Randomized Distributed Spatial Multiplexing: Adding capacity to the cell edge

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Abstract—This paper explores the spatial multiplexing gain in a relay assisted distributed wireless network, where multiple relays, each with a single antenna, form a virtual antenna array to transmit to a receiver with multiple antennas. Using a transmission scheme called Randomized Distributed Spatial Multiplexing (RDSM), the transmission rate between the relays and the destination is boosted to a level that is several times higher than the rate that can be achieved through a single relay. As a result, the end-to-end data rate between a source and a destination can be greatly improved. Consequently, in a wireless network, where multiple sources compete for channel access, the overall system aggregated throughput is also improved. An opportunistic rate adaptation algorithm is adopted to achieve the optimal average end-to-end performance. Randomized signal processing at the relays fundamentally changes the way how cooperation is established. Instead of picking nodes with good links or fast paths, our algorithm picks a transmission mode (modulation, coding, and number of streams). Any node that correctly receives from the source can act as a relay and participate in forwarding. We present the performance of RDSM with practical modulation and channel coding, and evaluate its performance in a fully distributed wireless scenario.

Index Terms—Cooperative Communications, Randomized Distributed Spatial Multiplexing (RDSM), Virtual MIMO

I. INTRODUCTION

Multiple-Input-Multiple-Output(MIMO) [1] is one of the innovative technologies in recent years that has provided a significant increase in data throughout, link reliability and communication range without requiring additional bandwidth or power. However, it is not easy to implement this multiple-antenna technology on mobile devices because of their relatively small size. On the other hand, the number of antennas on a base station (BS) or an access point (AP) can be much larger. Thus the mobile nodes become the bottleneck in such an asymmetrical system, and restrict the system from achieving MIMO capacity gains.

Cooperation wireless communications [2] [3], where nodes process and forward the overheard signal transmitted by other nodes to their intended destination, is another effective technique that exploits the broadcast nature of wireless channel to combat path loss and fading. While initial cooperation schemes employed a single relay, subsequent work has extended this to allowing multiple relays to forward the overhead signals to the destination at the same time; this is called cooperative MIMO or virtual MIMO [4]. Cooperative MIMO can achieve a MIMO capability in a network consisting of single antenna nodes. Some of the previous research [4] [5] [6] focuses on

the relaying strategies and space-time code (STC) designs that increase the diversity gain of the system. The basic idea is to coordinate and synchronize the relays so that each relay acts as one virtual antenna of a conventional MIMO system. Other papers [7] [8] discuss the diversity-multiplexing trade-off in a cooperative network. However, these schemes pose difficulties in synchronizing and coordinating transmissions for those distributed relays. In a distributed environment with mobility, it is very difficult to track and select the optimum relays, which could lead to extra signalling overhead. Another drawback of these schemes is that only the pre-chosen relay nodes can participate in relaying, even if there exists other nodes in the network that have a better instantaneous channel to the destination compared to those pre-chosen nodes. The above drawbacks are addressed by employing randomized signal processing at the relays[9], which eliminates the requirement of codeword assignment and reduces the need for coordination between the source and the relays. Randomized distributed space-time code (RDSTC) [9] provides a robust cooperative relaying scheme that, in contrast to a DSTC based system, has the potential of simplifying the protocol design.

Following the idea of randomized processing, we proposed randomized distributed spatial multiplexing (RDSM)[10] to achieve spatial multiplexing gains and boost the rate of a relay-destination link to a multiple of the peak transmission rate. In our scheme, the communication works in two steps as depicted in Fig. 1. The source first broadcasts the information stream over the wireless channel. When all the potential relays overhear the message, only the nodes that can decode it without error will act together to participate in the forwarding. In such a cooperation scenario, the degree of freedom for the second hop transmission is the minimum between the number of participating relays and the number of antennas on the receiver side. The receiver must be equipped with multiple antennas to decode the multiple parallel transmitted streams from the relays. As mentioned earlier, the number of antennas on a mobile device is limited, but it is easy to equip the BS or AP with multiple antennas. Thus our proposed RDSM scheme is more suitable for uplink transmission.

Note that the source-relay link will become the bottleneck, 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. Because of spatial multiplexing, the transmission rate for relay-destination link can be a multiple of the peak transmis-

sion rate for a single antenna system. We use R_1 and R_2 respectively to indicate the transmission data rate for the first hop and the second hop in a RDSM cooperation network, and assume the multiplexing gain on the second hop is K. It takes $(1/R_1 + 1/(KR_2))$ seconds to send 1 bit to the destination over the cooperative link. Thus the effective end-to-end date rate is defined by $R_{eff} = \frac{1}{1/R_1 + 1/(KR_2)}$. In our scheme, we can have a high R_1 and R_2, so the effective data rate from the source to the destination receiver can approach the peak data rate for all stations in the network. Nodes at the cell edge benefit the most; our system effectively adds capacity to the edge. While the initial results provided in [10] are information theory based, in this paper, we explore RDSM's performance with practical modulation and channel coding schemes in a distributed cooperative network.
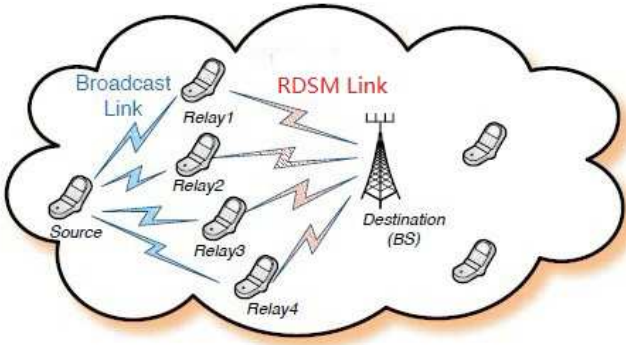

Fig. 1. Link layer cooperative transmissions for RDSM

Another contribution of our work is that it fundamentally changes the way how cooperation is established. Instead of picking nodes with fast links or finding a fast path in the network, our scheme picks a transmission mode (modulation, channel coding, and number of streams) that could most improve the end-to-end rate on the average. We will explain this further in this paper. Relays decide to participate or not to participate independently based on whether they receive the packet or not. In fact, neither the source nor destination station need to know who the relays are or where they are located. We evaluate our rate adaptation algorithm on an RDSM enabled wireless network, and compare the result to single relay cooperation, DSTC and RDSTC.

The rest of the paper is organized as follows. Section II describes how RDSM operates. In section III, we develop our opportunistic rate adaptation scheme to optimize the transmission parameters. Section IV presents the simulation results and the performance evaluation. Finally, in Section V, we present conclusions.

II. RDSM PHYSICAL LAYER DESCRIPTION

Information theoretic results show that MIMO architecture is able to provide extraordinary high spectral efficiencies in a rich multipath environment. The Bell Labs Layered Space-Time (BLAST) [11] algorithm proposed by Foschini is one such approach. However, it suffers from certain implementation issues because of its high complexity. Later, a simplified version of BLAST system known as Vertical BLAST (V-BLAST) [12] was proposed and implemented in a laboratory environment.

To apply the V-BLAST technique in a distributed wireless mobile network, following the idea of randomization processing, instead of transmitting only one stream from a relay, we let each of them transmits a random weighted sum of all the information streams. The weighting coefficients for each station are randomly generated locally and independently, thus enabling fully distributed processing. The only information required to coordinate the relays is the modulation, channel coding scheme and the number of independent streams for the second hop, which can be distributed in the frame header in the first hop. Our scheme enjoys all the benefits of V-BLAST in terms of flexibility, and enables high rate transmission in the second hop with minimal signalling overhead at the MAC layer.

The signal processing details are presented in Fig. 2. Because only nodes that can successfully decode a message from the source are allowed to help relay, the error propagation problem over the cooperative link is negligible. If a node is recruited as a relay, it splits the original information stream S into K parallel sub-streams $[S_1 S_2 ... S_K]$ as in a serial-parallel converter, and sends a random weighted sum of those sub-streams, using the RDSM scheme described in [10].
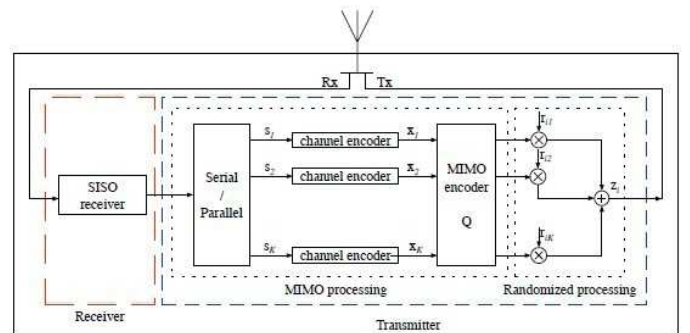

Fig. 2. Signal processing for RDSM transmissions

We assume each node supports a set of transmission rate $r \in \{r_0, r_1, ..., r_p\}$, where r_0 is the base rate and $r_0 \leq r_1 \leq ... \leq r_p$. A given transmission rate r_i is identified by the modulation level M_r and channel coding level C_r. We assume an additive white Gaussian noise (AWGN) channel with independent slow Rayleigh fading between all stations and AP's. Each fading duration is assumed to be longer than the packet duration. All stations have a symbol energy of E_s and the power spectral density of the noise signal is $N_0/2$.

The signal transmitted from station i can be expressed by:

$$z_i = \sqrt{E_s} r_i Q S, \tag{1}$$

where $r_i = [r_{i1} \ r_{i2} \ ... \ r_{ik}], S = [S_1 \ S_2 \ ... \ S_k]^T$ are the coded bits, and Q is a MIMO encoder, which is a standard MIMO signal processing procedure [11].

The messages received at the destination(BS or AP) can be expressed as:

$$Y = HZ + W = \sqrt{E_s}HRQS + W, \tag{2}$$

where H is the LXM channel matrix representing channel gain from each relay to the destination. $Z = [Z_1 \ Z_2 \ ... \ Z_M]^T$, L is the number of antennas at the destination and M is the number of nodes that participate in the forwarding for this transmission.

An interesting point is that, for our system, there is no need to estimate H and R separately, only the effective channel matrix $G := HR$ 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 G can be estimated at the receiver. The signal at the receiver can be described by:

$$Y = \sqrt{E_s}GX + W, \tag{3}$$

The decoder architecture could be a maximum-likelihood (ML) based decoder. Since the received signal mimics a MIMO system with channel matrix G, the standard minimum mean square error-successive interference cancellation (MMSE-SIC) decoder also achieves capacity, which greatly reduces the complexity of the decoder. Thus we use MMSE decoder for our detection.

As discussed in Section I, we use R_1 and R_2 as the transmission rate on the air interface for the first hop and the second hop, and R_{e2e} as the effective end-to-end rate for this transmission, while K is the number of sub-streams split by each relay. Thus the effective data rate for the second hop is boosted to KR_2, and we can express R_{e2e} as

$$\frac{1}{R_{e2e}} = \frac{1}{R_1} + \frac{1}{KR_2} \tag{4}$$

III. RATE ADAPTATION ALGORITHM

Rate adaptation refers to the tuning of transmission parameters based on the channel conditions. In RDSM, the tuning includes the rate for the first hop R_1, the rate for the second hop R_2, and the number of split sub-streams K on each relay.

In this section, we give a rate adaptation algorithm that tries to maximizing the effective end-to-end data rate while keeping the packet error rate (PER) within the pre-defined threshold γ. Intuitively we should choose the highest possible transmission rate for both the source-relay and relay-AP links while meeting the PER threshold γ. Although a higher R_1 consumes less time in the first hop, it may also result in fewer relays that can receive and decode the message from the source, therefore the number of relays participating the forwarding is decreased. Fewer relays means the spatial multiplexing capability is reduced and the supported data rate for the second hop will be lower as well. On the other side, a lower R_1 can enable more potential nodes in the network to help the transmission,

but there is no way to compensate the rate reduction during the first hop. The rate adaptation algorithm needs to perform a trade-off when choosing the appropriate rate pair for both hops. Cooperation should be employed only when cooperative transmission takes less time than direct transmission.

We have formulated the PHY layer error rates in [13], i.e., per-hop bit err rate (BER), per-hop PER and end-to-end PER performance for direct transmission, the two-hop single-relay (CoopMAC [14]) scheme, DSTC scheme and RDSTC scheme. In this paper, our focus is the BER/PER performance for the RDSM scheme. As long as we can get the BER for the first hop and second hop, we can use similar methods to calculate the end-to-end BER. However, a closed form BER expression for V-BLAST system is still an open problem due to its complexity, thus we will conduct a Monte Carlo simulation to evaluate the RDSM's performance. Algorithm 1 shows how we optimize end-to-end data rate and how we choose the transmission parameters.

Algorithm 1 Rate Adaptation based on User Number

1: The available rate set for both the first hop (R_1) and the second hop (R_2) is $\{r_1, r_2, ..., r_p\}$, and the set of available sub-streams for RDSM is K, where $K \in \{k_1, k_2, ..., k_{max}\}$. Suppose all stations are located in the WLAN cell based on a random distribution function χ. The fading level among nodes is φ and between nodes and BS is ϕ. Initialize $R^* = 0$.
2: **for** Each of the stations within the celll **do**
3:    **for** Each possible set of $\{(R_1, R_2, K)\}$ **do**
4:        **for** All possible stations that can be a relay **do**
5:            Find $P_p^{RDSM}(R_1, R_2, K)$ for RDSM transmission and average over all fading levels φ and ϕ
6:        **end for**
7:        **if** $E_{\varphi\phi}(P_p^{RDSM}(R_1, R_2, K)) \leq \gamma$ and $\frac{1}{R_1} + \frac{1}{KR_2} < \frac{1}{R^*}$ **then**
8:            $R^* \leftarrow \frac{1}{1/R_1 + 1/KR_2}, K^* \leftarrow K,$ $R_1^* \leftarrow R_1, R_2^* \leftarrow R_2$
9:        **end if**
10:    **end for**
11: **end for**

The source node chooses its optimal rate parameters by ensuring that the average PER over all possible spatial locations of stations is within the PER threshold γ. To get the optimal rate parameters for each source node in the network, the source first needs to check whether cooperation is necessary or not by comparing the achievable direct link capacity with the possible cooperation transmission rate pairs. If cooperation outperforms the direct link, we need to evaluate all the possible potential relays in the network, letting the source and relays transmit through all available rate combinations while satisfying the PER condition. If the cooperation scheme is DSTC/RDSTC or RDSM, we also evaluate all the possible STC for DSTC/RDSTC and number of sub-streams for RDSM on each relay. We repeat this procedure multiple times for each

cooperation scheme, until we find the best rate parameters for each node.

$$(r_1^*, r_2^*, K^*) = \arg\min_{r_1, r_2, K} \frac{1}{r_1} + \frac{1}{Kr_2} \qquad (5)$$
$$s.t. \quad P^{RDSM}(r_1, r_2, K) \leq \gamma$$

Traditionally, we set up cooperation by choosing nodes which have good channels between chosen source and destination. In our rate adaptation algorithm, the choice of rate parameters does not depend on a fast link or good path, but is based on a set of specified transmission modes, such as the modulation and channel coding, and the number of sub-streams. Thus our rate adaptation algorithm fundamentally changes the way how cooperation is established.

IV. PERFORMANCE EVALUATION

We conduct a Monte Carlo simulation to find how much network-wide capacity gain is possible via using RDSM. We compare the performance of RDSM with that of direct transmission, single relay cooperation, DSTC and RDSTC for stationary environments. All schemes use versions of the rate adaptation algorithm described in the previous section. The comparison and evaluation is done on a typical single-cell wireless network. We will consider multi-cell networks in future work.

A. Network Topology and Configuration

The simulation is based on a typical 802.11g system. Since it is in a wireless LAN setting, we assume that the radius of the considered wireless network is 100 meters. Independent Rayleigh fading among each pair of stations and additive white Gaussian noise is adopted as the channel model. The simulated system consists of one AP at the center and N mobile users. All users are randomly and uniformly distributed within the cell. The AP has four antennas while each user is equipped with a single antenna. For comparison fairness, we constrain the total transmission power of all the participating relays to the same as in a single relay scenario. Our simulations are conducted on the uplink from the mobile users to the AP, with the parameters shown in Table I.

TABLE I
SIMULATION CONFIGURATION

Parameters	Value
Cell Radius	100m
Received E_s/N_o at edge	1.4
Path loss exponent	3.0
Model	ITU-T Indoor Model and Rayleigh fading
PHY layer data rates, r	$6, 9, 12, 18, 24, 36, 48, 54$ Mbps
Modulation, M_r	BPSK, QPSK, 16-QAM, 64-QAM
Channel coding, C_r	Convolutional $1/2, 2/3, 3/4$
Acceptable PER γ	0.1
Centre Area	Distance to the AP between (0,20]m
Middle Area	Distance to the AP between (20,60]m
Far Area	Distance to the AP between (60,80]m
Edge Area	Distance to the AP between (80,100]m

B. Simulation Results

We first numerically calculate the capacity between each user and the AP using the formulations included in [13] for direct transmission, single user relay, DSTC and RDSTC. Because there is no closed form expression for RDSM, we evaluate RDSM BER through simulation. The capacity results are averaged over all possible distributions of users. We repeat this procedure multiple times until the average capacity converges.
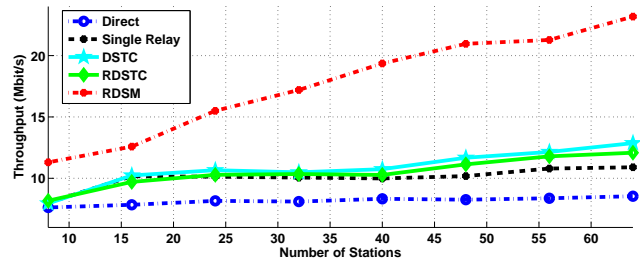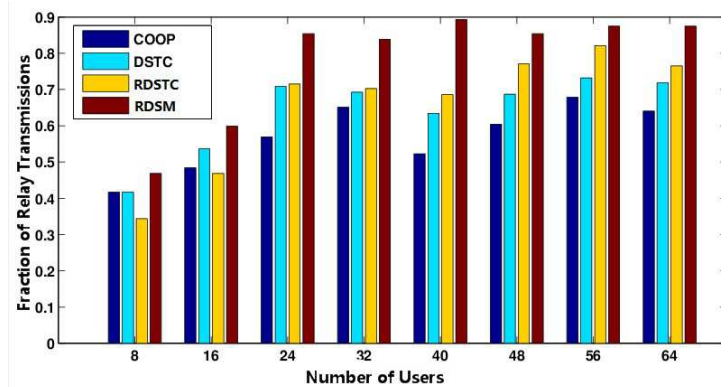

Fig. 3. Throughput Comparison

Fig. 4. Fraction of Cooperative Transmissions

Fig. 3 displays the aggregated uplink throughput in a stationary environment as the number of users N in the network increases from 8 to 64. As N becomes larger, the throughput of RDSM increases very fast compared to that of the other cooperation schemes. That is because, the more users in the network, the higher possibility a node is able to find relays to deliver its information. With the multiplexing gain, the RDSM obtains a much higher transmission rate during the second hop compared to other schemes.

Previous discussion has revealed that the multiplexing gain on the second hop for RDSM is the main reason that differentiates it from other cooperative schemes. Fig. 4 shows another reason why RDSM is more powerful in improving system throughput. Compared to other cooperative schemes, more transmissions are delivered to destinations using relays in RDSM. When the number of users N is not large, the fraction of transmission forwarded by relays are a bit higher for RDSM as compared to the other schemes. When N exceeds 24, more
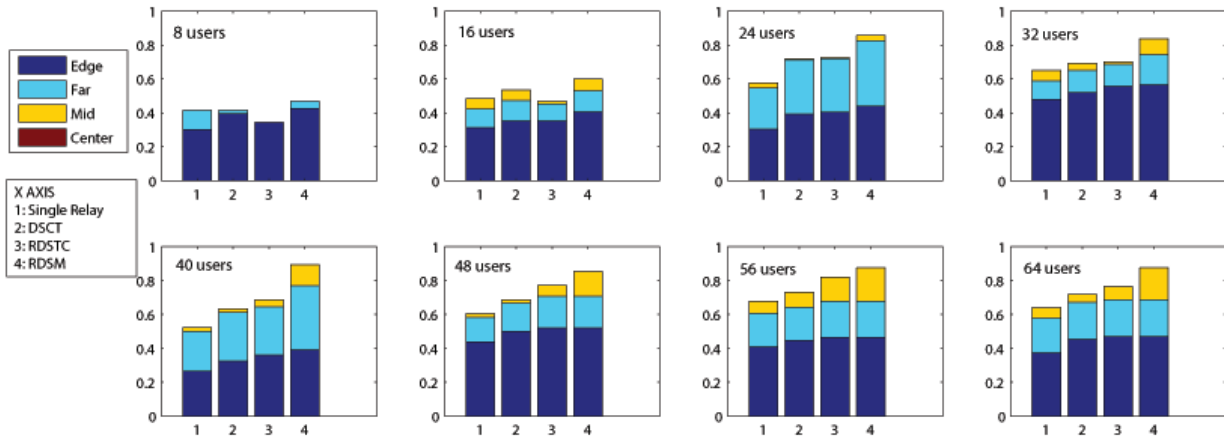
Fig. 5. Percentage of Cooperative transmissions

and more nodes participate in helping delivering the packet, with over 85% of messages are delivered by relays in RDSM.

Thus compared to other cooperative schemes, RDSM enables more relayed transmissions. We then investigated where these extra relay-assisted transmissions originated. To answer this question, we divided the cell into four regions based on the user's distance to the AP. The Center Area is the innermost region where a user's distance to the AP is within 20 meters, the Middle Area is the sector where a user's distance to the AP is between 20 meters and 60 meters, the Far Area is the sector where a user's distance to the AP is between 60 and 80 meters and the Edge Area is the outermost region where cell edge users are located.(see Table I).

Fig. 5 shows the percentage of transmissions that are delivered by relays in each region when the number of users in the network for the four specified cooperation schemes, and we use the numbers $1, 2, 3, 4$ in X-axis separately to indicate these four schemes, where 1 for single relay, 2 for DSCT, 3 for RDSTC and 4 for RDSM. In addition, we use different colors to stand for different regions in the bar chart. Intuitively, if a user is close to the AP, it is very likely that this user will transmit the information to the AP directly and cooperation is unnecessary. The simulation result confirms our intuition: for all the four cooperation schemes, we do not see any Center Area user (brown color) in the bar chart, which means Center Area users deliver their messages to the AP directly and no relays are involved in the transmissions.

From Fig.5, we also note that compared to users located in the Middle Area, the users located farther from AP, for example, Far Area users (light blue bar) and Edge Area users(dark blue bar), are more likely to get helped because of their poor direct link to the AP. This is also in accord with the intuition.

We have confirmed the fact that using relay enabled transmission can be beneficial for Edge Area users, considering their poor channel to the AP. We next illustrate to what extent RDSM can benefit Edge Area users compared to other popular

cooperative schemes. In the following, we will conduct a simple analysis for the edge users based on our simulation data. We randomly pick several edge users and compare their end-to-end performance for RDSM and RDSTC.

TABLE II
RDSTC FOR EDGE STATIONS

Edge User	R_{dir} (Mbps)	RDSTC			
		R_{rdstc}(Mbps)	R_1(Mbps)	R_2(Mbps)	$+\%$
1	6	9.00	18	24	50%
2	6	10.29	24	24	71%
3	6	10.80	18	36	80%
4	6	8.31	12	36	38%

TABLE III
RDSM FOR EDGE STATIONS

Edge User	R_{dir} (Mbps)	RDSM				
		R_{rdsm}(Mbps)	R_1(Mbps)	R_2(Mbps)	K	$+\%$
1	6	21.6	36	18	3	260%
2	6	21.6	36	18	3	260%
3	6	24	36	18	4	300%
4	6	24	24	18	4	300%

From Table II and Table III, we can see for edge users 1 to 4, their direct links to AP can only support 6Mbps while meeting the PER threshold γ. If RDSTC is enabled, the effective end-to-end rate can be improved to around 9Mbps, which is 50% higher compared to the direct link. If RDSM is applied, the effective end-to-end data rate can reach well over 20Mbps, almost 22Mbps, much higher than the rate RDSTC can achieve. The comparison tells us that although both cooperative schemes can increase the edge user's performance, RDSM brings much more benefits compared to others.

V. CONCLUSION

In this paper, we evaluated a physical layer protocol, RDSM, by employing it in a fully distributed wireless cooperative network. RDSM enables robust cooperation by using multiple relays and reduces the signalling and channel feedback

overhead due to the introduction of randomized processing. The proposed protocol is simple and realizes a significant performance gain. The scheme especially benefits the cell edge users; it can enhance the edge user's link capacity to as much as quadruple the direct rate. In addition, we propose an opportunistic rate adaptation algorithm to maximize the effective end-to-end data rate on average while keeping PER within the pre-defined threshold. Our rate adaptation algorithm fundamentally changes the way how cooperation is established. Instead of picking a fast link or good path, we pick a transmission mode (modulation, coding, and DSM). Relays decide to participate or not participate in the forwarding independently based on whether they receive the packet or not. Our simulation results reveal the performance gain using RDSM with practical modulation and channel coding in a distributed cooperative network. The RDSM is not only beneficial to system overall throughput, but also enables more relay transmissions, and adds capacity to the cell edge.

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