Randomized spatial multiplexing for distributed cooperative communications

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***Abstract*—In this paper, we design a *simple* and *robust* cooperation scheme that allows multiple relay stations, with only one antenna each, multiplex transmissions to a BS with multiple antennas. The data transmission is over two hops, where the source first sends information to relaying nodes. In the second hop, the data packet is split into multiple parallel streams in a deterministic manner. Each participating relaying node transmits a *random* and *independent* linear combination of the signal streams that would have been transmitted by all the elements of a multi-antenna system. This random processing eliminates the need to index and allocate a code for each participating relay, and thus makes the system more efficient and robust. We use the information-theoretic capacity as an upper bound for what can be achieved using this scheme. Since this scheme can achieve higher spatial multiplexing gain for the relay-destination link, it greatly improves the effective data rate for stations at the edge of the cell. This scheme requires multiple antennas at the receiver and is therefore more suitable for uplink transmission in wireless LANs and cellular networks.**

***Index Terms*—cooperative communications, distributed networks, spatial multiplexing, virtual MIMO**

I. Introduction

Due to the limited size of portable devices, there is a practical limitation on the number of antennas that can be integrated on these devices. The spatial multiplexing order for a MIMO system is defined as the minimum number of transmitting and receiving antennas. Thus, while the number of antennas on the base station (BS) can be large, the bottleneck is always the number of antennas on the mobile devices. In this paper, we will present user cooperation/relaying as a practical alternative when the size of the wireless device is limited.

Cooperative wireless communication [1]–[3] is a technique that exploits the broadcast nature of the wireless channel by allowing stations that *overhear* other transmissions to relay information to the intended receiver. While traditional wireless systems treat overheard information as harmful interference, cooperative communications systems achieve higher order of reliability and efficiency than stations send individually.

Advances in Multiple-Input Multiple-output (MIMO) communications system have significantly increased the data throughput, reliability and link range without additional bandwidth or transmission power. However, due to the limited size of the portable devices, there is a practical limitation on the number of antennas integrated on portable devices. On the other hand, the number of antennas on a base station (BS) or an access point (AP) can be much larger. If the transmitter is equipped with N_t antennas and the receiver has N_r antennas, the maximum spatial multiplexing order is $\min(N_t, N_r)$. In such an asymmetric configuration, the bottleneck is the number of antennas on a portable device (typically one or two) which limits the possible capacity gains for a MIMO system.

Recently, the concept of using distributed antennas over multiple stations have been considered [4], [5], and is referred to as *virtual* MIMO or *cooperative* MIMO. In such systems, more than two nodes will be able to participate in an ongoing communication in a constructive way, thereby enjoying the benefits of cooperation. Some of the previous research [4]–[7] focuses on relaying strategies and space-time code designs that increase diversity gains of the system. The basic idea is to coordinate and synchronize the relays so that each relay acts as one antenna of a regular space-time code (STC) of the type used in conventional Multi-Input Multi-Output (MIMO) systems. Other papers [8]–[10] discuss the diversity-multiplexing tradeoff in a cooperative network. However, those schemes pose difficulties in synchronizing and coordinating transmissions for those distributed relays.

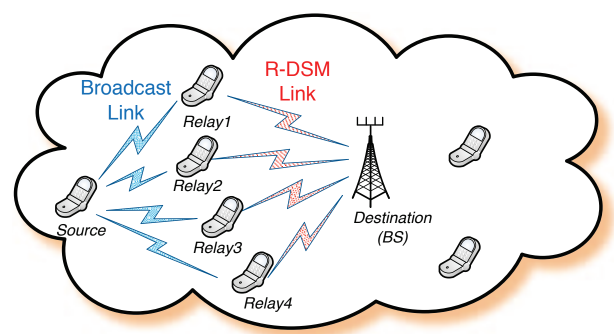

Fig. 1. Link layer cooperative transmissions for R-DSM

Modification to the higher layers of the protocol stack, in particular at the MAC sub-layer and the networking layer, is essential to fully exploit cooperation at the physical layer. Firstly, the MAC layer can help each station in the network to discover it neighbors, and collect information about their ability and channel conditions to the destination. Also, signaling protocols are needed to enable cooperative information

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delivery. In [11], [12], a cooperative medium access control (MAC) protocol (CoopMAC) is presented that enables MAC layer cooperation in IEEE 802.11 networks. Each station passively listens to the other ongoing transmissions and collects information about its neighbors. Stations transmit in a two hop fashion, first from the source to a dedicated relay, and then from the relay to the destination receiver. Since most of the current communication systems support various size QAM modulations and multi-rate channel codes, the data rate they support varies greatly. The authors of [13] demonstrate that the actual network throughput is much less than the average data rate due to the slow stations at the edge of the coverage area. CoopMAC utilizes the fact that high data rate transmissions over two short range hops can improve performance significantly.

In this paper, we proposed to use *multiple* distributed relays, each with only one antenna to send cooperatively to a destination station with multiple antennas. The goal is to achieve higher spatial multiplexing gains for the relay-destination link. Since the degrees of freedom for the channel for the second hop transmission is the lesser of the values of the number of cooperative relays and the number of antennas at the receiver, the receiver must be equipped with multiple antennas in order to decode multiple parallel transmitted streams. We assume that there are $L > 1$ antennas at the destination station, and the source and relay stations have only one antenna. One possible scenario is uplink transmissions in a cellular network, where the BS typically has multiple antennas and mobile stations (MS) are equipped with only one antenna.

In contrast to the past literature on cooperative communications and virtual MIMO, this paper focuses on the problem of designing a *robust* and *practical* scheme to exploit the *spatial multiplexing* gain from the relay to the receiver. We follow the idea of randomized processing as used in [14], [15], and propose randomized distributed spatial multiplexing (R-DSM) to achieve spatial multiplexing gains. We then evaluate its impact on the MAC layer using a simplified generic MAC model.

In our scheme, the bottleneck is the source-relay link, since both are equipped with only one antenna and there is no spatial multiplexing gain. However, we expect that the source can recruit multiple nearby relays at a high transmission rate. Due to the fact that the relay-destination transmissions rate can be a multiple of the peak transmission rate for a single antenna system because of spatial multiplexing, the effective data rate from the source to the destination receiver can approach the peak data rate for all stations in the network.

We use the information-theoretic channel capacity as an upper bound for what can be achieved using R-DSM. With practical coding and modulation scheme with limited selection of data rate, the results will be lower. Also, the MAC layer is an ideal MAC, which assumes no overhead for collisions and signaling. We did not design a full fledged MAC protocol because this paper focused on giving an insight of the impact R-DSM can have on the MAC layer and above, and not rely on a particular wireless standard. In future work, we plan to take a look at a practical wireless communication system, such as IEEE 802.11 and IEEE 802.16, and evaluate the performance using a practical transmission scheme with the overhead of a real MAC protocol.

The rest of the paper is organized as follows. Section II first describes how R-DSM operates, and then derives the capacity expression. We then use a numerical calculation to illustrate the average channel capacity and outage behavior in Rayleigh fading channels. In Section III, we show the achievable uplink data rate for mobile stations at various locations. The aggregate network throughput based on a simplified ideal MAC layer is also presented. Section IV contains discussion and conclusions.

II. System model for R-DSM

By employing multiple antennas at transmitters and receivers, a MIMO system can transmit multiple independent and separately encoded data signals. The larger the number of antennas, the higher the capacity. Bell Labs Layered Space-Time [16] (BLAST) is one such technique that can achieve a higher data rate than legacy single antenna systems. BLAST needs at least as many receive antennas as transmit antennas and a rich scattering environment to be able to distinguish the information streams.

In order to make multiple distributed stations mimic a BLAST system, one way is to assign an index number for each of them and let each of them transmit one data stream. However, from a system perspective, this has the following limitations:

1) Each relay participating in a distributed cooperative group has to be numbered, leading to a considerable signaling cost.
2) Some relays may not be able to decode the first hop transmission due to errors, and as a result, cannot participate in the second hop. System performance could deteriorate.
3) Global channel state information is needed to optimally select the relays. Mobility, channel fading and the large number of nodes in a typical wireless network make it very costly, if not impossible, to distribute such information with minimal overhead.
4) Even though nodes other than the chosen relays may decode the source information correctly, they are not allowed to transmit. This sacrifices diversity and coding gains.

Our scheme is to let *all* stations that correctly receive information packet from the source participate in the forwarding, and each station does not need to be indexed. Instead of transmitting only one stream from a relay, each of them transmits a weighted sum of all the information streams. The weighting coefficients for each station are generated locally and independently, thus enabling fully distributed processing. The only information required to forward is the modulation, channel coding scheme and the number of independent streams for the second hop, which can be included in the frame in the second hop. Our scheme enjoys all the benefits BLAST in terms of flexibility, and enables high rate transmission in the second hop with minimal signaling overhead at the MAC layer.

The proposed cooperative transmission scheme is in two steps as in Fig. 1. In the first time slot, the source station broadcasts information to its neighboring stations, which act as the potential relays for the second hop transmission. In common with all decode-and-forward strategies, the relays first decode the source message. 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 negligible. In the second time slot, relays that receives the information split the information into multiple parallel streams and send a random weighted sum of those streams, using the R-DSM scheme described below. If the data rate for first hop and second hop transmission is R_1 and R_{R-DSM}, respectively, it takes $1/R_1 + 1/R_{R-DSM}$ seconds to send 1 bit to the destination over the cooperative link. Thus effective date rate is defined by $R_{coop} := 1/(1/R_1 + 1/R_{R-DSM})$.

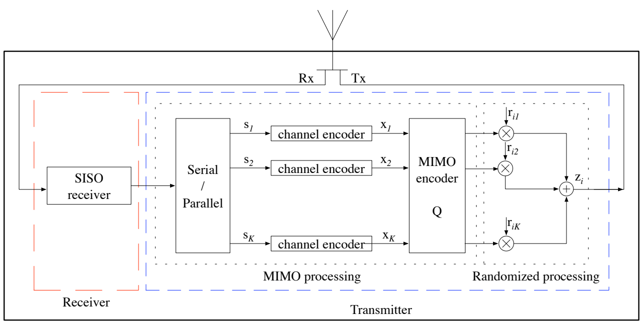


Fig. 2. Signal processing for R-DSM transmissions

A. Relay architecture

In this randomized cooperation scheme, we envision a group of relays that are close to the source receiving information at a high rate. Upon successful reception of the information from the source, each of them transmits in parallel to the destination using R-DSM, as depicted in Fig.2. This system is based on the vertical BLAST (V-BLAST) system [16].

We assume there are L antennas at the BS, and only one antenna transmitter on each of N mobile stations. All transmissions are from the mobile stations to the BS. The number of stations that participate in the cooperative relaying is M ($M < N$). Each relay first decodes the packet from the source using a regular Single-Input Single-Output (SISO) circuit, and then verifies the CRC for correctness of the received packet. If a correct packet is received, it splits the packet into K streams in a deterministic manner, as in a serial-to-parallel converter. As long as $K \leq \min(M, L)$, the system is expected to achieve a spatial multiplexing gain of K in the second hop. In our distributed cooperative system, K is known *a priori* at the source. In each of the data packet, the parameter K is piggybacked, so that all stations that are able to decode the packet know the value of K.

Each stream is then encoded via a channel encoder and passed through a MIMO encoder $\mathbf{Q}$, which is a standard MIMO signal processing procedure [16]. $\mathbf{Q}$ does not necessarily dependent on the channel information. It encodes the input to the MIMO system and defines the covariance matrix of the system. The output from the encoder is in the form of K parallel streams, each corresponding to an antenna in the BLAST transmissions with K transmit antennas. In other words, the virtual MIMO system has K *virtual* antennas.

Instead of letting each relay pick a separate data stream, the ith relay station independently generates a random vector $\mathbf{r}_i$ of length K and transmits a linear combination of the data streams. For each packet transmitted, a new $\mathbf{r}_i$ is generated by relay i. Each element of $\mathbf{r}_i$ is denoted by r_{ij}, where i, $1 \leq i \leq M$, is the index of the relays and j, $1 \leq j \leq K$, is the index of the virtual antennas. Each element is an independently generated random variable. One possible way to generate r_{ij} is using a complex Gaussian variable generator with zero mean and a variance of $1/K^2$. By doing so, the power radiated from each relay is just $1/K$'th of its full power. If the number of relays M equals K, the total power radiated by all relays is the same as in a centralized MIMO transmission. In this paper, we use a random Gaussian coefficient to get preliminary results. However, this choice may not necessarily maximize the capacity.

Relays for R-DSM are recruited *on the fly* based on whether they decode successfully or not, and up-to-date channel information is not required at either the transmitter or the relay. It also does not require pre-assigned index numbers for each of the relays, and each station independently generates the weighting coefficient. Signaling overheads are greatly reduced and it is expected to be much more *robust* in a mobile environment.

B. Average capacity and outage behavior in Rayleigh fading channels

The signal transmitted from station i can be expressed by

$$z_i = \sqrt{E_s}\mathbf{r}_i\mathbf{Q}\mathbf{X}, \tag{1}$$

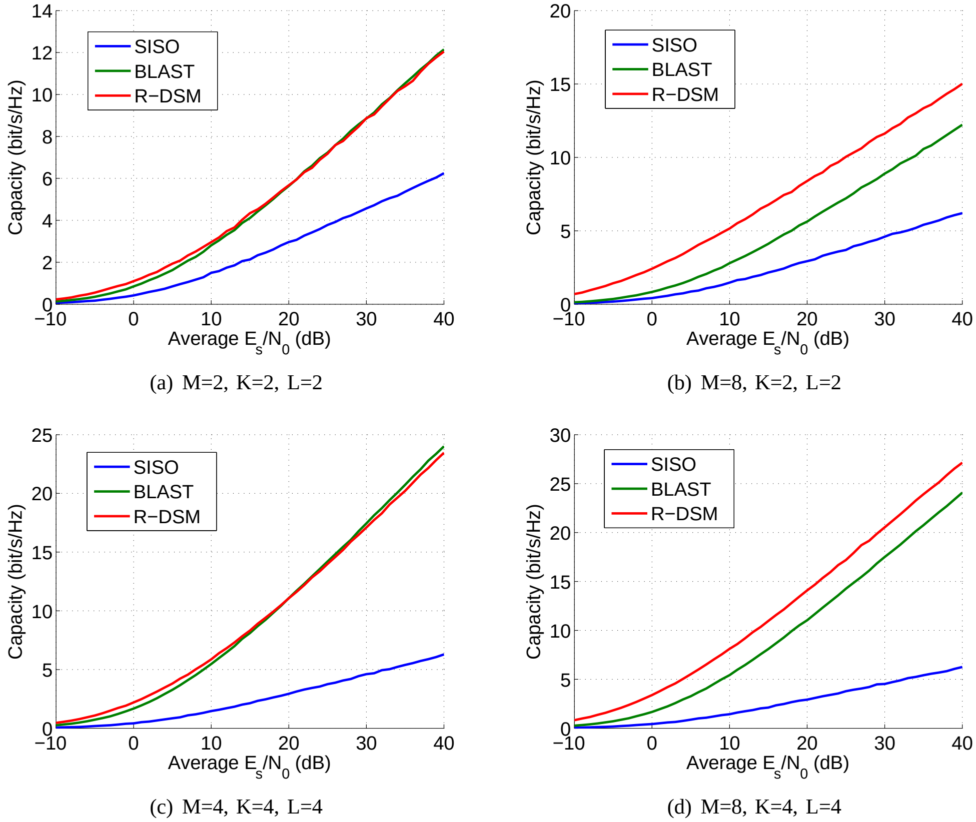
where $\mathbf{r}_i = [r_{i1}\ r_{i2}\ \ldots\ r_{iK}]$ and $\mathbf{X} = [x_1\ x_2\ \ldots\ x_K]^T$ are the coded bits.

The received signal at the destination can be expressed by

$$\mathbf{Y} = \mathbf{H}\mathbf{Z} + \mathbf{W} = \sqrt{E_s}\mathbf{H}\mathbf{R}\mathbf{Q}\mathbf{X} + \mathbf{W}, \tag{2}$$

where $\mathbf{H}$ is the $L \times M$ channel matrix representing channel gain from each relay to the destination, $\mathbf{Z} = [z_1\ z_2\ \ldots\ z_M]^T$ and

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



(a) M=2, K=2, L=2

(b) M=8, K=2, L=2

(c) M=4, K=4, L=4

(d) M=8, K=4, L=4

Fig. 3. R-DSM capacity in Rayleigh fading channels.

The additive Gaussian white noise is $\mathbf{W}$. Assuming coherent detection is employed at the receiver side, the capacity for the system is

$$I = \frac{1}{2}\log_2 \det(\mathbf{I} + \frac{E_s}{N_0}\mathbf{H}\mathbf{R}\mathbf{J}_x\mathbf{R}^H\mathbf{H}^H) \quad bits/s/Hz. \tag{4}$$

$\mathbf{J}_x$ is the covariance matrix of the signal after the coordinate system and is only a function of the multiplexing coordinate system:

$$\mathbf{J}_x := \mathbf{Q}\mathbf{Q}^H. \tag{5}$$

For simplicity, we let $\mathbf{Q} = \mathbf{I}$, the identity matrix, for the rest of this paper.

For practical communication systems, the information-theoretical capacity is an upper bound for the data rate that can be supported. Real systems performance will be somewhat lower. However, using this bound for the later analysis and simulations gives us an insight to what we believe can be achieved using R-DSM.

BLAST requires that the receivers know the channel information to achieve the capacity. However, in a real system, perfect channel information is not attainable. The channel is often estimated using pilot symbols. An interesting point is that, for our system, there is no need to estimate $\mathbf{H}$ and $\mathbf{R}$ separately, only the effective channel matrix $\mathbf{G} := \mathbf{H}\mathbf{R}$ is required. Thus we can employ the same pilot symbols as used in MIMO channel estimation to be transmitted before the data packet. Using the same channel estimation methods as in standard MIMO systems, the effective channel matrix $\mathbf{G}$ can be estimated at the receiver. The signal at the receiver can be described by:

$$\mathbf{Y} = \sqrt{E_s}\mathbf{G}\mathbf{X} + \mathbf{W}. \tag{6}$$

This decoder architecture could be a *maximum-likelihood* (ML) based decoder. Since the received signal mimics a MIMO system with channel matrix $\mathbf{G}$, the standard *minimum mean square error-successive interference cancelation* (MMSE-SIC) decoder also achieves capacity. This greatly reduces the complexity of the decoder.

This R-DSM system is effectively a communication system with K virtual antennas and channel matrix $\mathbf{G}$. When fading is present, the average channel capacity for our scheme is

$$C = \mathbb{E}_{\mathbf{G}}\left[\frac{1}{2}\log_2\ \det(\mathbf{I} + \frac{E_s}{N_0}\mathbf{G}\mathbf{G}^H)\right]. \tag{7}$$

This capacity is achievable by coding over multiple coherent time intervals. Unlike regular MIMO systems, the capacity for R-DSM does not only depend on the number of antennas and the distribution of the channel matrix $\mathbf{H}$, it is also a function of the randomization matrix $\mathbf{R}$.

In a slow fading Rayleigh channel, the random channel gain $\mathbf{H}$ can be assumed to be fixed over each packet transmission time. For each packet transmitted, the channel capacity is a random variable. Outage refers to the case that the actual channel capacity is below a pre-determined threshold rate.

Then the outage probability for the randomized distributed cooperative system is

$$P_{out}^{rand}(R) = \mathbb{P}\left\{\log_2 \det(I + \frac{E_s}{N_0}\mathbf{G}\mathbf{G}^H) < R\right\}. \quad (8)$$

C. Numerical analysis

We resort to a numerical calculation to calculate the exact channel capacity using Eq. (7). The average capacity for Rayleigh fading channel is shown in Fig. 3.

From the above results, we can see that when the physical environment is *richly scattered*, the capacity for R-DSM is very close to its BLAST counterpart. The capacity is approximately K times the capacity for single antenna systems in the high SNR region when Rayleigh fading is present. Also, if the number of relays is larger than the number of receiving antennas, the capacity for R-DSM is a little higher due to the extra power consumed.

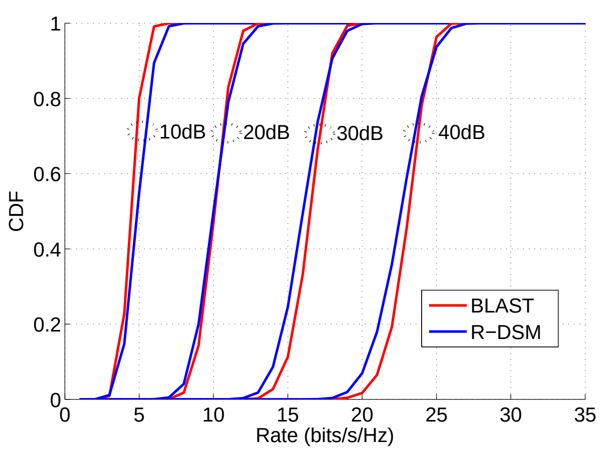


Fig. 4. CDF for channel capacity in slow Rayleigh fading channel (K=4).

We also take a close look at the outage probability in a slow fading Rayleigh channel. Fig. 4 shows the cumulative distribution function (CDF) for average SNR's of 10dB, 20dB, 30dB and 40dB. For example, when the average SNR is 20dB, there are 20% of chance the channel capacity is below 9 bit/s/Hz for R-DSM. Thus, the capacity is 9 bit/s/Hz with an outage probability of 20%. From all those curves, we discover that R-DSM mimics the outage probability of a real BLAST MIMO system under the same received SNR values. Thus, the performance of R-DSM should be very close to a real BLAST MIMO under slow Rayleigh fading.

III. MAC LAYER CAPACITY

In the previous section, we have shown the capacity for our proposed cooperative transmission schemes at the PHY layer for a given number of relays. However, this does not yet give us the throughput gain of R-DSM for each source-destination pair, which is a function of both the number of relays and the network topology. One of the main goals of the MAC layer is to choose the number of streams, the modulation scheme, as well as the parameters for the MIMO encoder and channel encoder used by all the relays. The MAC attempts to choose the number of parallel streams K, as close as possible to the number of relays M to maximize spatial multiplexing gains. However, the MAC has to guarantee that there are at least K relays in the network for most of the time. In a multi-rate environment, the MAC should also select the rates for both hops, since the effective throughput significantly depends on those rates. The higher the data rate for the first hop transmission, the less the time consumed, but the fewer relays can participate. Fewer relays means the spatial multiplexing capability is reduced and the supported data rate for the second hop will be lower. Therefore, there is a trade-off between the data rates of the first and the second hop to maximize the effective data rate R_{Coop}. Cooperative transmissions should be employed only when cooperative transmissions takes less time than direct transmissions.

In this paper, we neglect the details of a specific MAC protocol, such as IEEE 802.11 and IEEE 802.16 MAC. Our main focus is to find out how much network wide capacity gain can be obtained using R-DSM. Here we assume a centralized MAC protocol which has global information on the network. We also assume there is perfect scheduling between all stations and no bandwidth is wasted to resolve collisions. The MAC is set up to guarantee equal throughput among all stations no matter what their data rate is.

A. Numerical Results

We conducted a Monte Carlo simulation to evaluate the system performance. All stations were randomly and uniformly distributed within a circle of 1000 meters. The BS is located at the center of the circle and has 4 antennas. The transmissions undergo slow Rayleigh fading. The target outage probability is set to be 10%. The transmission power is set to a value such that, at the edge of the cell, the channel capacity is 0.5 bit/s/Hz for the given outage requirement. In the simulation, we first deploy all mobile stations in the cell and then numerically calculate the information theoretic capacity between each MS and the BS under the outage requirement using Eq. 8. This procedure is repeated by independently generating a new topology of the network by placing the MS randomly again and then calculating the capacity of the new network. We repeated this procedure multiple times until the average capacity converges.

The effective data rate as a function of the distance from the BS for cooperative R-DSM transmissions is shown in Fig. 5. We also display the rates for the case of direct transmissions and two hop single relay transmissions as in CoopMAC [11]. The highest data rate for direct transmissions can only be supported over a fairly short range, and then the data rate drops very rapidly with distance. CoopMAC improves the data rate a little bit, especially at the edge of the cell. The data rate for R-DSM is much higher than direct and single relay two hop transmission except for stations close to the center of the cell. What makes it more appealing is that, the data rate is almost flat for a very wide range of distances.

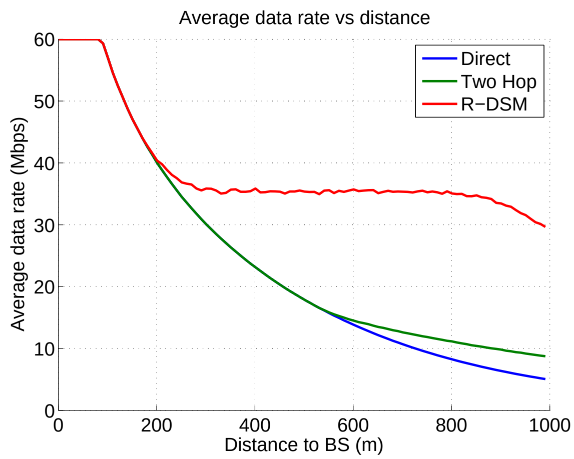


Fig. 5. Average data rate comparison (64 mobile stations)

Fig. 6 shows the cell throughput as a function of the number of stations within the cell. In this example, throughput for R-DSM is up to 3.7 times higher than the throughput for direct transmissions when the BS is equipped with 4 antennas. Fig. 5 also shows how R-DSM boosts the rate for stations at the edge of the cell. Under direct transmissions, stations at the edge reduce the cell throughput, due to the fact that they take much more channel time to send a packet. Also note that the capacity of R-DSM increases with the number of stations (Fig. 6) because of the larger number of candidate relays recruited with nodal density. This is a useful property since they provides additional capacity *when* needed, i.e., as the number of active stations in the cell increases, as well as *where* it is needed, i.e., at the poorly served edge of the cell.

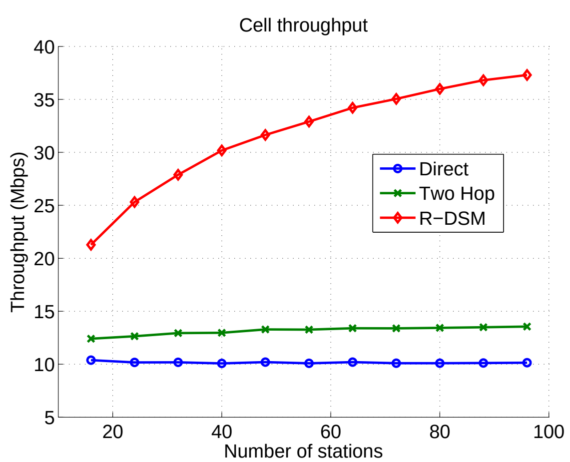


Fig. 6. Cell capacity comparison

IV. Discussion and Conclusions

In this paper, we introduced a physical layer transmission scheme that allows multiple relays to transmit at the same time for spatial multiplexing gain. This scheme utilizes randomized signal processing at each relay, and thus enables a robust and fully distributed cooperative transmission. Information theoretic analysis suggests that the performance for R-DSM should be very close to its conventional MIMO counterpart. We also designed a two hop transmission scheme to enable MAC layer cooperation, with minimal signaling overheads. The MAC layer simulation shows that such a scheme greatly boosts the data rate for stations at the edge of the cell and the aggregate cell throughput is substantially higher, with throughput increasing with the number of stations.

Since the receivers are required to have multiple antennas, this technique is more suitable for uplink transmissions. R-DSM can be easily extended to the case where some relays have two or more antennas by generating a random coefficient for each of the antennas on a relay station.

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