# Cooperative MAC for Rate Adaptive Randomized Distributed Space-time Coding

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***Abstract*—In a distributed wireless network, it is possible to employ several relays and *mimic* a multiple antenna transmission system. In this paper we propose a MAC layer solution that allows multiple relays to send information to the receiver at unison, using a randomized distributed space time code. The randomized space-time coding can recruit relays *on the fly*, thus significantly reducing signaling overhead. The cross-layer design between physical layer and MAC layer involves relay discovery and rate adaptation, and results in improvements in throughput and delay performance. The design is dynamic and can be adapted to changing network conditions. The proposed MAC scheme can be integrated into various wireless technologies such as distributed contention based networks (e.g., IEEE 802.11 BSS and ad hoc mode) as well as centralized multiple access networks (e.g., IEEE 802.16).**

## I. Introduction

In a typical wireless network, each transmitter is surrounded by several other stations. However, usually, only the link between the sender and the receiver is used to send data. In a fading environment, data transmission over this link may not be reliable. Deep fading and interference may cause signal corruption, which results in the data getting lost.

Cooperative wireless communication provides a potential solution by recruiting relays or helpers. When a relay is employed, the possibility of losing data or receiving inaccurate data decreases [1]–[4]. While cooperative communications at physical layer (PHY) has been extensively studied, modifications to the higher layer protocol stack are needed to discover and utilize all relays. However, the literature on this topic is limited. Our previous work [5] presented a cooperative MAC protocol for IEEE 802.11, where a single relay assists in transmissions. We demonstrated that *network performance* metrics, such as throughput and delay performance, can be greatly improved by user cooperation.

Typically, there might be more than one station that can overhear the packet sent by the source, and if the stations are willing and able to transmit cooperatively to the destination, significant diversity gains are achieved. However, if all relays transmit sequentially in time, the time required to complete transmission increases linearly with the number of relays. Despite the diversity gains, the network throughput, which is measured by the number of bits successfully received in unit time, may actually decrease when the system employs a lot of relays.

Simultaneous transmission from multiple relays can be accomplished by a distributed space-time code (DSTC) [4]. The basic idea is to coordinate and synchronize the relays that decode the source information correctly, so that each relay acts as one antenna of a regular STC [6], [7]. However, DSTC poses a number of challenges from a system perspective. Each relay participating in a DSTC needs to be numbered, so that it knows exactly which antenna it will mimic in the underlying STC. Even though stations other than the chosen relays may decode the source information correctly, they are not allowed to transmit. This sacrifices potential diversity and coding gains. Also, the synchronization requirement can be stringent.

An example of applying DSTC communications in mobile ad hoc networks is given in [8], where the source is constrained to recruit a fixed number of relays. The source transmits a packet in the first hop and expects a busy tone signal from each of the relays sent sequentially in time. Even if one of relays does not receive the packet from the source and therefore does not respond with a busy tone, the source gives up the transmission and schedules a retransmission in a later time.

Randomized DSTC (R-DSTC) [9] alleviates the problems by having each relay transmit a random linear combination of antenna waveforms. Some initial results on the use of randomized coding in a wireless network are described in [10], where the impact on the MAC layer performance is also discussed. However, there is no explicit error check at the relays, which causes error propagation to the receiver. In order to maintain a guaranteed end-to-end BER performance, the modulation and coding scheme have to be chosen in a conservative fashion. Especially when the number of participating relays is larger, the received signal is more prone to error. A detailed description of the required signaling that enables such cooperation in a distributed wireless network is not provided.

In this paper, we focus on the design of a MAC protocol that supports (R-DSTC). The signaling protocol enables discovery of neighboring relays for a generic wireless network, including infrastructure based networks and mobile ad hoc networks. Each station is able to recruit relays on the fly, which then send cooperatively the source information using a R-DSTC and a modulation/coding scheme assigned by the source station. Our cooperation is packet based, which means each relay decodes

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the whole packet before it forwards to the destination receiver. Since we assume that each packet is followed by a cyclic redundancy check (CRC) code, relays that receive corrupted packets do not participate in forwarding, and therefore the error propagation problem over the cooperative link can be made negligible. We propose two rate adaptation algorithms. One is based on the number of relays available, and the other is based on a more accurate estimate of the network state. In a dense network, we demonstrate that exact knowledge of the channel conditions is not required to unleash the full potential of R-DSTC.

The rest of the paper is organized as follows. Section II explains R-DSTC and derives the physical layer performance criteria for R-DSTC. In Section III, a MAC layer rate adaptation algorithm is introduced to maximize the network throughput. Section IV discusses a generic MAC protocol suitable for a R-DSTC based PHY layer. We then compare the performance of the R-DSTC with the CoopMAC [5] protocol and a basic system that does not employ cooperation in Section V. Section VI contains the conclusions.

## II. Physical Layer and R-DSTC Performance

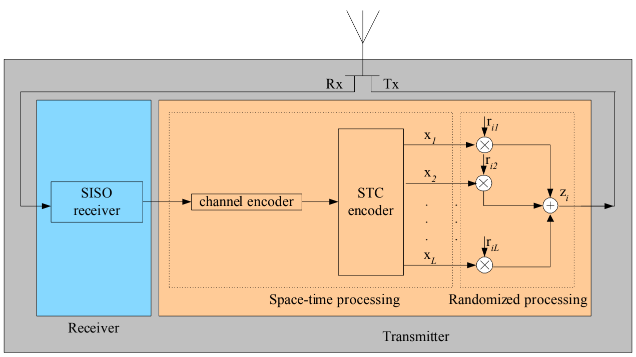



Fig. 1. Signal processing for relay stations

We assume all stations in the network are equipped with one antenna and have an average power constraint. The cooperative transmission of a packet takes two time slots. In the first time slot, the source station $S$ transmits the packet to all its potential relay station(s) $R$. Each relay first tries to decode the packet and verify the CRC. In the following time slot, only relay(s) that receive the packet correctly re-encode and send the packet to the destination. The transmission for a packet takes two hops, as in CoopMAC [5]. However, in the R-DSTC scheme, multiple relays are allowed to transmit simultaneously in the second time slot. The signals from all relays propagate to the destination, where it is received by a single antenna.

The relay transceiver is depicted in Fig. 1. Note that this only depicts the signal processing for relaying purposes. All stations can act as source, relay or destination on the fly for each packet. We do not require dedicated purpose-built relay stations.

We assume there are $N$ relays participating in the second hop transmissions. Each relay employs a regular single-input and single-ouput (SISO) decoder to decode the information from the source sent in the first hop. The relay first re-encodes the information bits from the source using a channel encoder, which are then passed to a space-time (STC) encoder. The output of the STC encoder is in the form of $L$ parallel streams, each corresponding to an antenna in a MIMO system with $L$ transmission antennas. We assume an underlying full rank space-time code $\mathcal{G}$ is of size $L \times K$, where $L$ is the number of signal streams and $K$ is the number of symbols transmitted by each antenna. Each relay transmit a randomly weighted sum of all the streams. In order to achieve a diversity order of $L$ for the second hop, the number of relay stations $N$ should be at least $L$. For the $i$'th relay at time $m$, the transmitted signal is

$$z_i(m) = \sqrt{E_s}\mathbf{r}_i\mathbf{X}(m), \tag{1}$$

where $i = 1, 2, \cdots, N$ and $m = 1, 2, \cdots, K$. $E_s$ is the symbol energy and $\mathbf{r}_i = [r_{i1}\ r_{i2}\ \ldots\ r_{iL}]$ is the random weight at relay $i$. Each element of $\mathbf{r}_i$ is assume to be an independent complex Gaussian random variable with zero mean and variance $1/L$ [9]. $\mathbf{X(m)} = [x_1(m)\ x_2(m)\ \ldots\ x_L(m)]^T$ denotes the $m$th column of the space time code $\mathcal{G}$.

The destination receiver is similar to a regular STC receiver with one antenna. Assuming $N$ stations participate in relaying, the received signal at the receiving antenna at the $m$th symbol time can be expressed as

$$y(m) = \mathbf{HZ}(m) + w(m) = \sqrt{E_s}\mathbf{HRX}(m) + w(m). \tag{2}$$

Here $\mathbf{H}$ is the $1 \times N$ channel vector representing channel gain from each relay to the destination. Also $\mathbf{Z(m)} = [z_1(m)\ z_2(m)\ \ldots\ z_N(m)]^T$ and

$$\mathbf{R} = \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \vdots \\ \mathbf{r}_N \end{bmatrix}, \tag{3}$$

and $w(m)$ denotes additive white Gaussian noise with power spectrum density $N_0/2$. The receiver estimates $\mathbf{HR}$ perfectly before decoding the data.

For a given $\mathbf{HR}$, the pairwise error probability (PEP) between two space time coded symbols $\mathcal{G}_i$ and $\mathcal{G}_k$ is

$$\mathbb{P}\left\{\mathcal{G}_k \to \mathcal{G}_i|\mathbf{HR}\right\} = Q\left(\sqrt{\frac{E_s\|\mathbf{HR}(\mathcal{G}_i - \mathcal{G}_k)\|^2}{2N_0}}\right), \tag{4}$$

where $\|\cdot\|$ represents for the Frobenius norm. Using $Q(x) < e^{-x^2/2}$, we have

$$\mathbb{P}\left\{\mathcal{G}_k \to \mathcal{G}_i|\mathbf{HR}\right\} < e^{\left(-\frac{E_s\|\mathbf{HR}(\mathcal{G}_i - \mathcal{G}_k)\|^2}{4N_0}\right)}. \tag{5}$$

Assuming the channel from each relay undergoes independent Rayleigh fading, the pairwise error probability averaged over fading is upper bounded by [9]:

$$\begin{aligned} PEP_{ik} &\triangleq \mathbb{E}_R\left\{\mathbb{P}\left\{\mathcal{G}_k \to \mathcal{G}_i|\mathbf{R}\right\}\right\} \quad (6)\\ &= \mathbb{E}_R\left\{\frac{1}{det(\mathbf{I}+\frac{1}{4}\frac{E_s}{N_0}\mathbf{A}_{ik}\mathbf{R}^*\mathbf{\Sigma}_h\mathbf{R})}\right\}\\ &\leq \mathbb{E}_R\left\{\frac{1}{det(\mathbf{I}+\frac{1}{4}\frac{E_s}{N_0}(\lambda^{ik}_{min})^2\mathbf{R}^*\mathbf{\Sigma}_h\mathbf{R})}\right\}, \end{aligned}$$

where $\mathbf{A}_{ik} = (\mathcal{G}_i - \mathcal{G}_k)(\mathcal{G}_i - \mathcal{G}_k)^*$, and $\lambda^{ik}_{min}$ is the minimum eigenvalue for $\mathbf{A}_{ik}$. $\mathbf{\Sigma}_h$ is covariance matrix of the channel matrix and if we assume the fading from different antennas to the receiver is independent Rayleigh fading, $\mathbf{\Sigma}_h$ is a diagonal matrix with $i$th element equals to the path loss between relay $i$ and the receiver.

In the high SNR region, we use the PEP upper bound as a good approximation for the exact symbol error rate. For a Q-QAM modulation using Gray code, the bit error rate can be approximated by

$$P_e \approx \frac{1}{\log_2 Q}\cdot\mathbb{E}_R\left\{\frac{1}{det(\mathbf{I}+\frac{3E_s\lambda^2_{min}}{2(Q-1)N_0}\mathbf{R}^*\mathbf{\Sigma}_h\mathbf{R})}\right\}. \quad (7)$$

## III. Rate adaptation

In order to maximize the network layer performance metrics, such as throughput and delay, the PHY operations have to be coupled with the activities of the MAC layer. Most wireless networks use rate adaptation to handle different received SNR values, so that a satisfactory error probability can be maintained. One of the criteria for rate adaptation is to keep the error rate below a pre-set threshold while maximizing the throughput for each source and destination pair.

We assume all stations have the same hardware and can transmit using various coding and modulation schemes, resulting in a set of transmission rates. The MAC selects the rates for both hops (source to the relay and relay to destination). The higher the data rate for the first hop transmission, the less time is consumed for the first hop. But then the fewer relays can decode the source information and participate in the second hop. This means the supported data rate for the second hop is expected to be lower and more time is consumed in the second hop. Therefore, there is a trade-off between the data rates of the first and the second hop, when the objective is to maximize the throughput.

Another task of our MAC is to choose a suitable STC to be used by the relays. The MAC attempts to choose a STC dimension $L$ as close as possible to the number of relays $N$ to maximize diversity gains. However, in practice, good space-time codes only exist for particular $L$'s.

The PHY is designed to handle different size QAM constellations. We denote the rate that PHY can support as $R_p$, $p = 0, \ldots, P$, where $R_0$ is the basic rate at which the stations exchange control information, and $R_0 < R_1 < \cdots < R_P$.

We assume that there are $M$ stations in the network and each station can reach locations for which data at the basic rate $R_0$ is decoded with high probability. Stations beyond this range cannot communicate with each other. We further assume that the packet header is at the basic rate $R_0$ and that the received signal strength is available at the MAC. Hence assuming channel reciprocity, each station can estimate the channel conditions towards the stations that it can communicate at base rate. For each rate $R_p$ let $\{\mathbf{A}_p\}_{ij} = a_{p,ij}$ be the correspondent adjacency matrix, where $a_{p,ij} = 1$ means the $i$th station can communicate with station $j$ using rate $p$ and $a_{p,ij} = 0$ means they cannot. We set $a_{p,ii} = 0$. Obviously, $\mathbf{A}_0$ is equal to a matrix of all ones except for the diagonal terms.

Since each station is able to communicate at the basic rate $R_0$ to its neighbors, we will assume that all stations overhear the control packets and the packet headers of the data packets sent from its neighbors and, therefore, collect information to update the matrices $\mathbf{A}_p$. We further assume that if two terminals communicate directly, they always do so at the maximum possible rate. For the CoopMAC protocol [5], when a station $s$ sends to $d$, there are potentially

$$N_{sd} = \sum_{k=1}^{M} a_{p',dk}a_{p,ks} = \{\mathbf{A}_{p'}\mathbf{A}_p\}_{sd} \quad (8)$$

stations that can be used as *relays* if rate $p$ and $p'$ is used as the first and the second hop rate respectively. Then, the effective two hop rate is defined as

$$R_C = 1/(R_p^{-1} + R_{p'}^{-1}), \quad (9)$$

$R_C$ is called the effective rate for cooperative transmission since $1/R_C$ is the time required to send an information bit, if we ignore MAC overheads. Suppose $R_{p*}$ is the maximum rate that the source-destination pair can support without cooperation, that is

$$R_{p*} = \max_p R_p \quad \text{s.t.} \quad a_{p,ds} = 1. \quad (10)$$

If $R_C > R_{p*}$, cooperative relaying saves time in sending a packet than direct transmissions. In CoopMAC, each source tries all combination of $p$ and $p'$ and picks the highest effective rate. If the effective rate is higher than direct transmission, it transmits the packet cooperatively. Otherwise, it falls back to non-cooperative direct transmission.

The difficulty of the CoopMAC procedure is selecting and recruiting, on the fly, the best one out of the $N_{sd}$ relays available. The objective of R-DSTC is to overcome this difficulty, while at the same time providing increased link resilience and rate gains through the recruitment of multiple cooperative stations simultaneously.

For R-DSTC cooperation, we note that a group of

$$N_{p,s} = \sum_{k=1,k\neq s}^{M} a_{p,sk} \quad (11)$$

cooperative stations, capable of communicating with the source at a rate greater or equal to $R_p$, might be collectively able to support a higher rate towards the same destination than any of them can do separately. Note that the performance not only depends on the number of relays, but also relies on the average channel quality of relays. Let $q_{p,sd,i}$ be the channel gain of $i$'th relay relay of source $s$ using rate $p$ to destination $d$, with $\mathbf{Q}_{p,sd} = [q_{p,sd,1} \ q_{p,sd,2} \ \cdots \ q_{p,sd,N_{p,s}}]$. Then the highest rate supported towards station $d$ by all $N_{p,s}$ relays is $f(R_p, N_{p,s}, \mathbf{Q}_{p,sd})$. $f(\cdot)$ stands for the highest rate that can be supported by the relays towards the destination for a given BER threshold. It can be solved numerically by checking the BER for all transmission rates using Eq. (7) and then finding out the highest supported rate. Overall, assuming that the cooperative stations adopt a decode and forward strategy, the rate of the cooperative link $R_C$ will be:

$$R_C^{-1} = R_p^{-1} + \frac{1}{f(R_p, N_{p,s}, \mathbf{Q}_{p,sd})}. \tag{12}$$

Hence, the maximum rate the MAC can request for the overall link is

$$\max R_C = \max_p \frac{R_p f\left(R_p, N_{p,s}, \mathbf{Q}_{p,sd}\right)}{R_p + f\left(R_p, N_{p,s}, \mathbf{Q}_{p,sd}\right)} \tag{13}$$

## IV. Signaling protocol

We next study the signaling requirements for R-DSTC for a infrastructure based access network. Such networks including contention based network, where each station finds a transmission opportunity via contention with its neighboring stations. An example network is the IEEE 802.11 DCF, which is the standard technology for wireless access in a local area environment. The widely used IEEE 802.11a/b/g/n DCF mode is based on a CSMA/CA MAC layer, where each station conducts carrier sensing before each transmission and a random back-off after each collision. Another example of the infrastructure based network is the cellular network (GSM, WiMAX, etc.), where there is a centralized controller that schedules the transmissions from all stations. Most of the signaling protocol discussed below can be extended to an *ad hoc* network.

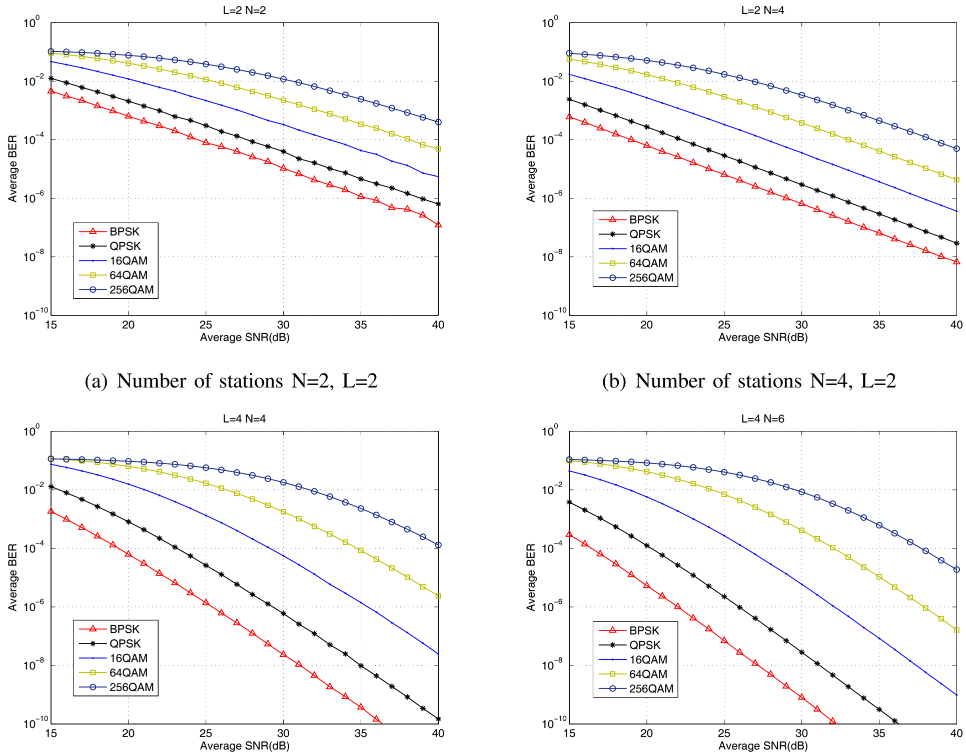
All stations in the network detect and measure the average number of its neighbors, and the average channel quality to their neighbors. Each station is required to passively listen to the packets sent by their neighbors and measure the received signal strength, which can then be used to estimate the channel quality. The measurement is averaged over time so that each station has the knowledge of the statistical channel information to all neighbors. Also, by decoding the source/destination address contained in the header of the overheard packets, each station can discover which stations can communicate with its neighbors, but not the channel qualities between them. Also, the required neighbor information can be retrieved by an active discovery procedure. But still, each station only have channel information to its neighbors.

In order for the distributed relays to cooperate together, the parameters for the underlying STC and the modulation scheme have to be identical among all participating relays for each packet transmitted. This makes it impractical to let the relays make decision in a distributed manner. Instead, a single station, either the source, destination or the network controller (access point), have to choose a rate and a STC for the cooperative transmissions beforehand. In this paper, we pick the source station to make such decisions.

The performance of R-DSTC depends on the number of relays and the channel between the relays and the destinations. Ideally, such information should be available at the source in order to use the bandwidth efficiently. Note that this requires the source station understands the channel between its neighbors, which is not available by only employing passive listening and requires explicit reporting of channel information between stations. It might be costly to feedback the number of relays and related channel information on the fly, especially when the number of stations is large. Based on whether stations exchange such information, we can categorize the MAC into two categories:

- **Channel information based MAC**: All the channel information retrieved from the physical layer is passed to the MAC layer and is then stored in a database called the *Neighbor Table*. Since relay-destination channel cannot be measured locally at the source, it will not have such information without an explicit exchange of *Neighbor Tables*. This can be done either by periodically broadcasting using a control packet or piggybacking in a data packet. Every station in the network then has a clear picture of who their neighbors are, and the average channel quality between their neighbors. The higher the frequency of information exchange, the more accurate the channel information is and the higher the throughput. The frequency of information exchange should be adapted to network mobility, of course at the expense of signal overhead.
- **Neighbor count based MAC**: Alternatively, to reduce overheads, we assume the source only knows its own *neighbor table*. In this case, the source only knows on average how many relays are able to receive at a particular rate. But not the channel information between its neighbors. By assuming all relays are *i.i.d* uniformly distributed in a circle of a radius identical to the transmission range of the first hop rate, the average error performance can be then calculated by averaging over all possible relay locations. Source makes a decision on the second hop rate without knowing the location of relays, and only based on average error rate. Such a MAC saves bandwidth that is used to exchange information globally. However, the performance is expected to be lower than channel information based MAC. In a dense network, we expect the difference in performance to be small since for any relay locations, the performance should be very close to the average. Therefore channel information is no longer necessary. This is verified in Section V.

Ideally, $L$ is close to the estimated number of relays that can actual decode the packet from the source. This ensures highest diversity/data rates at the destination. When a data packet arrives at the MAC layer from a higher layer, the MAC layer inspects the *Neighbor Table*. For each possible transmission




(a) Number of stations N=2, L=2

(b) Number of stations N=4, L=2

(c) Number of stations N=4, L=4

(d) Number of stations N=6, L=4

Fig. 2. BER performance for R-DSTC in a wireless network.

rate in PHY, the source can estimate how many relay stations would be able to receive its transmitted packet. Based on this number, the source picks a size $L$ for the underlying STC. Using the information in the *Neighbor Table* and the proposed analytical framework in Section II, the source also picks the transmission rate pair for the relays so that the destination can decode the second hop transmission with error probability below a pre-set threshold. By comparing all the transmission rate for both hops, the scheme that requires minimum time is used in the data packet transmission, as is explained in Eq. (12) and (13). Note that the function $f(\cdot)$ in Eq. (12) and (13) depends on the error rate of the R-DSTC scheme.

For every packet transmission, in the header of the first hop packet, the source indicates which space-time code and rate to use for the second hop. Upon receiving the data packet from the source, each individual relay station re-encodes and modulates according to the parameters set by the source. The timing of the simultaneous transmissions from the relays can follow after a fixed time interval, such as the short inter-frame space (SIFS) used in IEEE 802.11. Thus all relaying stations forward at the same time.

## V. Numerical performance assessment

We resort to Monte Carlo computer simulation to evaluate the performance of our proposed MAC scheme. There is a base station(BS)/access point(AP) at the center of the network and mobile stations (MS) are randomly *i.i.d* located within a circle that has a radius of 100 meters. All stations are equipped with one antenna and the modulation schemes supported are BPSK, QPSK, 16-QAM, 64-QAM and 256-QAM. There is no channel coding. Considering practical limitations, we assume each station supports an orthogonal STC [11] up to $L = 6$. The target bit error probability is $10^{-3}$. The symbol duration is equal to $T_s = 10^{-7}$ seconds. The transmission power is such that the range of BPSK modulation reaches the boundary of the network.

We assume the basic MAC scheme guarantees equal throughput to all MS's. One example is IEEE 802.11 DCF MAC, in which all stations equally share the network throughput. The MAC layer overheads and time wasted on contention are neglected. The run length of the simulation is 1 million packets sent by the source.

For various modulation scheme and different $L$ and $N$, we numerically compute the BER of R-DSTC as shown in Fig. 2. The figures follow the results in [9]. As expected, a higher modulation scheme requires higher SNR to achieve the same BER performance. By comparing Fig. 2(a) and Fig. 2(b), we discover that the greater the number of relays, the lower the BER is. This also holds for a larger space time code as we shown in Fig. 2(c) and Fig. 2(d). The second observation is that, for a given number of relays, as long as the the size of space-time code $L$ is less than the number of participating relays, picking a larger $L$ yields better performance. This is why the BER performance in Fig. 2(b) is better than Fig. 2(c).

By taking a closer look at the performance of R-DSTC in the high SNR region, we can observe the slope of the BER curve is actually $L$, confirming that the diversity order of R-DSTC is $L$.

Fig. 3 shows the average aggregated throughput as a function of the number of stations. We compare the two proposed MAC schemes (based on channel information and neighbor count) with legacy non-cooperative transmission and CoopMAC [5]. When channel information is available at the source, R-DSTC based PHY delivers the largest throughput. The throughput increases with the number of stations in the network since each source is able to find more relays on the average. The BER performance improves with the number of relays, and the MAC switches to a higher two hop rate. However, there is still a throughput upper bound for cooperative transmissions, which is approximately half of the highest data rate due to two hop transmission (40 Mbps in this example). The upper bound for the network throughput is slightly higher than 40 Mbps, because stations near the BS can transmit at the highest modulation scheme (256-QAM with data rate 80 Mbps) using just one hop. In a dense network, the throughput for R-DSTC MAC is about twice that of the legacy MAC. Roughly speaking, the throughput for CoopMAC is 50% more than direct transmission.

We observe that the MAC based on neighbor count does not perform well when the number of stations is small. It may even perform worse than CoopMAC since CoopMAC also utilizes the channel information between the relay and the destination. However, when the network is denser, the throughput of the neighbor count based MAC quickly exceeds that of CoopMAC and is only slightly inferior to the R-DSTC with channel information.

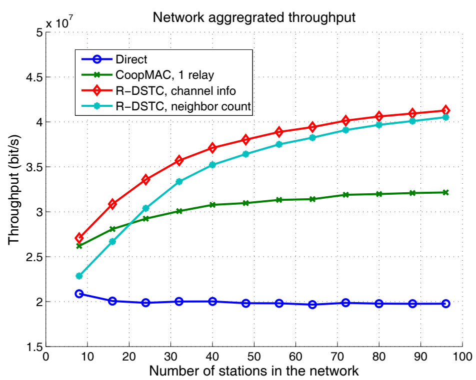



Fig. 3. Network aggregated throughput

Fig. 4 displays the average delay performance for different MAC algorithms. Delay for each packet consists two parts, the queuing delay and the service delay. Service delay is defined as the time from when the packet becomes the head-of-line packet in the queue to the time the packet is received by the receiver. Here the packet length is equal to 1500 bytes. The average delay for a packet is much less if stations transmit cooperatively. Also, R-DSTC based on channel information

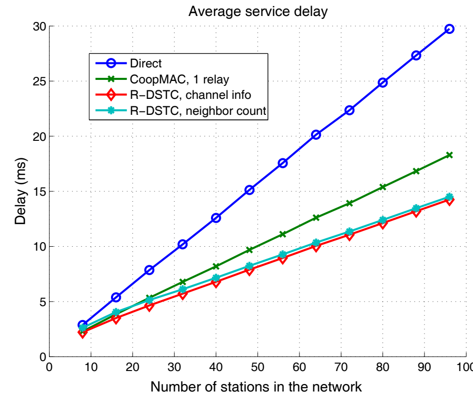



Fig. 4. Service delay

and neighbor count provide similar improvement in delay performance.

## VI. Conclusion

In this paper, we discussed a joint design of PHY and MAC for a randomized cooperative scheme. The proposed MAC designs enable robust cooperation under loose knowledge of network topology. The rate adaptation and signaling protocol are flexible and can be adjusted based on the mobility of the stations and density of the network. The throughput is up to 100% more than a legacy non-cooperative network for networks with a large number of users.

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