Asynchronous Cooperative MIMO Communication

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***Abstract*— We consider a cluster-based cooperative transmission scheme where the source node and destination node form clusters for transmission. Instead of using perfect synchronization technique, we assume the cooperative transmission is asynchronous. Each member in transmitting cluster relays signal to the receiving cluster after obtaining information from source node. A general decision feedback equalizer (DFE) is used in the receiving cluster members to equalize the received MISO signal and detect as soft symbols. The receiving cluster members send the soft-decision outputs to the destination node. Thus, the decision node combines the soft-decision outputs and makes hard-decision detection for the transmitted information.**

The performance of proposed system is shown and compared with conventional MIMO system. Major factors for system performance is discussed. The over-sampling rate plays an important role in system performance. We also present a simple capacity analysis for proposed cooperative transmission system. The capacity ratio between cooperative MIMO system and direct transmission (SISO) system is also presented and compared to the capacity ratio of conventional MIMO system and direct transmission (SISO) system. We also extend the analysis to heterogeneous network and show the capacity ratio.

I. INTRODUCTION

In wireless environments the fading effects and channel variation often degrade signal transmission and increases bit error rate. Diversity techniques have been widely used for suppressing channel variation in wireless channels. The diversity can be achieved in network layer, link layer, or physical layer. In link layer and network layer, opportunistic routing and other designs, such as network coding [1] and ExOR [2] are proposed to achieve diversity. In physical layer, MIMO (multi-input multi-output) systems are proposed to use multiple transmitting and receiving antennas for signal transmission. If fading effect degrades the performance in one of the wireless links, MIMO system can use receiving signals from other links to detect the transmitted signal. Thus 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 [3]. However, MIMO systems require multiple antennas equipped in each device, which may not be feasible in some wireless communication device because of the cost and size limitations. To achieve diversity in physical layer without multiple antennas, cooperative network has been proposed to achieve virtual MIMO systems with single antenna devices. [4]–[14]

In cooperative networks, the transmitting nodes use idle nodes as relays to reduce the adverse effect of multi-path fading in wireless channels. Different cooperative schemes and performance evaluation are discussed. An overview of cooperative transmission systems is given in [10] and the performance of several cooperation methods such as amplify-and-forward cooperation, decode-and-froward cooperation, and coded cooperation are evaluated. The conclusion is that the required mean uplink signal-to-noise ratio (SNR) with cooperative methods is significantly less than that of non-cooperative transmission. There have been efforts that go beyond the basic methods and models. For example, Stefanov and Erkip [15] consider cooperation of two users with different channel qualities and under both symmetric and asymmetric channels. Sendonaris, Erkip and Aazhang [5], [8] discuss the system model of a cooperation diversity system and give a theoretic view of cooperative communication systems. They also consider the practical implementation and performance issues for code-division multiple-access (CDMA) systems.

Laneman et al. [7] present several cooperative diversity protocols, which includes fixed relaying, selection relaying, and incremental relaying schemes, and elucidate the outage behaviors and the robustness to fading characteristics. A. Scaglione and Y. Hong [6] elaborate broadcasting in wireless network and provide the idea of opportunistic large array (OLA). The idea of using space-time coding in cooperative networks is also explored in [4]: all relay nodes transmit space-time coded symbols to the destination node at the same time, i.e. synchronously. Kojima et al. [13] also take synchronous space-time coding into account, and present a distributed ARQ protocol for OFDM-based Ad-hoc networks. Cooperative space-time block coding (STBC) is used when each node relays to packet to the destination.

However, most of these cooperative communication proposals require symbol-level synchronization between cooperative nodes, but it is hard to achieve even in an infrastructure mesh involving managed base-stations. The lack of synchronization may result in inter-symbol interference and dispersive channels.

To address asynchronous diversity, Li [17], [18] thinks of cooperative transmission with delay and contributes joint estimation schemes for asynchronous receiving signals.However, there are several limitations among these approaches. In [18] they allow up to two asynchronous senders using the Alamouti space-time code and assume that the single receiver node has multiple antennas. The multiple receiving antennas are used to obtain copies of signals to facilitate joint decoding. However, only two transmitting antennas are allowed (due to the limitations of the Alamouti scheme) and there is no receive cluster (i.e. it is a multiple sender, single multi-antenna receiver setup).

In [17] the authors do not require multiple receive antennas, but instead choose an arbitrary number of relay nodes. At each time, only two nodes (one sender and one receiver) can communicate, assisted by the relays. The receiver waits until the transmission ends and all signal copies are received (for a period depending upon the number of relays) and uses joint decoding/equalization for signal estimation. This setup (developed in the sensor network context) will not be favorable for a number of concurrent network transmissions in infrastructure mesh networks, and will incur large delay penalties.

Recently, Wei and Goeckel [19] regard the asynchronous transmission as an equalization problem. The system model is a multi-relay channel and they propose a novel minimum mean-square error (MMSE) receiver to combine the multiple inputs in this 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 needs to be further considered.

In this paper we consider a general scenario with multiple senders, multiple receivers and a single antenna per-receiver, allowing for the possibility of higher cooperative gain. There is no theoretical limit on the number of transmitting or receiving nodes. We present a new scheme for asynchronous cooperative wireless networks. The system model is shown in Figure 1 and 2. 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 nodes 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 [20]. The assumption of bounded delay discrepancy is reasonable.

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.

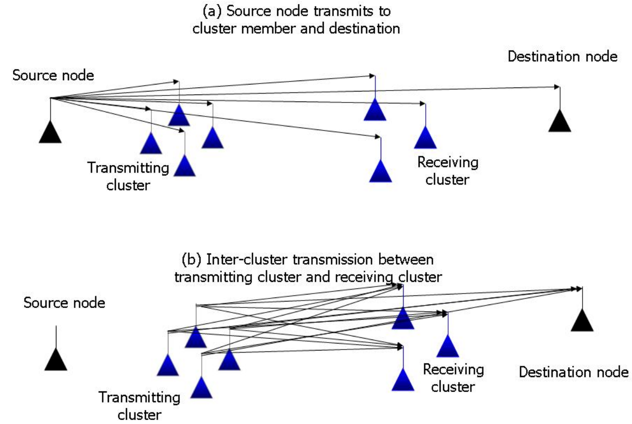

Fig. 1. Proposed cooperative scheme: (a) neighbor nodes recruiting to form clusters. (b)Inter-cluster transmission.

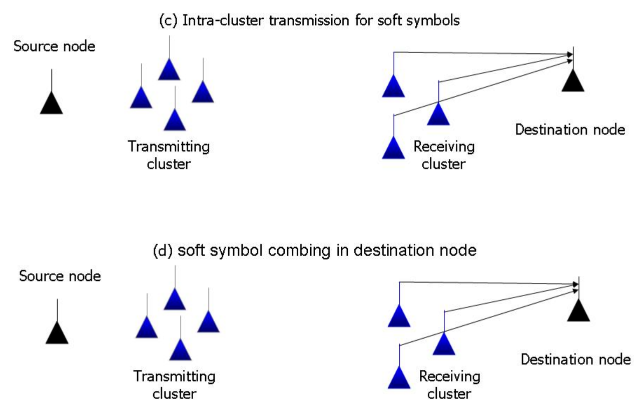

Fig. 2. Proposed cooperative scheme: (c) Relaying copies to destination node. (d) soft symbol combining

II. System Model

Our cooperative diversity design is illustrated in Figure 1 and 2. When the source node wants to transmit information to the destination node, 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 the master nodes in their respective 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. 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 equalize

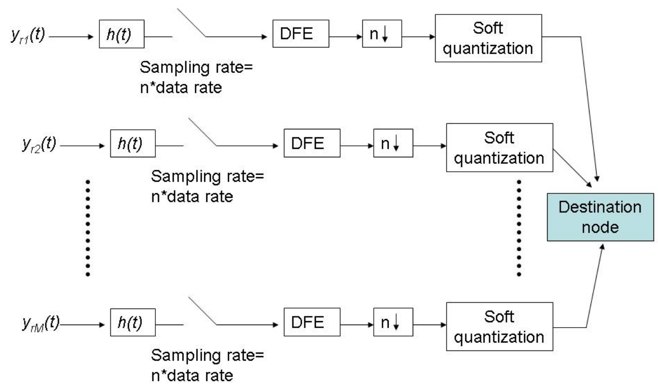

Fig. 3. Signals in each destination cluster member are processed by match filter and DFE before soft symbol quantization. The quantized soft symbols are sent to destination node.

the MISO signal and perform soft-decision decoding rather than the hard-decision decoding. Then, each member will send their soft decisions to the destination node. The destination node then combines these soft decisions (along with its soft-symbol) using a MLE combiner to achieve the cooperative MIMO diversity, as shown in Figure 2.

The receiver structure is shown in Figure 3. 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 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 result 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 flat fading with additive white Gaussian 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 $1, 2, \cdots, M$. To detect the BPSK symbol, the maximum aposterior (MAP) detection rule is

$$max P(d_k|\mathbf{y}) = max \frac{P(\mathbf{y}|d_k)P(d_k)}{P(\mathbf{y})}$$

The BPSK symbol is detect as 1 if

$$\frac{P(\mathbf{y}|d_k = 1)P(d_k = 1)}{P(\mathbf{y})} > \frac{P(\mathbf{y}|d_k = -1)P(d_k = -1)}{P(\mathbf{y})}$$

Assume the BPSK symbol is equiprobable and express above equation as log likelihood. The equation becomes

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

$y_1, y_2, \cdots, y_M$ is the MISO signal sequence from each receiving cluster member respectively. The links between transmitting cluster members and receiving cluster members are assumed independent. Thus the log likelihood is

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

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

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

which is the sum of the likelihood ratio for each MISO signal sequence. 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 is

$$L(\hat{d_k}) = L_1 + L_2 + \cdots + L_M \tag{1}$$

$$= \hat{L_1}q \cdot q_1 + \hat{L_2}q \cdot q_2 + \cdots + \hat{L_M}q \cdot q_M \tag{2}$$

And $q_1, q_2, \cdots, q_M$ is the representation of corresponding quantization level.

For each receiving cluster member, it receives MISO signal and use decision feedback equalizer (DFE) to eliminate the effect due to delay discrepancy. The equalized signal is used to compute the likelihood ratio $L_1, L_2, \cdots, L_M$. Assume the received MISO signal is x_k and noise is AWGN noise. The log likelihood is

$$L_c(x_k) = log[\frac{P(x_k|d_k = 1)}{P(x_k|d_k = -1)}]$$

$$= log \frac{\frac{1}{\sqrt{2\pi\sigma^2}} exp(-\frac{(x_k-\mu_k)^2}{2\sigma^2})}{\frac{1}{\sqrt{2\pi\sigma^2}} exp(-\frac{(x_k+\mu_k)^2}{2\sigma^2})}$$

$$= -\frac{2x_k\mu_k}{\sigma^2} \tag{3}$$

where σ^2 is Gaussian noise energy and μ is the transmitting signal energy multiplied by path-loss, which is the receiving signal energy without fading. The transmission energy is known and the path-loss can be estimated since the distance between transmitting nodes and receiving nodes are known. Thus μ can be precisely estimated. The computation result in equation 3 is then quantized to soft symbols, L_c. The soft symbols are transmitted to the destination node. The destination node combines soft symbols from all cluster members with its own copy by equation 2. If the combined log likelihood $L(d_k)$ is larger than 0, the symbol is detected as 1.

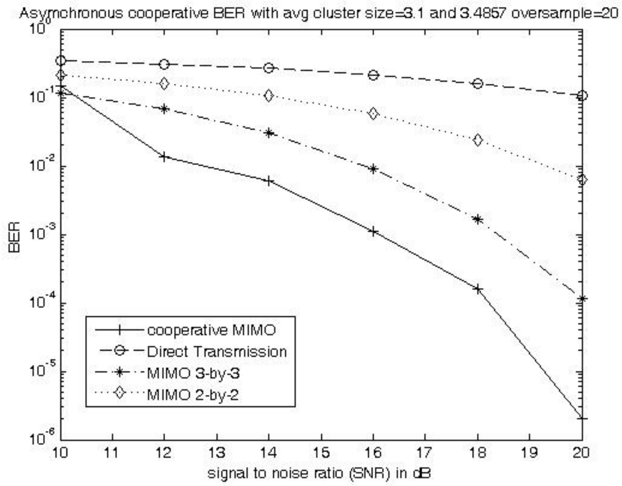

Fig. 4. BER performance comparison of proposed system with typical MIMO systems and direct transmission (Note: over-sampling rate=20, average cluster size is 3.1 for transmitting cluster and 3.49 for receiving cluster respectively.)

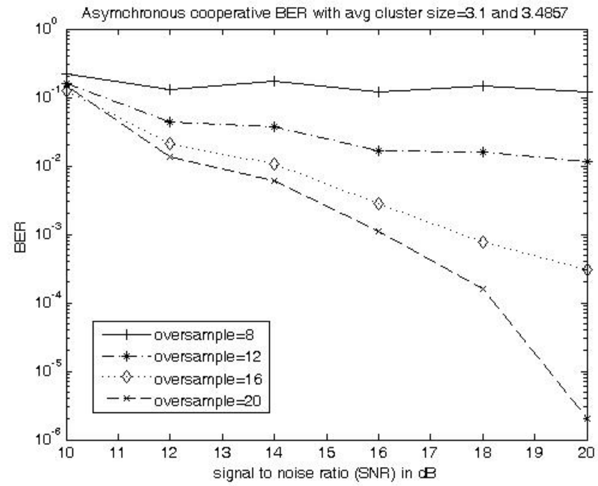

Fig. 5. BER performance with different oversampling rate

III. Simulation Results

A network with 64 random distributed users is employed. The users are distributed over the range in a 1000 meter by 1000 meter square. The 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 virtual wireless MIMO channels are assumed quasi-static flat fading and independent of each other.

The cooperative cluster recruits nearby nodes, which can response the cluster recruiting message within one symbol time. Thus the maximum distance between cluster head and cluster members is 27.27 meter, which is corresponding the transmission distance in 1/2 symbol time.

In each receiving node, a corresponding SRRC match filter is used, which is corresponding to the $h(t)$ block in Figure 3. A decision feedback equalizer (DFE) with least mean square (LMS) adaptive algorithm is used. The forward filter has 3 complex weight taps and the feedback filter has 2 complex weight taps.

The performance of proposed system and comparison with MIMO systems is illustrated in Figure 7. 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 increase when the number of transmitting and receiving antennas increases, which explains the performance improvement for 3-by-3 MIMO system.

The proposed system has average cluster size as 3.0429 for transmitting cluster and 3.2671 for receiving cluster, respectively. The performance of proposed system is close to the performance of 3-by-3 MIMO system since the sizes of cooperative clusters are near 3. But the proposed system has better performance in low SNR scenario compared to 3-by-3 MIMO. In high SNR the performance of proposed system and 3-by-3 MIMO system does not have large difference. This is because the decision feedback equalizer (DFE) corrects the delay discrepancy in MISO signals received by receiving cluster member and improves performance close to corresponding conventional MIMO systems.

The performance of equalizer also depends on the over-sampling factor. When the over-sampling factor is larger, the decision feedback equalizer (DFE) 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. The performance will be near to the performance without DFE. However, larger over-sampling factor results in large amount of sampled data and longer processing time. The trade-off in bit error rate (BER) performance and processing complexity is illustrated in Figure 5.

In Figure 5 we consider the performance with over sampling factor 8,12, 16, and 20. When the over sampling factor is 8, the decision feedback equalizer (DFE) does not catch the delay discrepancy in received MISO signal. The performance is close to the performance of direct signal detection without decision feedback equalizer (DFE). The bit error rate remains high in different SNR scenario due to the asynchronous MISO signal. The delay discrepancy dominates the performance and noise power becomes a minor factor. As the over sampling factor increases, the decision feedback equalizer (DFE) becomes effective and delay discrepancy no longer affects bit error rate. Noise power becomes the major factor of bit error rate. As SNR increases, the performance improves. When SNR is 20dB and the over sampling rate is 20, the bit error rate approaches to 0, which means perfect signal transmission.

IV. System Capacity Analysis

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 would like to consider the capacity in proposed cooperative MIMO system. We start the analysis with a simple model, where only one transmitting cluster and one receiving cluster exist. The system assumption is as follows:

1) Only one transmitting cluster and one receiving cluster. We do not consider interference and opportunity cost here.
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 is AWGN channel with power spectral density $N_0/2$ 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 between node i and node j is denoted as d_{ij}.
7) The gain of channel between node i and node j is denoted as λ_{ij}.
8) The radius in cluster recruiting algorithm is r.
9) The number of quantization levels for soft symbol is 2^Q, which means each soft-symbol is represented by Q bits.

Suppose the system transmits K bits and the cooperative transmission consists of three parts. The first phase is broadcasting, in which the source node sends information to its cluster member and the destination cluster. The second phase is inter-cluster transmission. All members of source cluster relay information to destination cluster. The third phase is intra-cluster transmission in destination cluster. Each member of destination cluster relay the soft symbols to destination node. We use the three-phase cooperative transmission and analysis channel capacity in each phase.

A. Phase I: Broadcasting

Broadcasting, as shown in Figure 1 (a), indicates that 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, the channel capacity for the first phase is

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

and the time required to finish the first phase is

$$t_1 = \frac{K}{C_1} \leq \frac{K}{Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M}\frac{\lambda_i^2}{r^{\alpha}})} \tag{4}$$

B. Phase II: Inter-Cluster Transmission

The second phase is inter-cluster transmission. All members of transmitting cluster relay information to the destination cluster. Each channel is assumed to be independent with each other. For each receiver node j, the channel is MISO channel and the channel capacity is

$$\begin{aligned} C_{2j} &= Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M+1}\frac{\lambda_{ij}^2}{d_{ij}^{\alpha}}) \\ &\geq Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M+1}\frac{\lambda_{ij}^2}{(d_{SD}+2r)^{\alpha}}) \end{aligned}$$

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

$$t_2 = \frac{K}{C_2} \leq \frac{K}{\sum_{j=1}^{N+1} Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M+1}\frac{\lambda_{ij}^2}{(d_{SD}+2r)^{\alpha}})} \tag{5}$$

C. Phase III: Intra-cluster Transmission to Destination

In third phase, each member in receiving cluster makes soft-symbol decision and send the 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 information from all cluster members and then combine the soft symbols to make hard decision. We assume each node use power P/N for intra cluster transmission. For each cluster member j, the channel capacity is

$$C_{3j} = Wlog(1+\frac{P\lambda_{jD}^2}{NN_0Wd_{jD}^{\alpha}})$$

And the transmission time for cluster member j to relay information to destination node is

$$t_{3j} = \frac{KQ}{Wlog(1+\frac{P\lambda_{jD}^2}{NN_0Wd_{jD}^{\alpha}})}$$

Thus the time required to finish the third phase will be

$$t_3 = \sum_{j=1}^{N} t_{3j} = \frac{KQ}{W}(\sum_{j=1}^{N}\frac{1}{log(1+\frac{P\lambda_{jD}^2}{NN_0Wd_{jD}^{\alpha}})}) \tag{6}$$

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

$$\begin{aligned} T &= t_1 + t_2 + t_3 \\ &\leq \frac{K}{Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M}\frac{\lambda_i^2}{r^\alpha})} \\ &+\frac{K}{\sum_{j=1}^{N+1} Wlog(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M+1}\frac{\lambda_{ij}^2}{(d_{SD}+2r)^\alpha})} \\ &+\frac{KQ}{W}(\sum_{j=1}^{N}\frac{1}{log(1+\frac{P\lambda_{jD}^2}{NN_0Wd_{jD}^\alpha})}) \end{aligned} \tag{7}$$

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

$$\begin{aligned} C_{coop} &= \frac{K}{T} \\ &= W/(\frac{1}{log(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M}\frac{\lambda_i^2}{r^\alpha})} \\ &+\frac{1}{\sum_{j=1}^{N+1} log(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M+1}\frac{\lambda_{ij}^2}{(d_{SD}+2r)^\alpha})} \\ &+Q(\sum_{j=1}^{N}\frac{1}{log(1+\frac{P\lambda_{jD}^2}{NN_0Wd_{jD}^\alpha})})) \end{aligned} \tag{8}$$

If we consider the non-cooperative case where the system transmits information directly from source node to destination node, the capacity of direct transmission with channel gain λ will be

$$C_{direct} = Wlog(1+\frac{P\lambda^2}{N_0Wd_{SD}^\alpha}) \tag{9}$$

Comparing equation 8 and 9, we can estimate the system capacity ratio as

$$\begin{aligned} \frac{C_{coop}}{C_{DT}} &= 1/(\frac{log(1+\frac{P\lambda^2}{N_0Wd_{SD}^\alpha})}{log(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M}\frac{\lambda_i^2}{r^\alpha})} \\ &+\frac{log(1+\frac{P\lambda^2}{N_0Wd_{SD}^\alpha})}{\sum_{j=1}^{N+1} log(1+\frac{P}{N_0W(M+1)}\sum_{i=1}^{M+1}\frac{\lambda_{ij}^2}{(d_{SD}+2r)^\alpha})} \\ &+\sum_{j=1}^{N}\frac{Qlog(1+\frac{P\lambda^2}{N_0Wd_{SD}^\alpha})}{log(1+\frac{P\lambda_{jD^2}}{NN_0Wd_{jD}^\alpha})}) \end{aligned} \tag{10}$$

By equation 10 we can estimate the improvement in capacity due to node cooperation. The relation of system capacity ratio, which is defined in equation 10 and other major system factors is shown in Figure 6, Figure 7 and Figure 8. From Figure 6 we can find the capacity radio is not affected much by SNR. But the sizes of transmission cluster and receiving cluster play an important rule for capacity ratio. As the size of cooperative cluster increases, the capacity ratio decreases because the increase in diversity gain compensates transmission delay which is caused by three-phase cooperative transmission. In figure 6 the capacity ratio for $M = 3, N = 4$ is smaller than it for $M = 4, N = 3$. This is because each receiving cluster member makes soft symbol decision after inter cluster transmission. For each receiving cluster member, the transmission can be modeled as MISO channel. In phase II, the channel capacity is equivalent to sum of MISO channels. When the size of transmission cluster M increases, it only provides possibly larger diversity gain for each MISO channels. On the other hand, the increase of receiving cluster size N increases the number of MISO channels and offers larger capacity. Thus, with the same number of nodes joining cooperation $M + N$, larger receiving cluster size has smaller system capacity ratio.

The capacity ratio provided in equation 10 is also compared to the conventional MIMO systems in Figure 7. Similar to equation 10, the capacity ratio of the conventional MIMO systems is defined as C_{MIMO}/C_{DT}, the capacity of the conventional MIMO systems divided by the capacity of direct transmission. In Figure 7 the capacity ratio of the conventional MIMO systems is fixed. SNR does not affect the capacity ratio of the conventional MIMO systems because there is no delay from intra-cluster transmission. The conventional MIMO systems transmit and receive signals by multiple antennas and do not need broadcasting (phase I) and the intra-cluster transmission to destination (phase III) in the cooperative MIMO systems. So the capacity ratio is fixed and proportion to the number of antennas on the devices. But SNR affects the capacity ratio of the cooperative MIMO systems. When SNR is low, the capacity ratio is larger because node cooperation provides transmission diversity and thus better performance in bit error rate(BER). As SNR increases, the channel quality is better and the performance of one-to-one direct transmission is acceptable. Diversity gain from node cooperation only improves the performance a little. Consider the sacrifice in capacity due to intra-cluster transmission delay, cooperative MIMO system is not so attractive in high SNR environment.

The effect of transmission cluster size is also clearly observed in Figure 8. In Figure 8 we discuss how the transmission distance and cluster radius affect system capacity ratio. The X-axis in Figure 8 is defined as distance ratio , which is $\frac{d_{SD}}{r}$. The equation 10 considers the path-loss, fading and spatial diversity gain provided by node cooperation. When the distance ratio is low, the system capacity ratio is dominated by the intra-cluster transmission. The short distance transmission does not encounter much signal power degradation due to path-loss effect. Thus, the short distance direct 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. From Figure 8 the capacity ratio is approximately stable when the distance ratio is larger than 15.

V. System Capacity for Heterogeneous Network

In this section we consider the system Capacity for the network that nodes may have more than one antenna. The number of antenna in node i is denoted as a_i and we

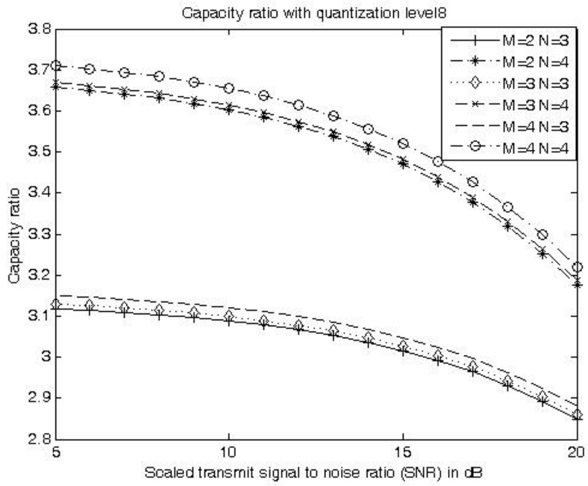

Fig. 6. Capacity ratio of different transmitting/receiving cluster size with scaled SNR. (Note: scaled SNR is defined as P_T/r^α, r is cluster radius and P_T is transmission power)

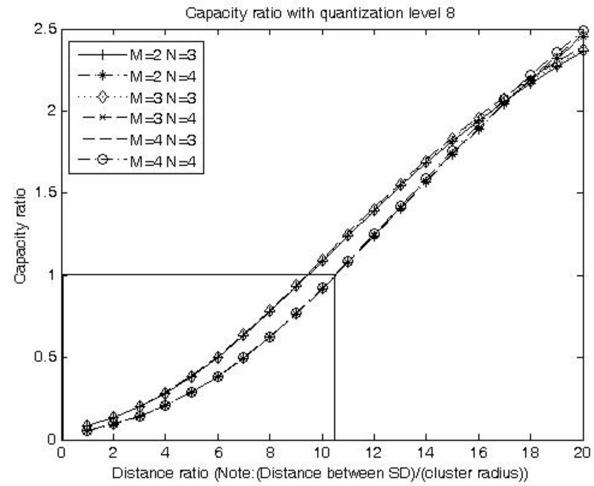

Fig. 8. Capacity ratio with distance ratio (Note: scaled SNR is defined as P_T/r^α, where r is cluster radius and P_T is transmission power. Distance ratio is defined as d_{SD}/r, where d_{SD} is distance between source and destination node)

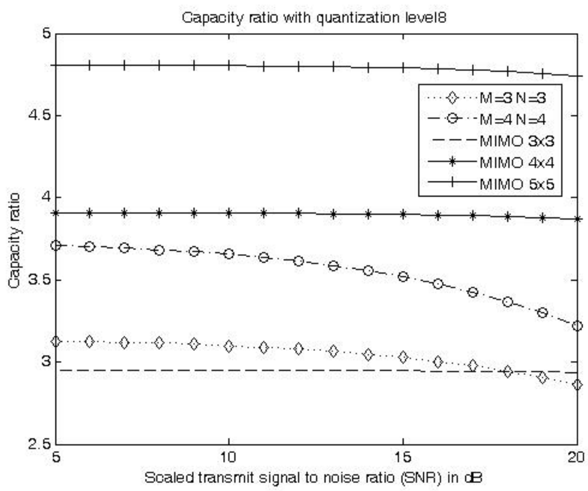

Fig. 7. Capacity ratio compared to conventional MIMO system with scaled SNR (Note: scaled SNR is defined as P_T/r^α, r is cluster radius and P_T is transmission power)

assume 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.

A. Phase I:Broadcasting

The source node sends information to its cluster member and destination cluster. Assume the source node has a_S antennas and each cluster member i has a_i antennas. The channel matrix H is a $a_S \times \sum_{i=1}^{N} a_i$ matrix. If all channels are i.i.d Rayleigh fading, the MIMO capacity is

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

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

$$C_1 \geq \sum_{i=1}^{a_S} Wlog(1 + \frac{P\lambda_i^2}{N_0 W a_S r^\alpha}) \tag{11}$$

The transmission time for K bits is

$$\begin{aligned} t_1 &= \frac{K}{C_1} \\ &\leq \frac{K}{\sum_{i=1}^{a_S} Wlog(1 + \frac{P\lambda_i^2}{N_0 W a_S r^\alpha})} \end{aligned} \tag{12}$$

B. Phase II: Inter-Cluster Transmission

For each node in receiving cluster, the MISO channel model becomes MIMO channel model due to multiple receiving antennas. For node j in receiving cluster, the corresponding MIMO channel matrix H_j is a $(\sum_{i=1}^{M+1} a_i) \times a_j$ matrix. We assume all nodes in transmitting cluster have the same number of antennas and each antenna use power P/a to transmit signal. Apply SVD decomposition to H_j and the channel capacity for node j is

$$\begin{aligned} C_j &= \sum_{k=1}^{a_j} Wlog(1 + \frac{P\lambda_{j,k}^2}{N_0 W a}) \\ &\geq \sum_{k=1}^{a_j} Wlog(1 + \frac{P\lambda_{j,k}^2}{N_0 W a (d_{SD} + 2r)^\alpha}) \end{aligned} \tag{13}$$

Thus, the capacity and the transmission time is

$$\begin{aligned} C_2 &= \sum_{j=1}^{N+1} C_j \\ &\geq \sum_{j=1}^{N+1}\sum_{k=1}^{a_j} Wlog(1+\frac{P\lambda_{j,k}^2}{N_0Wa(d_{SD}+2r)^\alpha}) \end{aligned} \quad (14)$$

$$\begin{aligned} t_2 &= \frac{K}{C_2} \\ &\leq \frac{K}{\sum_{j=1}^{N+1}\sum_{k=1}^{a_j} Wlog(1+\frac{P\lambda_{j,k}^2}{N_0Wa(d_{SD}+2r)^\alpha})} \end{aligned} \quad (15)$$

where $\lambda_{j,k}$ is the singular values for H_j.

C. Phase III: Intra-Cluster Transmission to Destination

Here each member in destination cluster transmits soft symbols to the destination node. For node j, the transmission is MIMO with channel matrix H_j, which is a $a_j \times a_D$ matrix. The channel capacity is

$$\begin{aligned} C_j &= \sum_{k=1}^{min(a_j,a_D)} Wlog(1+\frac{P\lambda_{j,k}^2}{N_0Wa_jd_{jD}^\alpha}) \\ &\geq \sum_{k=1}^{min(a_j,a_D)} Wlog(1+\frac{P\lambda_{j,k}^2}{N_0Wa_jr^\alpha}) \end{aligned} \quad (16)$$

Thus, the transmission time is

$$\begin{aligned} t_{3j} &= \frac{QK}{C_j} \\ &\leq \frac{QK}{W\sum_{k=1}^{min(a_j,a_D)} log(1+\frac{P\lambda_{j,k}^2}{N_0Wa_jr^\alpha})} \end{aligned} \quad (17)$$

$$\begin{aligned} t_3 &= \sum_{j=1}^{N} t_{3j} \\ &= \sum_{j=1}^{N}\frac{QK}{W}\frac{1}{\sum_{k=1}^{min(a_j,a_D)} log(1+\frac{P\lambda_{j,k}^2}{N_0Wa_jr^\alpha})} \end{aligned} \quad (18)$$

The total transmission time T is

$$\begin{aligned} T &= t_1+t_2+t_3 \\ &\leq \frac{K}{\sum_{i=1}^{a_S} Wlog(1+\frac{P\lambda_i^2}{N_0Wa_Sr^\alpha})} \\ &+ \frac{K}{\sum_{j=1}^{N+1}\sum_{k=1}^{a_j} Wlog(1+\frac{P\lambda_{j,k}^2}{N_0Wa(d_{SD}+2r)^\alpha})} \\ &+ \sum_{j=1}^{N}\frac{QK}{W}\frac{1}{\sum_{k=1}^{min(a_j,a_D)} log(1+\frac{P\lambda_{j,k}^2}{N_0Wa_jr^\alpha})} \end{aligned} \quad (19)$$

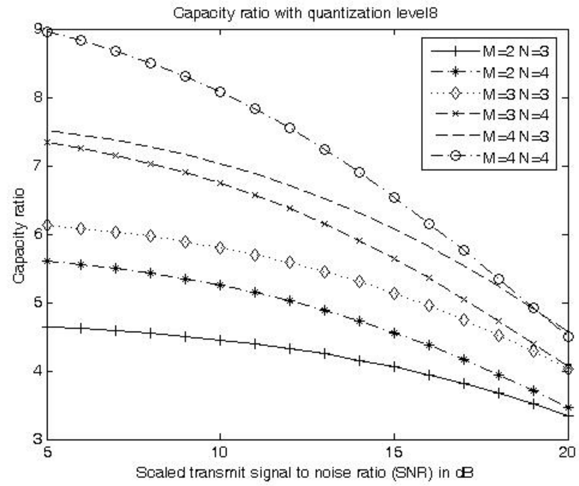

Fig. 9. Capacity ratio with scaled SNR (Note: each node has 2 antenna)

Thus the system Capacity ratio is

$$\begin{aligned} \frac{C_{Coop}}{C_{DT}} &= 1/(\frac{\sum_{i=1}^{min(a_S,a_D)} log(1+\frac{P\lambda_i^2}{N_0Wa_Sd_{SD}^\alpha})}{\sum_{i=1}^{a_S} log(1+\frac{P\lambda_i^2}{N_0Wa_Sr^\alpha})} \\ &+ \frac{\sum_{i=1}^{min(a_S,a_D)} log(1+\frac{P\lambda_i^2}{N_0Wa_Sd_{SD}^\alpha})}{\sum_{j=1}^{N+1}\sum_{k=1}^{a_j} log(1+\frac{P\lambda_{j,k}^2}{N_0Wa(d_{SD}+2r)^\alpha})} \\ &+ \sum_{j=1}^{N}\frac{Q\sum_{i=1}^{min(a_S,a_D)} log(1+\frac{P\lambda_i^2}{N_0Wa_Sd_{SD}^\alpha})}{\sum_{k=1}^{min(a_j,a_D)} log(1+\frac{P\lambda_{j,k}^2}{N_0Wa_jr^\alpha})}) \end{aligned} \quad (20)$$

In Figure 9 we assume two antennas per node. The system Capacity ratio is much smaller due to the improvement in diversity gain and degree of freedom. Multiple antennas provide MIMO transmission for all three phases of cooperative transmission and thus improve the channel capacity.

VI. 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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