Asynchronous Cooperative MIMO Communication and Capacity Analysis

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I. Introduction

In wireless environment the fading effects and channel variation often degrade signal transmission and increase bit error rate. Diversity techniques have been widely used to suppress channel variation. MIMO (multi-input multi-output) systems are proposed to employ multiple transmitting and receiving antennas for signal transmission. The bit error rate decreases due to the diversity gain and the increase in degree of freedom for signal detection. The capacity of MIMO system is discussed in [1]. However, MIMO systems require multiple antennas equipped in each device. To achieve spatial diversity without multiple-antenna equipments, cooperative network has been proposed to achieve virtual MIMO systems with single antenna devices [2]–[10].

In cooperative networks, the transmitting nodes use neighbor nodes as relays to obtain spatial diversity gain. Different cooperative schemes and performance evaluation are discussed in previous literature. An overview of cooperative transmission systems is given in [8] and an evaluation on several cooperative methods is also provided. The general conclusion is that the required mean uplink signal-to-noise ratio (SNR) of cooperative methods is significantly less than that of non-cooperative transmission.

There has been work that goes beyond the basic methods and models. Sendonaris, Erkip and Aazhang [3] discussed the system model of a cooperation diversity system and gave a theoretic view of cooperative communication systems. They also considered the practical implementation and performance issues for code-division multiple-access (CDMA) systems [6]. Laneman et al. [5] presented several cooperative diversity protocols and discussed the outage behaviors and the robustness to fading characteristics. A. Scaglione and Y. Hong [4] considered broadcasting in wireless network and proposed the idea of opportunistic large array (OLA). In 2006, the Virtual MIMO design is presented for WiMax standard [10] and used for uplink channels in WiMAX system. It assumes the base stations (BS) have multiple antennas and the user devices have single antenna. The mobile user cooperates to other users to form virtual transmission diversity in uplink. The mobile users are synchronized to each other and transmit to the BS simultaneously.

However, most of these cooperative communication proposals require symbol-level synchronization between cooperative nodes. The lack of synchronization may result in inter-symbol interference and dispersive channels. To address asynchronous diversity, Li [11], [12] considered cooperative transmission with delay and presented joint estimation schemes for asynchronous receiving signals. However, there are several limitations. In [12] they considered a multiple sender and single multi-antenna receiver setup. In [11] an arbitrary number of relay nodes is chosen and only two nodes can communicate at each time. The receiver waits until the transmission ends and all signal copies are received, which incurs large delay penalties. Recently, Wei and Goeckel [13] proposed a novel minimum mean-square error (MMSE) receiver to combine the multiple inputs in a multi-relay channel. The joint decision feedback equalizer (DFE) includes a feed-forward filter (FFF) and fractional-spaced feedback filter (FBF). The coefficients are chosen to achieve MMSE decision at the receiver. But the multi-relay channel model assumes that the communication system is a MISO system. For distributed MIMO systems, asynchronous MIMO cooperative communication need to be further considered.

In this paper we present a scheme for asynchronous cooperative wireless networks. The system model is shown in Figure 1. Each node relays information to receiving cluster after receiving signal from source node. The received MISO signal is with delay discrepancy. For cluster-based cooperative network, the propagation delay between each node from transmitting cluster and receiver cluster would be different due to discrepancy in geographical distance. However, the discrepancy in propagation delay is upper bounded because the cluster recruiting algorithm recruits nodes within certain geographical range [14]. To detect the sending information from the MISO signal with delay discrepancy, decision feedback equalizer (DFE) is used in receiver node. The equalized signal is then quantized and represented by soft symbol. Each node in receiving cluster sends soft-decision results to the destination node. The destination node then combines the soft-decision results and detect the transmitted symbols.

This paper is organized as below: the new system is proposed in section II, followed by the simulation results, section III. The performance of proposed scheme and comparison with direct transmission, 2-by-2 MIMO, and 3-by-3 MIMO system are also shown. The theoretical model of capacity ratio and the extended model for heterogeneous network are discussed in section IV. Finally, conclusions are presented in Section V.

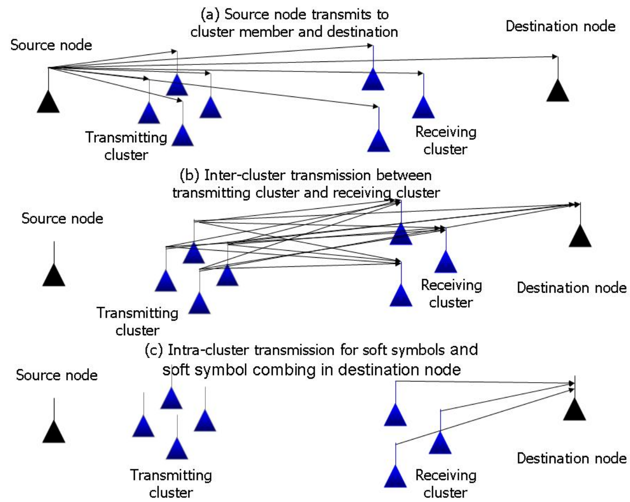

Fig. 1. Proposed cooperative scheme: (a) neighbor nodes recruiting to form clusters. (b)Inter-cluster transmission. (c) Relaying copies to destination node and soft symbol combining

II. System Model

Our cooperative diversity design is illustrated in Figure 1. Before transmission begins, both source node and destination node recruit neighbor nodes and form the transmitting and receiving cluster, respectively. The source node and destination node are automatically regarded as the master nodes in their own clusters. The source node then transmits information to its cluster members and destination. Then the nodes in transmitting cluster relay their signals asynchronously to receiving cluster, as shown in Figure 1 (b). Note that there is a limit to the degree of asynchrony tolerated and the channels are assumed to be quasi-static and flat fading. When the receiving cluster nodes obtain the signals, they use the decision feedback equalizer (DFE) to equalizer the MISO signal and perform soft-decision decoding rather than the hard-decision decoding. Thus, each member will send its soft decisions to the destination node. The destination node combines these soft symbols along with its soft-symbol to achieve the cooperative MIMO diversity, as shown in Figure 1 (c).

The receiver structure is shown in Figure 2. For each node in the receiving cluster, it receives MISO signal from transmitting cluster. For node m in receiving cluster, the received signal $y_{rm}(t)$ is first filtered by match filter $h(t)$. The analog waveform output of match filter is then sampled to discrete-time signal. The sampling rate is set as n times of the original data rate so the equalizer can appropriately correct the delay discrepancy. The discrete signal is processed by decision feedback equalizer (DFE) and then down-sampled by n. After down-sampling, the signal is quantized to soft symbols. The soft-symbol output is sent to the master node in receiving cluster, which is the destination node. The destination node combines soft-symbol results with its own copy and detects the transmitted information.

The members of receiving cluster receive MISO signal from nodes in transmitting cluster. The channel is assumed quasi-static fading with AWGN noise and the transmitted symbols are assumed equiprobable BPSK symbols. The destination node receives soft-symbol sequences $y_1, y_2, \cdots, y_M$ from its cluster members $1, 2, \cdots, M$. The links between transmitting cluster members and receiving cluster members are assumed independent. Thus the log likelihood is

$$log\frac{P(y_1, y_2, \cdots, y_M|d_k = 1)}{P(y_1, y_2, \cdots, y_M|d_k = -1)} = log\frac{P(y_1|d_k = 1)}{P(y_1|d_k = -1)} + \cdots + log\frac{P(y_M|d_k = 1)}{P(y_M|d_k = -1)}$$

But the log likelihood of each MISO signal sequence $L_1, L_2, \cdots, L_M$, are quantized to soft-symbol $\hat{L_1}, \hat{L_2}, \cdots, \hat{L_M}$. Thus the estimated likelihood in destination node for kth data bit is

$$L(\hat{d_k}) = \hat{L_1} + \hat{L_2} + \cdots + \hat{L_M} = \hat{L_{1q}} \cdot q_1 + \hat{L_{2q}} \cdot q_2 + \cdots + \hat{L_{Mq}} \cdot q_M$$

And $q_1, q_2, \cdots, q_M$ is the representation of corresponding quantization level and $L_{1q}, L_{2q}, \cdots, L_{Mq}$ are the quantized likelihood represented by soft symbols.

III. Simulation Results

We consider a network with 64 random distributed users. They are distributed within a 1000 by 1000 meter square. The carrier frequency is assumed as 2.4G Hz and data rate is 5.5 Mbits/sec. The data is BPSK modulated. The BPSK symbols are then filtered by square root raised cosine (SRRC) transmitting filter and transmitted to the receiving cluster. The wireless

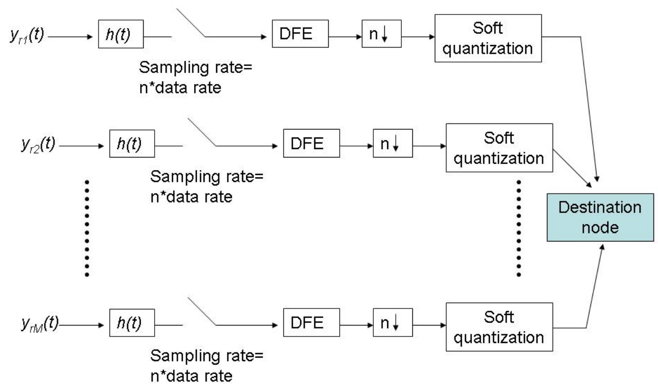

Fig. 2. Signals in each destination cluster member are processed by match filter and DFE before soft symbol quantization. The quantized soft symbols are sent to destination node.

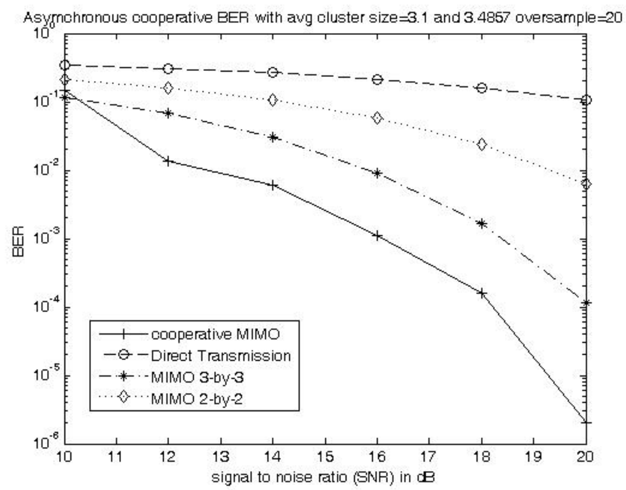

Fig. 3. BER performance comparison of proposed system with typical MIMO systems and direct transmission (Note: over-sampling rate=20, average cluster size is 3.1 for transmitting cluster and 3.49 for receiving cluster respectively.)

channels are assumed to be quasi-static flat fading and independent. The cooperative cluster recruits nodes nearby, which can response the cluster recruiting message within one symbol time. Therefore, the cluster radius is 27.27 m. In each receiving node, a corresponding SRRC match filter and a decision feedback equalizer (DFE) with least mean square (LMS) adaptive algorithm are used. The forward filter has 3 complex weight taps and the feedback filter has 2 complex weight taps.

The bit error rate performance of proposed system and comparison with MIMO systems is illustrated in Figure 3. The signal transmission energy in each user is the same. The performance of direct transmission from source node to destination node is worst due to large path loss and fading effect. The 2-by-2 MIMO system transmits signals by $1/2$ signal energy in each transmitting antenna and obtains better performance because the increase in diversity gain and degree of freedom suppress performance degradation from fading. The degree of freedom and diversity gain increases when the number of transmitting and receiving antennas increases, which explains the improvement for 3-by-3 MIMO system.

From Figure 3, it is obvious the errors caused by asynchrony are corrected by DFE. The average transmitting cluster size in our system is 3.1 and 3.49 for receiving cluster, respectively. The performance of bit error rate in proposed system is better than 3-by-3 MIMO system due to larger cluster size and larger diversity gain. In low SNR scenario, each link suffers from noise power and the performance of proposed system is close to 2-by-2 and 3-by-3 MIMO systems. As SNR increases, the effect of diversity gain and degree of freedom dominate the performance. The differential between proposed system and 3-by-3 MIMO system is increased due to larger diversity gain.

The performance of equalizer also depends on the over-sampling factor. When the over-sampling factor is larger, the decision

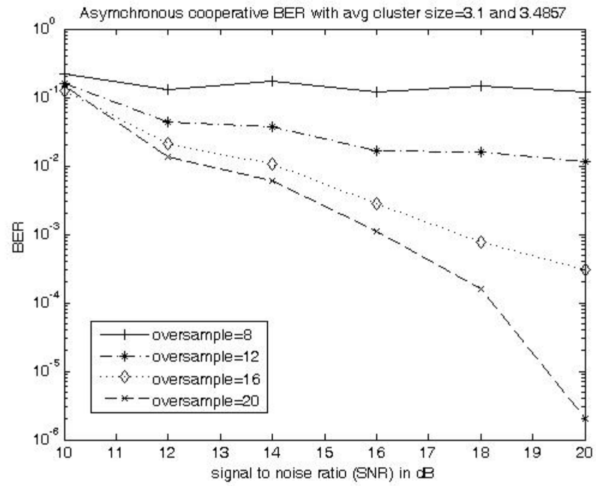

Fig. 4. BER performance with different oversampling rate

feedback equalizer (DFE) at each receiving cluster member can catch the delay discrepancy well and recover the asynchronous MISO signal as synchronous copies. If the over-sampling factor is small, the DFE can not catch delay discrepancy because the delay discrepancy is much smaller than the sampling time interval for each tap in DFE equalizer. DFE seems not to improve the performance. However, larger over-sampling factor results in large amount of sampled data and longer processing time. The trade-off in bit error rate (BER) and processing complexity is illustrated in Figure 4.

IV. Capacity Ratio of Cooperative Transmission

From simulation result, the performance of proposed cooperative MIMO scheme is close to MIMO system with corresponding number of antennas. However, cooperative MIMO scheme needs to deal with intra-cluster transmission in both source cluster and destination cluster. Although cooperative MIMO scheme provides spatial diversity, the transmission capacity decreases due to node cooperation.

In this section we consider the capacity in proposed cooperative MIMO system. We begin with a simple model. The system assumptions are as follows:

1) Only one transmitting cluster and one receiving cluster. Assume no interference and opportunity cost.
2) The size of transmitting cluster is $M+1$ and the size of receiving cluster is $N+1$ (including the source node and destination node).
3) The channel bandwidth is W and each node in transmitting cluster transmits with power $P/(M+1)$.
4) The channel are AWGN channels with noise PSD $N_0/2$ and is assumed quasi-static fading.
5) Signals degrade due to pathloss. The pathloss constant α is usually between 2 and 4.
6) The distance and the fading gain between node i and node j is denoted as d_{ij} and λ_{ij}, respectively.
7) The radius in cluster recruiting algorithm is r and the number of quantization levels for soft symbol is 2^Q, which means each soft-symbol is represented by Q bits.

The system transmits K bits. The cooperative transmission contains three parts: broadcasting, inter-cluster transmission, intra-cluster transmission in destination cluster.

A. Phase I: Broadcasting

The first phase is broadcasting, as shown in Figure 1 (a). The source node sends information to its cluster member and destination cluster. The intra-cluster transmission in source cluster can be approximated as SIMO channel model since the source node broadcasts information to all of its cluster members.

By using SIMO channel model approximation [15], the channel capacity for the first phase is

$$
\begin{aligned}
C_1 &= Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M}\frac{\lambda_i^2}{d_{Si}^{\alpha}}), i=1,2,\cdots,M \\
&\geq Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M}\frac{\lambda_i^2}{r^{\alpha}})
\end{aligned}
$$

and the time required to finish the first phase is

$$t_1 = \frac{K}{C_1} \leq \frac{K}{Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M} \frac{\lambda_i^2}{r^\alpha})} \tag{1}$$

B. Phase II: Inter-Cluster Transmission

In second phase, all members of transmitting cluster relay information to the destination cluster. Each channel is assumed to be independent. For each receiver node j, the channel is MISO channel and the channel capacity is

$$\begin{aligned} C_{2j} &= Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M+1} \frac{\lambda_{ij}^2}{d_{ij}^\alpha}) \\ &\geq Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M+1} \frac{\lambda_{ij}^2}{(d_{SD} + 2r)^\alpha}) \end{aligned}$$

The capacity for Phase II is $C_2 = \sum_{j=1}^{N+1} C_{2j}$. Thus the time required to transmit K bits in the second phase is

$$t_2 = \frac{K}{C_2} \leq \frac{K}{\sum_{j=1}^{N+1} Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M+1} \frac{\lambda_{ij}^2}{(d_{SD}+2r)^\alpha})} \tag{2}$$

C. Phase III: Intra-cluster Transmission to Destination

In this phase, each member in receiving cluster makes soft-symbol decision and sends soft symbols to destination node. For K bits information, each receiving cluster member will make soft-symbol decision and transmit KQ bits to the destination node. The destination node will wait until receiving all information, and then combine the soft symbols to make hard decision. We assume each node uses power P/N for intra cluster transmission. For each cluster member j, the channel capacity is

$$C_{3j} = Wlog(1 + \frac{P\lambda_{jD}^2}{NN_0 W d_{jD}^\alpha})$$

Thus the time required to finish the third phase will be

$$t_3 = \sum_{j=1}^{N} t_{3j} = \frac{KQ}{W}(\sum_{j=1}^{N} \frac{1}{log(1 + \frac{P\lambda_{jD}^2}{NN_0 W d_{jD}^\alpha})}) \tag{3}$$

Therefore, to transmit K bits by cooperative MIMO scheme, the total transmission time T is

$$\begin{aligned} T &= t_1 + t_2 + t_3 \\ &\leq \frac{K}{Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M} \frac{\lambda_i^2}{r^\alpha})} + \frac{K}{\sum_{j=1}^{N+1} Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M+1} \frac{\lambda_{ij}^2}{(d_{SD}+2r)^\alpha})} + \frac{KQ}{W}(\sum_{j=1}^{N} \frac{1}{log(1 + \frac{P\lambda_{jD}^2}{NN_0 W d_{jD}^\alpha})}) \end{aligned}$$

The actual capacity for cooperative MIMO scheme will be K/T since the systems require no longer than time T to complete the transmission for K bits. Thus the capacity is

$$\begin{aligned} C_{coop} &= \frac{K}{T} \\ &\geq W/(\frac{K}{Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M} \frac{\lambda_i^2}{r^\alpha})} + \frac{K}{\sum_{j=1}^{N+1} Wlog(1 + \frac{P}{N_0 W(M+1)} \sum_{i=1}^{M+1} \frac{\lambda_{ij}^2}{(d_{SD}+2r)^\alpha})} \\ &\quad + \frac{KQ}{W}(\sum_{j=1}^{N} \frac{1}{log(1 + \frac{P\lambda_{jD}^2}{NN_0 W d_{jD}^\alpha})})) \end{aligned} \tag{4}$$

And the capacity of direct transmission with channel gain λ will be

$$C_{direct} = Wlog(1 + \frac{P\lambda^2}{N_0 W d_{SD}^\alpha}) \tag{5}$$

Comparing equation 4 and 5, we can estimate the capacity ratio as

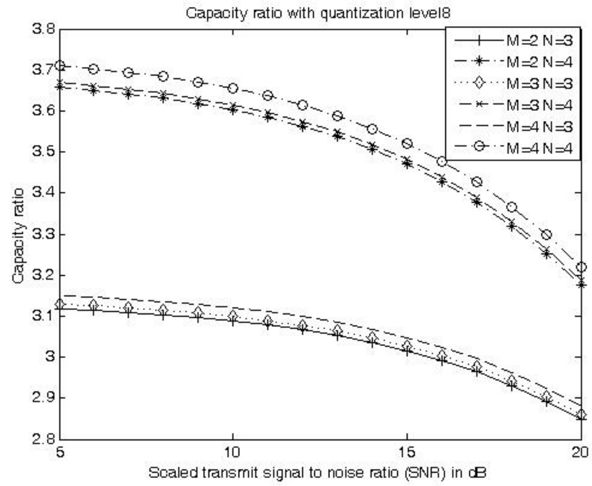

Fig. 5. Capacity ratio of different transmitting/receiving cluster size with scaled SNR. (Note: scaled SNR is defined as P_T/r^α, r is cluster radius and P_T is transmission power)

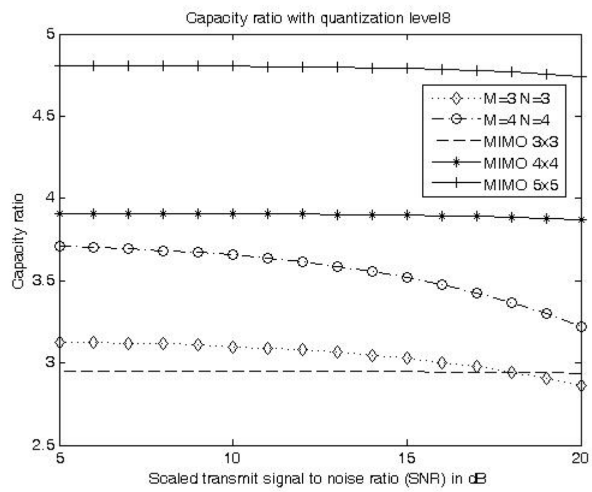

Fig. 6. Capacity ratio compared to conventional MIMO system with scaled SNR (Note: scaled SNR is defined as P_T/r^α, r is cluster radius and P_T is transmission power)

$$\frac{C_{coop}}{C_{DT}} = 1/(\frac{log(1+\frac{P\lambda^2}{N_0 W d_{SD}^\alpha})}{log(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M} \frac{\lambda_i^2}{r^\alpha})} + \frac{log(1+\frac{P\lambda^2}{N_0Wd_{SD}^\alpha})}{\sum_{j=1}^{N+1} log(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M+1}\frac{\lambda_{ij}^2}{(d_{SD}+2r)^\alpha})} + \sum_{j=1}^{N} \frac{Qlog(1+\frac{P\lambda^2}{N_0Wd_{SD}^\alpha})}{log(1+\frac{P\lambda_{jD^2}}{NN_0Wd_{jD}^\alpha})}) \qquad (6)$$

The capacity ratio and the comparison to conventional MIMO are shown in Figure 5, 6 and 7. In Figure 5 the capacity radio is affected by SNR because the node negotiation and cooperation in cooperative MIMO system sacrifices system capacity. When the channel quality is improved as SNR increases, the effect of node cooperation dominates and reduces the capacity ratio. The capacity ratio is also compared to the capacity ratio between conventional MIMO systems and direct transmission in Figure 6. The performance degradation due to node cooperation is more significant in Figure 6

The cluster sizes affect capacity ratio. As size of cooperative cluster increases, the capacity ratio increases due to larger diversity gain. In phase II, the channel capacity is equivalent to the sum of MISO channels. When the size of transmission cluster M increases, it only provides possibly larger diversity gain for each MISO channels. The larger the receiving cluster

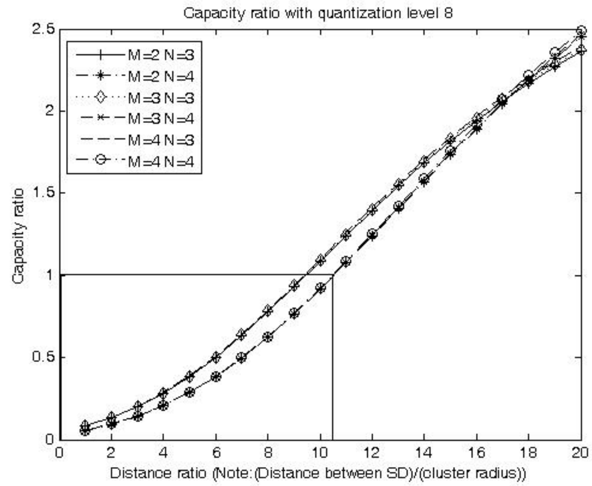

Fig. 7. Capacity ratio with distance ratio (Note: scaled SNR is defined as P_T/r^{α}, where r is cluster radius and P_T is transmission power. Distance ratio is defined as d_{SD}/r, where d_{SD} is distance between source and destination node)

size N is, the stronger capacity and larger number of MISO channels will be seen. Thus, the size of receiving cluster plays an more important role on system capacity, as shown in Fig 5.

Figure 7 shows the relation between capacity ratio and distance ratio. The X-axis in Figure 7 is defined as distance ratio , which is $\frac{d_{SD}}{r}$. The equation 6 considers path-loss, fading and spatial diversity gain provided by node cooperation. When the distance ratio is low, the short distance transmission does not have a severe path-loss effect. Hence the direct short distance transmission is more preferred than cooperative MIMO scheme. In long distance transmission, the path-loss is much higher and node cooperation to obtain spatial diversity is more desirable.

D. Capacity Ratio for Heterogeneous Network

Here it is the capacity ratio for the network that nodes may have more than one antenna that is considered. The number of antenna in node i is denoted as a_i. The source node and destination node has a_S and a_D antennas respectively. It is assumed each node transmits with power P for both inter-cluster and intra-cluster transmission. The transmission power is equally applied to each antenna in node i, which means the transmission power for each antenna in node i is P/a_i. The assumption of wireless environment and other symbol notation is the same as previous section. We consider the three-phase transmission model as presented in previous section.

In each phase the channel model becomes MIMO channel model with channel matrix H. If all channels are i.i.d Rayleigh fading and H is channel matrix with size $a_S \times \sum_{i=1}^{N} a_i$, the MIMO capacity in first phase is

$$C_1 \quad \geq \quad logdet[I_{a_S} + \frac{P}{N_0 W a_S r^{\alpha}} HH^*]$$

Using Singular Value Decomposition (SVD) with the assumption that a_S is larger than $\sum_{i=1}^{N} a_i$ and donating the singular values as λ_i, the above equation becomes

$$C_1 \quad \geq \quad \sum_{i=1}^{a_S} W log(1 + \frac{P\lambda_i^2}{N_0 W a_S r^{\alpha}})$$

Similarly, the capacity and transmission time for second phase and third phase can be obtained by applying SVD to the channel matrix in each phase. Thus, the capacity ratio is

$$\begin{aligned} \frac{C_{Coop}}{C_{DT}} \quad &= \quad 1/(\frac{\sum_{i=1}^{min(a_S,a_D)} log(1 + \frac{P\lambda_i^2}{N_0 W a_S d_{SD}^{\alpha}})}{\sum_{i=1}^{a_S} log(1 + \frac{P\lambda_i^2}{N_0 W a_S r^{\alpha}})} + \frac{\sum_{i=1}^{min(a_S,a_D)} log(1 + \frac{P\lambda_i^2}{N_0 W a_S d_{SD}^{\alpha}})}{\sum_{j=1}^{N+1} \sum_{k=1}^{a_j} log(1 + \frac{P\lambda_{j,k}^2}{N_0 W a (d_{SD}+2r)^{\alpha}})} \\ &+ \quad \sum_{j=1}^{N} \frac{Q \sum_{i=1}^{min(a_S,a_D)} log(1 + \frac{P\lambda_i^2}{N_0 W a_S d_{SD}^{\alpha}})}{\sum_{k=1}^{min(a_j,a_D)} log(1 + \frac{P\lambda_{j,k}^2}{N_0 W a_j r^{\alpha}})}) \end{aligned} \tag{7}$$

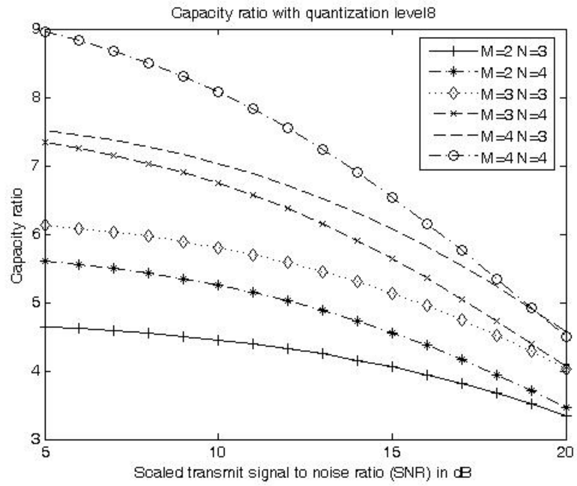

Fig. 8. Overhead ratio with scaled SNR (Note: each node has 2 antenna.)

In Figure 8 all nodes in the network have two antennas per node. The capacity ratio is much larger due to the improvement in diversity gain and degree of freedom. Multiple antennas provides MIMO transmission for all three phases of cooperative transmission and thus improves the channel capacity.

V. Conclusion

We propose a new method for asynchronous cooperative MIMO communication. The nodes in transmitting cluster relay the information after they receive information from source node. In receiver nodes, a decision feedback equalizer (DFE) is used to correct the delay discrepancy in asynchronous MISO signals. The equalized signals are then represented by soft symbols. The destination node combines soft symbols to make signal detection.

The performance of proposed system is shown and the comparison of proposed system with conventional MIMO systems is illustrated. The major performance factors, such as over sampling rate and SNR, are also discussed and shown in figures. The proposed system can precisely correct the asynchronous signals and has performance close to conventional MIMO systems. However, the over sampling rate must be large enough to achieve such performance. We also analyze capacity ratio for proposed system and extend the analysis to heterogeneous network. On one hand, the cooperative system has a larger capacity than does direct transmission. On the other hand, the capacity is smaller than that of conventional MIMO due to node cooperation.

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