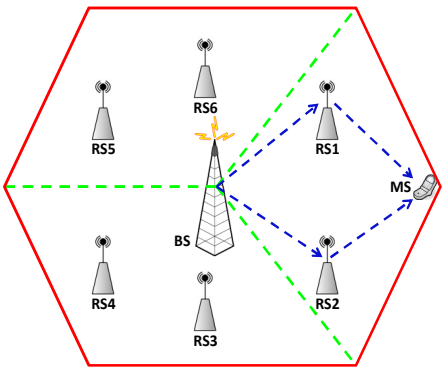

Figure 1. IEEE 802.16j multi-hop relay configuration

relay diversity gain, either via parallel relaying using various code matrices at relays [2,3,4], or via sequential relaying [5]. In both cases, the relayed data from all RS at any time instant belong to the same stream. In this paper, we propose relay multiplexing alternative for capacity enhancements in IEEE 802.16j. For comparison of the proposed scheme with the relay diversity method, we first discuss some capacity-enhancing relay diversity schemes in the context of the two-hop network in IEEE 802.16j.

3.1. Relay diversity methods using STBC at relays

The first scenario of interest is a two-hop communication with two or more RS between the BS and the MS. The Alamouti's space time block codes (STBC) [6] are employed at the RSs. In such case, the RSs employ decode and forward (DF) protocol, and the transmission from the BS to the MS takes three time slots. In the first time slot, the BS transmits vector $\mathbf{s}=[s_1\ s_2]^T$ to the RSs. The signal received at the kth RS in the first time slot is:

$$\mathbf{r}_k = \mathbf{H}_k\mathbf{s} + \mathbf{n}_k\ , \qquad k = 1, 2 \tag{1}$$

where $\mathbf{H}_k$ is the MIMO channel matrix between the BS and the kth RS, with elements modeled as iid complex Gaussian random variable, and $\mathbf{n}_k$ is the additive white Gaussian noise (AWGN) vector at the kth RS. In the second time slot, RS_1 transmits its decoded signal $\mathbf{s}_{RS_1} = [\hat{s}_1\ \hat{s}_2]^T$, while in the third time slot RS_2 transmits the complex conjugates of its decoded signal, $\mathbf{s}_{RS_2} = [-\hat{s}_2^{\ *}\ \hat{s}_1^{\ *}]^T$, to the destination. Thus the signal available at the MS after the third time slot is given by:

$$\mathbf{y} = \mathbf{G}_1\mathbf{s}_{RS_1} + \mathbf{G}_2\mathbf{s}_{RS_2} + \mathbf{n}_D \tag{2}$$

where $\mathbf{n}_D$ is the noise vector at the MS corrupting the STBC decoding, and $\mathbf{G}_i$ is the MIMO channel matrix representing the fading coefficients from the ith RS to the MS, $i = 1, 2$, with elements modeled also as iid complex Gaussian random variable. The capacity for this case is given by

$$C = E[\log_2(1 + SNR)] \text{ bits/sec/Hz} \tag{3}$$

where *SNR* denotes the signal-to-noise ratio of the system. We can express the *SNR* for this case as [6]

$$SNR = \gamma\|\mathbf{G}_1\|_F^2 + \gamma\|\mathbf{G}_2\|_F^2 \tag{4}$$

where γ is the average SNR, and $\|\cdot\|_F^2$ is the Frobenius norm.

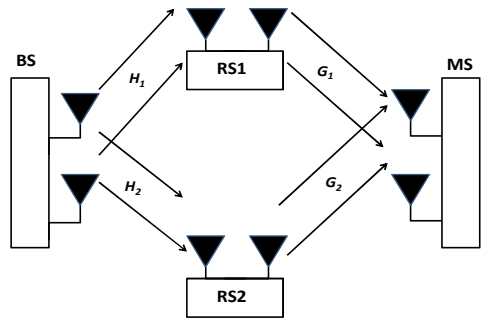

Figure 2. Illustration of two-hop two parallel MIMO-multiplexing relaying

3.2. Relay diversity methods using pre-coding matrix at relays

Next we consider a two-hop relaying system with two or more parallel relays, in which RSs apply pre-coding matrix $\mathbf{A}$ before amplifying and forwarding (AF) the received data to the MS. Each relay in this case employs AF protocol, with amplifier gain α. In this paper, we propose that the pre-coding matrix $\mathbf{A}$ can be chosen as Hadamard matrix or its scalar multiples. For example, for two-antenna RS, $\mathbf{A}$ can be chosen as

$$\mathbf{A} = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad \text{or} \quad \mathbf{A} = \begin{pmatrix} 2 & 2 \\ 2 & -2 \end{pmatrix} \tag{5}$$

In the first time slot the BS transmits the vector $\mathbf{s} = [s_1\ s_2]^T$ to the two relays RS_1 and RS_2. The received signal at the kth RS in the first time slot is thus given by

$$\mathbf{r}_k = \mathbf{H}_k\mathbf{s} + \mathbf{n}_k\ , \qquad k = 1, 2 \tag{6}$$

In the second time slot, both RSs, RS_1 and RS_2, pre-code their received signals, $\mathbf{r}_1$ and $\mathbf{r}_2$, using the pre-coding matrix $\mathbf{A}$ and transmit the pre-coded and amplified data to the MS. Thus the received signal at the MS in the second time slot is given by

$$\mathbf{y} = \alpha_1\mathbf{G}_1\mathbf{A}\mathbf{r}_1 + \alpha_2\mathbf{G}_2\mathbf{A}\mathbf{r}_2 + \mathbf{n}_D \tag{7}$$

The capacity for this case is also given by Eq. (3), where

$$SNR = \gamma(\alpha_1^2\|\mathbf{G}_1\mathbf{A}\mathbf{H}_1\|_F^2 + \alpha_2^2\|\mathbf{G}_2\mathbf{A}\mathbf{H}_2\|_F^2)/(\alpha_1^2\|\mathbf{G}_1\mathbf{A}\|_F^2 + \alpha_2^2\|\mathbf{G}_2\mathbf{A}\|_F^2 + 1) \tag{8}$$

Therefore, the capacity enhancements of the relay diversity methods grow with the log of the *SNR* enhancement provided by the scheme, and it is generally much less than that of relay multiplexing approach as shown next.

3.3. Relay multiplexing method using CDMRA

Next we consider relay multiplexing approach for the two-hop network in Fig 2, where the multiple RSs are exploited for relay multiplexing gain, with RSs relaying different data sub-stream to the MS in parallel. Using the concept of code-division multiple relay access (CDMRA), we propose in this paper that the RSs are assigned unique access codes for multiplexing of multiple RSs data (and retrieval of the individual data from the multiplexed streams), transmitted from the BS on the same time slot. In the first slot, the chip-level received signal at RS_i, i=1,2 , from the BS is given by:

$$\mathbf{R}_i = \mathbf{H}_i\mathbf{S} + \mathbf{N}_i \tag{9}$$

where $\mathbf{S}$ is the matrix of the chip-level transmitted signal, whose n^{th} row, $n = 1, \cdots, N_t$, is the data transmitted on the nth

antenna of the BS, given by $\mathbf{s}_n = \sum_{i=1}^{2} \sqrt{P/KN_t}\, b_{i,n} \mathbf{c}_{i,n}$, where P is the transmitted power, $b_{i,n}$=data of RS_i, i=1,2, and $\mathbf{c}_{i,n}$ the corresponding access code. After pre-filtering, matched filtering, RS_i, i=1,2, uniquely retrieve its substream, while nulling others, from the multiplexed data from the BS as

$$z_{i,n} = \mathbf{z}_{i,n} \cdot (\mathbf{c}_{i,n})^H ; \tag{10}$$

where $z_{i,n}$= n^{th} row of $\boldsymbol{R}_i$ after pre-filtering. In the second slot, the RS simultaneously forward their substreams to the MS, where the MS again decodes them.

3.4. Capacity analysis for relay multiplexing method

We next analyze the capacity enhancement of multi-hop MIMO relay network employing the proposed CDMRA. We assume that N x N antenna multiplexing is employed at all nodes in the network, in addition to the proposed relay multiplexing. The capacity of the system, from source to destination, is thus given by

$$C = C_1 + C_2 + \cdots + C_K \tag{11}$$

where C_i denotes the capacity of the ith relay path from BS to MS. The multihop capacity of MIMO systems with one relay path from source to destination was derived in [1]. In this section, we extend the results in [1] to the general case of K parallel relay paths, using the concept relay multiplexing presented in this paper. Thus for the case of two-hop network specified in IEEE 802.16j, we express the capacity of the proposed CDMRA system as

$$C = \sum_{j=1}^{K} E_{\mathbf{H}_j,\mathbf{G}_j}\left[\log_2\left\{\det\left[\mathbf{I}_N + \frac{\alpha^2}{\sigma_{n_D}^2}\frac{P}{N}(\mathbf{H}_j\mathbf{G}_j)(\mathbf{H}_j\mathbf{G}_j)^H\right]\right\}\right] \tag{12}$$

where $\sigma_{n_D}^2 = \sigma^2(1+\alpha^2 N)$, σ^2 is the power of the AWGN noise generated at each hop. Using eigen-value decomposition of the matrices $\mathbf{H}_j\mathbf{H}_j^H$ and $\mathbf{G}_j\mathbf{G}_j^H$, Eq. (12) can be written as

$$C = \sum_{j=1}^{K}\sum_{i=1}^{N} E_{\lambda_i^j,\beta_i^j}\left[\log_2\left(1+\rho\lambda_i^j\beta_i^j\right)\right] \tag{13}$$

where $\{\lambda_1^j, \lambda_2^j, \cdots, \lambda_N^j\}$ and $\{\beta_1^j, \beta_2^j, \cdots, \beta_N^j\}$ are the eigen-values of the matrices $\mathbf{H}_j\mathbf{H}_j^H$ and $\mathbf{G}_j\mathbf{G}_j^H$ respectively, and $\rho = \frac{\alpha^2}{\sigma^2(1+\alpha^2 N)}\frac{P}{N}$. Eq (13) can also be expressed as

$$C = \sum_{j=1}^{K} N\, E_{\lambda^j,\beta^j}\left[\log_2\left(1+\rho\lambda^j\beta^j\right)\right] \tag{14}$$

where λ^j, β^j, $j = 1, \cdots, K$, are the randomly chosen eigen values from the eigen-value set $\{\lambda_1^j, \cdots, \lambda_N^j\}$ and $\{\beta_1^j, \cdots, \beta_N^j\}$ of the matrices $\mathbf{H}_j\mathbf{H}_j^H$ and $\mathbf{G}_j\mathbf{G}_j^H$ respectively.

If we assume that $\mathbf{H}_j$ and $\mathbf{G}_j$ are iid, $j = 1, \cdots, K$, then K-fold capacity increase is achieved in the proposed relay multiplexing scheme, providing tremendous capacity boost compared to the relay diversity methods [2-5].

After substituting the pdf of λ^j, β^j, $j = 1, \cdots, K$, the final closed-form result for Eq (14) is obtained as:

$$\begin{aligned}
C \approx & \sum_{j=1}^{K}\sum_{q_{0j}=0}^{N-1}\sum_{l_1^0=0}^{q_{0j}}\sum_{l_2^0=0}^{q_{0j}} (-1)^{l_1^0+l_2^0} A_{l_1^0}(q_{0j}) A_{l_2^0}(q_{0j}) (l_1^0+l_2^0)! \\
& \cdot\left\{\ln(\rho)\cdot\left(\frac{1}{N}\sum_{q_{1j}=0}^{N-1}\sum_{l_1^1=0}^{q_{1j}}\sum_{l_2^1=0}^{q_{1j}}(-1)^{l_1^1+l_2^1} A_{l_1^1}(q_{1j}) A_{l_2^1}(q_{1j})\left(l_1^1+l_2^1\right)!\right)\right. \\
& +\left(\frac{1}{N}\sum_{q_{1j}=0}^{N-1}\sum_{l_1^1=0}^{q_{1j}}\sum_{l_2^1=0}^{q_{1j}}(-1)^{l_1^1+l_2^1} A_{l_1^1}(q_{1j}) A_{l_2^1}(q_{1j})\left(\sum_{\mu=0}^{(l_1^1+l_2^1-1)}\frac{(l_1^1+l_2^1)!}{(l_1^1+l_2^1-\mu)} - (l_1^1+l_2^1)!\,b\right)\right) \\
& +(-b)\cdot\left(\frac{1}{N}\sum_{q_{1j}=0}^{N-1}\sum_{l_1^1=0}^{q_{1j}}\sum_{l_2^1=0}^{q_{1j}}(-1)^{l_1^1+l_2^1} A_{l_1^1}(q_{1j}) A_{l_2^1}(q_{1j})\left(l_1^1+l_2^1\right)!\right) \\
& \left.+\sum_{\mu=1}^{l_1^0+l_2^0}\frac{1}{\mu}\cdot\left(\frac{1}{N}\sum_{q_{1j}=0}^{N-1}\sum_{l_1^1=0}^{q_{1j}}\sum_{l_2^1=0}^{q_{1j}}(-1)^{l_1^1+l_2^1} A_{l_1^1}(q_{1j}) A_{l_2^1}(q_{1j})\left(l_1^1+l_2^1\right)!\right)\right\}
\end{aligned} \tag{15}$$

Effect of Amplifier Gain at Relays: Asymptotically in high-SNR regime, the capacity of the CDMRA system can be approximated, for iid assumption of $\mathbf{H}_j$ and $\mathbf{G}_j$, as

$$\begin{aligned}
C \approx & \sum_{j=1}^{K} E_{\mathbf{H}_j}\left[\log_2\left\{\det\left[\rho_0\mathbf{H}_j\mathbf{H}_j^H\right]\right\}\right] + KN\log_2(\rho_1) \\
& + \sum_{j=1}^{K} E_{\mathbf{G}_j}\left[\log_2\left\{\det\left[\mathbf{G}_j\mathbf{G}_j^H\right]\right\}\right] \\
= & \underbrace{E_{\mathbf{H}_1}\left[\log_2\left\{\det\left[\rho_0\mathbf{H}_1\mathbf{H}_1^H\right]\right\}\right]}_{\text{1-hop capacity}} + \underbrace{N\log_2(\rho_1) + E_{\mathbf{G}_1}\left[\log_2\left\{\det\left[\mathbf{G}_1\mathbf{G}_1^H\right]\right\}\right]}_{\text{capacity loss due to two-hop transmission in first relay path}} \\
& + \underbrace{\sum_{j=2}^{K} E_{\mathbf{H}_j}\left[\log_2\left\{\det\left[\rho_0\mathbf{H}_j\mathbf{H}_j^H\right]\right\}\right]}_{\text{capacity boost due to relay multiplexing gain}} \\
& + \underbrace{(K-1)N\log_2(\rho_1) + \sum_{j=2}^{K} E_{\mathbf{G}_j}\left[\log_2\left\{\det\left[\mathbf{G}_j\mathbf{G}_j^H\right]\right\}\right]}_{\text{loss due to two-hop transmission in (K-1) relay paths}}
\end{aligned} \tag{16}$$

where $\rho_0 = P/N\sigma^2$, and $\rho_1 = \alpha^2/(1+\alpha^2 N)$. Thus, it can be observed that for fixed N, the overall capacity enhancement at certain SNR in the proposed relay multiplexing depends on: (i) the number of parallel relays K, possible in the system, (ii) the amplifier gain α at the relays. From Eq. (16), it is clear that C grows linearly with K (as observed earlier in Eq. (14)), since the third term of Eq. (16) which represents the capacity boost due to relay multiplexing, is linearly proportional to K in iid case, and this term is much higher than the last term of the equation, which represents capacity loss as the multiplexed data traverse the second hop. For establishing the relationship between C and α, we write the asymptotic form of Eq. (16) and divide through by K to obtain the capacity per relay path, C_k, as

$$C_K = N\log_2(\rho_0) + N\log_2(\rho_1) \tag{17}$$

It is clear from Eq. (17) that C_k, has convex relationship with the amplifier gain α at the relays. An economically optimum value of α for this system can thus be obtained by observing the plot of C_k versus α using Eq. (17).

4. SIMULATION RESULTS

This section presents the simulation results for various cases discussed in section 3. The modulation scheme used in the simulations is 4-QAM signal, and all the links experience flat Rayleigh fading. Also, 2x2 MIMO antennas are assumed in all cases, except where otherwise stated. Fig. 3 presents the simulation result for the bit error rate (BER) performance of the relay diversity system in section 3.1, where STBC is employed at the RS. It is first observed from the results that two-hop communication with AF relaying and no encoding at RS has a degraded BER performance compared to an equivalent 1-hop transmission. However with STBC at the RS, a two-hop communication with BER similar to its equivalent 1-hop transmission can be achieved

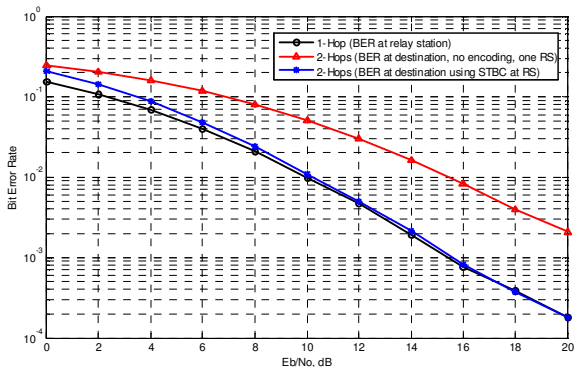

Figure 3. BER for 4-QAM 2x2 two-hop MIMO system with STBC at RSs

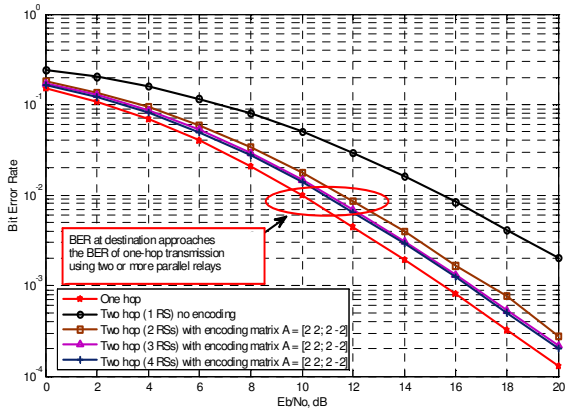

Figure 4. BER for 4-QAM 2x2 two-hop MIMO relay multiplexing (2, 3 and 4 parallel RSs)

(i.e. the BER performance is as if the MS is located at the relays).

Fig 4 presents the simulation results for the BER performance of the relay diversity system in section 3.2, where Hadamard pre-coding matrix **A** is employed at the RS. It is observed from the figure that using Hadamard pre-coding matrix or its multiples at the RS improves the bit error rate compared to the case of no coding. Also, comparing this figure with Fig 3, it is observed that AF relaying (with two RS) employing Hadamard pre-coding matrix has BER performance close to a DF relaying (with two RS) employing STBC. This is an important result for the AF relaying protocol since DF relaying introduces extra complexity and more importantly delay, which degrades quality in broadband transmission. It is also observed from Fig 4 that using three or more RS only slightly improves the BER performance compared to the case of two RSs. Thus two RS around a BS per sector specified in IEEE 802.16j can be considered optimum in terms of cost and performance. Fig 5 presents the summary of the capacity analysis of the proposed relay multiplexing system in comparison with various relay diversity schemes discussed. From this figure, it is observed that the proposed scheme provides capacity boost that grows linearly with the number of relays. This level of capacity enhancement is not readily achievable in the relay diversity methods. Finally in Fig 6 we illustrate the optimization of amplifier gains at relays, for maximizing capacity in the proposed scheme (at *SNR*=20dB). It is observed from the figure that an economically optimum value of the amplifier gain α , at RS, exist after which increasing α further provides only

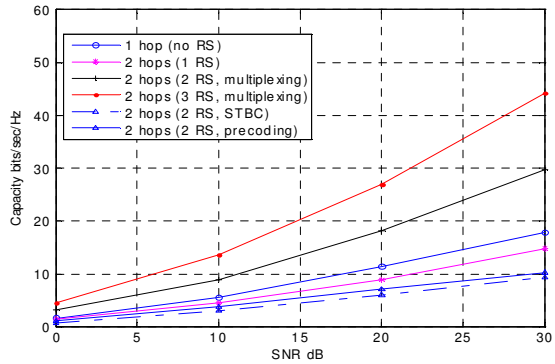

Figure 5. Capacity enhancements using relay multiplexing

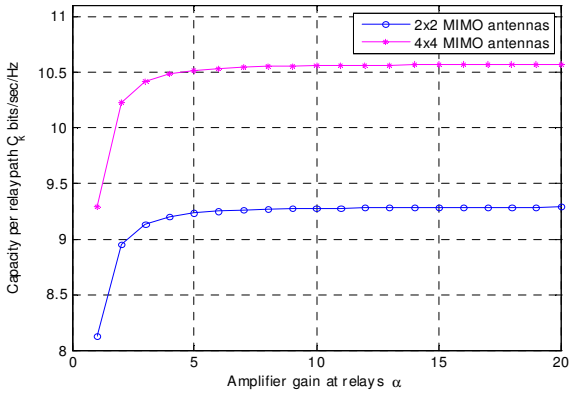

Figure 6. Optimizing amplifier gains at RS for high capacity

marginal extra capacity enhancement in AF relaying system, because of noise enhancements. An economically optimum value of α for the cases in this figure is roughly $\alpha = 5$.

5. CONCLUSIONS

This paper proposes MIMO relay multiplexing systems where RSs are assigned access codes for parallel relaying of independent data streams from source to destination. The capacity of the proposed scheme grows linearly with the number of relays, and well surpasses the capacity of the relay diversity methods. Economically optimum amplifier gains at the RS are also illustrated for the proposed scheme. This study provides valuable insights for relay configuration deployments in IEEE 802.16j.

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