Robust Cooperative Relaying in a Wireless LAN: Cross-layer Design and Performance Analysis

Pei Liu, Chun Nie, Elza Erkip and Shivendra Panwar
Polytechnic Institute of New York University, Brooklyn, NY, 11201, USA

Abstract—**A key technology in cooperative communications is distributed space-time coding (DSTC) which achieves spatial diversity gain from multiple relays. A novel DSTC, called *randomized distributed space-time coding* (*R-DSTC*), shows considerable advantages over a regular DSTC in terms of system complexity. In this paper, we exploit the benefits of R-DSTC physical (PHY) layer and develop a *distributed* and *opportunistic* medium access control (MAC) layer protocol for R-DSTC deployment in an IEEE 802.11 wireless local area network (WLAN). Unlike other cooperative MAC designs, in our proposed PHY-MAC cross-layer framework, there is no need to decide which stations will serve as relays before each packet transmission. Instead, the MAC layer opportunistically recruits relay stations on the fly; any station that receives a packet from the source correctly forwards it to the destination. Through extensive simulations, we validate the efficiency of our MAC layer protocol and demonstrate that network capacity and delay performance is considerably improved with respect to legacy IEEE 802.11g network.**

I. INTRODUCTION

As WiFi grows into one of the most popular wireless technologies, the IEEE 802.11 [1] standard has established itself as the most prevalent wireless LAN (WLAN) protocol and has delivered several versions, such as IEEE 802.11a/b/g/n.

While a conventional WiFi system can support a relatively high speed for data transmission, e.g. up to 54Mbps for IEEE.802.11a/g, the aggregated throughput of a WLAN cell may be severely degraded by low-data-rate stations at the edge of the cell [2]. In recent years, the concept of cooperative wireless communication has attracted significant research attention in the PHY layer [3], [4]. As one of the MAC layer designs to support a cooperative PHY layer in a WLAN, *CoopMAC* enhances the system throughput via two-hop transmission using an intermediate station, called a *relay station* [5], [6]. The performance of *CoopMAC*, albeit superior to direct communication, is still limited as it only selects a single relay.

To improve diversity gain over a single relay system, multiple relays can be employed at the PHY layer to collaboratively transmit the source signal to the destination. *Distributed space-time coding* (DSTC) across the relay stations achieves a high spatial diversity while maintaining spectral efficiency. A cooperative MAC layer incorporating DSTC is expected to improve performance over *CoopMAC*; however, it still has inherent drawbacks that lead to difficulties and inefficiencies at the MAC layer.

A detailed distributed MAC layer protocol that deploys DSTC in a cooperative ad hoc network is described in [7]. In this protocol, the source station needs to discover the set of selected relays and assign the antenna array index to each relay for the underlying DSTC by the use of a broadcast message, while each chosen relay, upon receiving that message, must respond with a pilot tone to verify its availability as a relay. This process consumes significant signaling overhead which could be very costly in a mobile environment. Whenever any selected relay fails to receive from the source, DSTC cannot be established and the transmission falls back to direct transmission from the source to the destination. Thus the system robustness to the channel fading and mobility effects is limited. Furthermore, the source station in [7] does not allow stations other than the chosen set of relays to cooperate even if those stations may successfully decode the source signal, thus sacrificing the potential additional diversity gains.

The above problems can be addressed by *randomized distributed space-time coding* (R-DSTC) [8], which reduces the coordination among the source station and the relays. R-DSTC provides an alternative to DSTC by providing robust cooperative relaying of the source signal. Unlike a regular DSTC, R-DSTC does not allocate the antenna array index to each relay, which simplifies the protocol design and leads to a reduction of signaling cost. A generic cooperative MAC layer protocol is presented in [9] showing the throughput gain of R-DSTC technique over the conventional single-hop and two-hop single-relay, e.g. *CoopMAC*, approaches. However, no detailed MAC layer design and signaling operation are described in [9] to enable randomized cooperation. Furthermore, for simplicity, channel coding and forward error correction are ignored. Also in [9], the transmission rate for the first hop and second hop are picked independently without guaranteeing an end-to-end PER for the packet received.

In this paper, we design a simple yet robust IEEE 802.11 compliant cooperative PHY-MAC cross-layer framework based on R-DSTC, that fully exploits the opportunistic diversity gain of multiple relays. In contrast to our previous results [5], [9], the proposed work in this paper details the MAC layer signaling in an IEEE 802.11 system. Furthermore, it enables fully *distributed* cooperation. Particularly, even stations far away from the source can participate.

The remainder of this paper is outlined as follows. Section

This work is supported by NSF Grant CNS-0520054, by the New York State Center for Advanced Technology in Telecommunications (CATT), and by the Wireless Internet Center for Advanced Technology (WICAT), an NSF Industry/University Cooperative Research Center.

II introduces the PHY layer background of a R-DSTC system and summaries the key advantages that distinguish R-DSTC from a regular DSTC. In Section III, we present a cross-layer protocol that facilitates robust cooperative forwarding. It also describes the opportunistic rate adaptation that R-DSTC employs to optimize the throughput performance. Simulation results in Section IV quantify the significant performance gains of our protocol. In section V, we present conclusions and future work.

II. R-DSTC PHYSICAL LAYER DESCRIPTION

This section introduces the basic operation of the R-DSTC scheme at the PHY layer [8], [10]. In a generic wireless network, suppose a source station intends to transmit a packet to its destination station. The end-to-end transmission takes places in two hops via relay stations. In the first hop, the source station broadcasts its packet to its neighbors. Neighbors that successfully decode the source packet are recruited as relay stations. The R-DSTC encoded signals from all relays are transmitted simultaneously and decoded by a STC receiver at the destination station yielding a considerable diversity gain.

In an R-DSTC system, each relay is allowed to have one or multiple antennas to support R-DSTC using a virtual antenna array. In this paper, we assume that each station is equipped with a single antenna for simplicity.

A single-antenna relay employs a regular single-input and single output (SISO) decoder to decode the information sent by the source station in the first hop. The relay then re-encodes the information bits and passes them to a space-time code (STC) encoder. We assume the underlying space-time codeword $\mathbf{G}$ is of dimension $L \times K$, where L is the number of antennas and K is the block length transmitted by each antenna. Hence, the output from the STC encoder is in the form of L parallel streams, $\mathbf{X}_1$, $\mathbf{X}_2$, ..., $\mathbf{X}_L$, each stream corresponding to an antenna. In a standard MIMO system, the ith antenna would transmit stream $\mathbf{X}_i$ of K symbols. In contrast, in a R-DSTC system, each relay transmits *a linear weighted combination of all L streams*. Each weight is an independently generated random variable with zero mean and variance $1/L$. It is shown in [8], [10] that random variables drawn from the complex Gaussian distribution have desirable properties in terms of error rates. Assuming n relays participate in the second hop, then the vector $\mathbf{r}_i = [r_{j1} \; r_{j2} \; \ldots \; r_{jL}]$, where $j = 1, 2, \ldots n$, represents the random weights at relay j and $\mathbf{R} = [\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_n}]^T$ is the weight matrix for all n relays. The receiver at the destination station is a regular STC receiver with one antenna and is able to decode the received signal with a conventional STC decoding implementation.

A. R-DSTC error rates

In this section, we discuss the computation of BER and PER for the first hop SISO transmissions and the second hop transmissions using R-DSTC. These error rates will be used to select appropriate transmission rates to guarantee the packet error rate at the MAC layer. We first compute the BER performance for SISO and R-DSTC in an Additive White Gaussian Noise (AWGN) channel for a certain modulation level, M, by assuming all the channel gains are fixed. The packet error rate (PER) for a channel code, C, can be then derived numerically for any given BER. In a fading environment, the average PER is derived by averaging over all fading levels.

1) BER performance for direct link (SISO): We assume that the source transmits with a symbol energy of E_s. Then the received signal is

$$y = \sqrt{E_s} h x + w, \tag{1}$$

where y is the received signal and x is the transmitted signal. h is the channel gain and w is complex AWGN with power spectrum density $N_0/2$.

For a M-QAM square constellation, the symbol error rate can be computed as [11]

$$P_{s,h}(M) = 1 - [1 - P_{\sqrt{M}}]^2, \tag{2}$$

with

$$P_{\sqrt{M}} = 2(1 - \frac{1}{\sqrt{M}}) Q\left(\sqrt{\frac{3E_s\|h\|^2}{(M-1)N_0}}\right), \tag{3}$$

where $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-z^2/2}\,\mathrm{d}z$.

If the constellation uses Gray coding, the bit error rate for the M-QAM can be approximated by

$$P_{b,h}^{direct}(M) \approx \frac{1}{\log_2 M} P_{s,h(M)}, \tag{4}$$

where we denote explicitly the dependence on the modulation level M.

Note that the instantaneous BER computation for the SISO transmissions can be applied to the first hop of the proposed two hop cooperative R-DSTC transmissions, because each relay makes decoding decisions independently. The above can also be used to calculate the performance for both hops of the two-hop transmission for CoopMAC with no receiver combining, which employs only one relay. Here we define the BER between AP and node i as $P_{b,i}^{direct}(M) = P_{b,h_i}^{direct}(M)$, and the BER between node pair i and j as $P_{b,ij}^{direct}(M) = P_{b,h_{ij}}^{direct}(M)$.

2) BER performance for R-DSTC: Suppose there are n relays and the symbol energy at each relay is E_s. We consider a space-time code of size $L \times K$, where L is the number of antennas and K is the block length. The underlying space-time code is based on real orthogonal designs, page 55 [12]. For $L = 2, 4, 8$, the orthogonal design provides full rate for a square QAM constellation [11], [12]. Using random weights represented by the vector $\mathbf{r}_j$ for relay j, we can express the transmitted signal from the j'th relay at time m, as

$$z_j(m) = \sqrt{E_s} \mathbf{r}_j \mathbf{X}(m), \tag{5}$$

where $j = 1, 2, \cdots, n$ and $m = 1, 2, \cdots, K$. Here, $\mathbf{X}(m)$ is the m'th column of the STC. We assume that each element of $\mathbf{r}_i$ is an independent complex Gaussian random variable with zero mean and variance $1/L$ [8]. We denote the symbols sent by the STC as u_l, where $l = 1, 2, ..., L$.

The received signal at node i (destination) at the mth symbol interval can be expressed as

$$y_i(m) = \mathbf{H}_i\mathbf{Z}(m)+w_i(m) = \sqrt{E_s}\mathbf{H}_i\mathbf{R}\mathbf{X}(m)+w_i(m), \quad (6)$$

where $\mathbf{H}_i = [h_{i1}\ h_{i2}\ \cdots\ h_{in}]$ is the $1 \times n$ channel vector representing channel gain from each relay to the ith node, $w(m)$ denotes AWGN with power spectrum density $N_0/2$, and $\mathbf{Z(m)} = [z_1(m)\ z_2(m)\ \ldots\ z_n(m)]^T$.

Assuming coherent detection and using the orthogonality of the STC, a sufficient statistics to estimate each symbol, $\widehat{u}_l$ can be expressed as [12]

$$\widehat{u}_l = \sqrt{E_s\|\mathbf{H}_i\mathbf{R}\|^2}u_l + \breve{w}_l, \quad (7)$$

where $\|\cdot\|$ represents for the Frobenius norm and $\breve{w}_l$ is complex Gaussian noise. Hence, we can model the impact of R-DSTC transmissions as an SISO transmission with an equivalent channel gain of $\|\mathbf{H}_i\mathbf{R}\|$. Similarly, BER for the second hop R-DSTC transmissions using M-QAM, $P_{b,i}^{R-DSTC}(\mathbf{H}_i, M)$ can be computed following steps used in Eq. (2) and Eq. (4).

B. PER performance in fading channels using convolutional codes

We employ convolutional coding with rates 1/2, 2/3 and 3/4, using the generator polynomial functions specified in the IEEE 802.11g standard [13]. Assuming the bit errors in the received bit stream, which serves as the input to the channel decoder, are independent and identically distributed (*i.i.d.*), we can use simulations to derive PER for a given BER for different channel codes. The simulation first generates a bit stream, which is than encoded. The coded bits are flipped randomly according to the BER derived above. The output of the decoder is compared with the original bit stream to calculate the PER. We use $PER(C, P_b)$, where C is the coding rate, to denote the PER performance with BER P_b.

In a fading channel, the received signal strength, as well as the PER performance changes over time. The average PER in a fading channel can be calculated by averaging the above computed PER over all possible fading levels. Thus, for any given channel fading statistic, $P_{e,i}^{direct}(M, C)$, the average PER for station i transmitting packets directly to the source, using modulation M and rate C coding used for IEEE 802.11g can be computed by simulations.

Similarly, the average PER between any pair of stations (i,j), $P_{e,ij}^{direct}(M, C)$ and the average PER for a R-DSTC transmission (second hop, from the relays to the destination), using an STC size of L and using n relays, $P_{e,i}^{R-DSTC}(\{1, 2, \cdots, n\}, M, C, L)$, can be computed by assuming the fading is independent across nodes. Here $\{1, 2, \cdots, n\}$ is the index set of n relays.

III. A MAC LAYER FRAMEWORK FOR R-DSTC IN A WIRELESS LAN

A. Wireless LAN Medium Access Control Overview

According to [1], The IEEE 802.11 standards specifies two forms of medium access control (MAC): Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The DCF scheme is based on the carrier sensing multiple access/collision avoidance (CSMA/CA) algorithm and is a collision-based channel access mechanism. Before a station transmits its data packets, it needs to sense the channel to ensure it is idle. Meanwhile, virtual carrier sensing is also employed to avoid collisions, by means of the Request To Send (RTS) and Clear To Send (CTS) frames. In this paper, we will focus on DCF mode with RTS/CTS messaging and develop our R-DSTC based cross-layer framework to be fully backward compatible with current IEEE 802.11 standard.

B. Protocol Design for R-DSTC in a WLAN

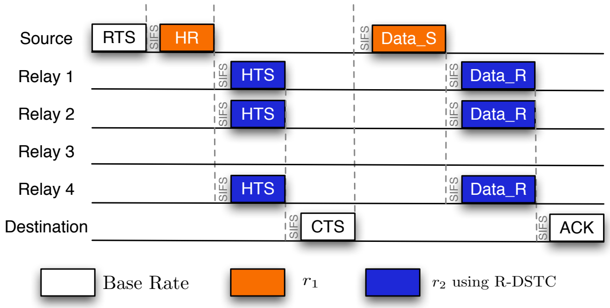

Fig. 1: Signaling procedure for R-DSTC based cooperation.

In order to translate the PHY layer benefits of R-DSTC to enhance the network performance of a wireless LAN, we develop a MAC layer protocol to incorporate R-DSTC in the operation of the DCF mode. RTS/CTS signaling is retained to resolve the hidden terminal problem.

Fig. 1 illustrates the proposed protocol procedure. Before the source station starts its data transmission, it first transmits a RTS frame at the base rate in compliance with the IEEE 802.11 standard. The RTS frame reserves the channel for subsequent signaling and data messages. Then the source continues to send a *Helper-Recruiting (HR)* frame after a *short inter-frame spacing* (SIFS) period. This HR frame is transmitted at the chosen first-hop rate r_1, determined by the modulation level M_1 and code rate C_1. Only those stations that can support rate r_1 from the source can decode the HR frame, which indicates that they will be able to receive the subsequent data packet. By the use of HR, the relays can be recruited on-the-fly even in the presence of fluctuations of the fading channel. More specifically, at different fading levels, the set of recruited relays may vary. As long as the instantaneous channel from the source is strong enough, any station in the network can serve as a relay, no matter how far they are from the source. The HR frame also contains the underlying STC dimension L and the transmission rate r_2, which is specified by the modulation level M_2 and coding rate C_2, for cooperative relaying over the second hop. We separate HR and RTS with a SIFS because these two frames are sent at different rates. In addition, the RTS message is kept unchanged so that our protocol is backward compatible with the current IEEE 802.11 standards.

When the relays successfully decode the HR frame, they *collaboratively* send in unison the *helper-ready to send* (HTS) frame in the same time slot, a SIFS period after HR frame is received. These relays use R-DSTC with rate r_2 and an STC of size L. The HTS frame is initiated for two reasons. Firstly, it is used as an acknowledgement to the source station and indicates that the source signal is correctly received by some relays at the rate r_1. Secondly, the destination station, as long as it receives the HTS frame correctly, can verify that the second hop rate r_2 is achievable and will reply with a CTS message to the source station after a SIFS period.

The above handshaking procedure reduces the potential collisions and packet loss when transmitting a long data packet. The source station then proceeds with sending the *Data-S* frame over the first hop, and the relays cooperatively transmit the *Data-R* frame using R-DSTC over the second hop at rate r_2 with STC dimension L. Finally, the destination station receives *Data-R* and sends back an *Acknowledgement (ACK)* if the data packet is successfully decoded.

In the above protocol, the values of r_1, r_2 and L are jointly optimized by the end-to-end rate adaptation algorithm that will be described in Section III-C. The source station may collect the station-to-station channel statistics by letting each station send a *Hello* packet periodically, which includes its neighbors' average channel signal to noise ratios (SNRs). The numerical results in Section IV show that, if the average channel state information (CSI) on the source-relay(s) link and the relay(s)-destination link are available at the source, the network capacity for R-DSTC based cooperation is much higher than direct transmissions or two-hop single-relay transmissions (*CoopMAC*). However, Section IV also shows that R-DSTC based MAC can deliver a comparable throughput gain *even if the average CSI is not available* at the source station in a R-DSTC system. This advantage considerably eliminates the need for channel estimation and thus greatly reduces the cost of signaling overhead.

C. Rate adaptation

Most wireless networks use rate adaptation to handle variable received SNR values, so that a satisfactory error probability can be maintained. In this paper, the criteria for rate adaptation is to keep the packet error rate below a threshold, γ . Typical values for γ are 5% or 10%. If γ is set too high, there are too many retransmissions and packet losses at the MAC layer. On the other hand, if γ is set too low, the bandwidth is not used efficiently because the communication link could support higher modulation and coding rates. In this section, we derive the optimum two hop data rate and STC size for the downlink. Solution for the uplink can be derived using similar techniques and is not included.

Assume there are N mobile stations in the network, with a PHY layer that is designed to handle different size QAM constellations and various channel coding rates, resulting in a set of transmission rates $R_0, R_1, \ldots, R_p$, where R_0 is the basic rate at which the stations exchange control information, and $R_0 < R_1 < \cdots < R_P$.

1) Transmission rate for direct transmissions (legacy systems): If a source (AP) sends the packet to a destination station i directly, without using any relays, the transmission rate is chosen as

$$r_i^* = \max r \quad s.t. \;\; P_{e,i}^{direct}(M_r, C_r) \leq \gamma, \tag{8}$$

where $r \in \{R_0, R_1, \ldots, R_P\}$, and $P_{e,i}^{direct}(M_{R_p}, C_{R_p})$ is the PER for direct transmissions using a M_{R_p}-QAM modulation and channel coding C_{R_p}. Note that M_{R_p} and C_{R_p} define modulation level and code rates used for rate R_p.

2) Transmission rate for two hop transmissions using one relay (CoopMAC): In CoopMAC [5], before each transmission, the source picks a dedicated relay for the current packet, as well as the suitable first hop and second hop rate. If node j serves as the relay for transmissions to node i, and r_1 and r_2 are the first hop and second hop data rates, the end-to-end PER can be calculated by

$$\begin{aligned} P_{e,i}^{coop}(r_1, r_2, j) = 1 - &\left(1 - P_{e,j}^{direct}(M_{r_1}, C_{r_1})\right) \\ &\times \left(1 - P_{e,ij}^{direct}(M_{r_2}, C_{r_2})\right), \end{aligned} \tag{9}$$

.

The optimum rate pair $r_{i,1}^*$, $r_{i,2}^*$ and relay selection j^* for CoopMAC is the triplet

$$\begin{aligned} (r_{i,1}^*, r_{i,2}^*, j^*)_i = &\arg\min_{r_{i,1}, r_{i,2}, j} \frac{1}{r_1} + \frac{1}{r_2} \\ &s.t. \;\; P_{e,i}^{coop}(r_1, r_2, j) \leq \gamma. \end{aligned} \tag{10}$$

This optimum rate guarantees the end-to-end PER requirement γ, while minimizing channel time used to deliver a packet to the destination in a two hop manner with only one relay.

3) Transmission rate for R-DSTC: The difficulty of the CoopMAC procedure is in selecting and recruiting, on the fly, the best one out of the $N-1$ relays available. The objective of R-DSTC and the proposed MAC 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 our proposed system, rate adaptation only needs to determine the rates for both hops (source to the relays and relays to destination), and the STC size L. Since the PER performance depends on the actual set of relays participating in the forwarding, it is required to examine the performance of using all possible sets of relays to derive the end-to-end packet error performance.

There is a trade-off between picking the first hop rate r_1 and second hop rate r_2. The higher the data rate for the first hop transmission, the less time is consumed for the first hop. But then 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.

Another task for the proposed MAC is to choose a suitable STC to be used by the relays. The diversity gain is limited by the minimum of the STC dimension L and number of relays n [8]. If L is too small, the diversity gain is limited. The MAC should pick an L that is large enough, and at the same time, it should guarantee that there is at least L relays for most of the time. Also, in practice, good space-time codes only exist for particular values of L.

For the set of all mobile stations excluding station i, $S_i = \{1, 2, \cdots, i-1, i+1, \cdots, N\}$, the power set of S_i, denoted by $\mathcal{P}(S_i)$, is the set of all subsets of S_i. The relay set for node i, whose elements are all the possible sets of relays assisting transmission to node i, is denoted by

$$\mathcal{RS}_i = \mathcal{P}(S_i), \tag{11}$$

Since there are $N-1$ possible relay stations, the relay set $\mathcal{RS}_i$ contains 2^{N-1} elements, each corresponding to a possible scenario for the actual relays.

For any $T \in \mathcal{RS}_i$, we define the average probability that all nodes in T receive the packet from the source, and all nodes not in T fail to receive by

$$\begin{aligned} p_i(T) &= \prod_{all\ j\in T} \left(1 - P_{e,j}^{direct}(M_{r_1}, C_{r_1})\right) \\ &\quad \times \prod_{all\ k\notin T} P_{e,k}^{direct}(M_{r_1}, C_{r_1}). \end{aligned} \tag{12}$$

The second hop $P_{e,i}^{R-DSTC}(T, r_1, r_2, L))$, using a fixed set of relays T, can be calculated using $P_{e,i}^{R-DSTC}(\{1, 2, \cdots, n\}, M, C, L)$.

Assuming all links fade independently, the overall end-to-end average PER, considering all possible relaying scenarios, can be expressed by

$$\begin{aligned} &P_{e,i}^{R-DSTC,2hop}(r_1, r_2, L) \\ &= \sum_{all\ T\in\mathcal{RS}_i} \left(p_i(T) \times P_{e,i}^{R-DSTC}(T, M_{r_2}, C_{r_2}, L)\right) \end{aligned} \tag{13}$$

The transmission scheme that maximizes the throughput while maintaining the packet loss rate threshold for transmissions to destination node i, i.e., the triplet (r_1^*, r_2^*, L^*), can be found by solving the following minimization problem:

$$\begin{aligned} (r_1^*, r_2^*, L^*)_i &= \arg\min_{r_1, r_2, L} \frac{1}{r_1} + \frac{1}{r_2} \\ s.t.\ \ P_{e,i}^{R-DSTC,2hop}&(r_1, r_2, L) \le \gamma. \end{aligned} \tag{14}$$

Eq. (13) and Eq. (14) provide the the optimal per-hop rates and STC size. The computational complexity depends on the size of available rate set and STC codes, which is typically not so large. The complexity only linearly scales with the number of users in the system. In a practical scenario, a heuristic algorithm can be adopted to solve for suboptimal r_1, r_2, L with lower complexity. In that case, the optimal solution in this paper represents an upper-bound. Note that equations (13) and (14) only depend on the average channel statistics regarding all inter-user link qualities. Alternatively, the error rate in Eq. (13) can be averaged over all user locations and further used in Eq. (14), leading to an optimal choice of (r_1, r_2, L) which is only a function of the number of users N in the network.

IV. PERFORMANCE EVALUATION

We evaluated the performance of our proposed protocol in a typical wireless LAN environment (IEEE 802.11g) with OPNET Modeler. The simulated scenario consists of one access point (AP) at the center of a cell and N stations that are uniformly distributed in the cell. The simulation is focused on the uplink with the corresponding parameters shown in Table. I. The simulation results display 90% confidence intervals.

TABLE I: Simulation Configuration

Parameters	**Value**
Transmit Power	100 mW
Path loss exponent	2.8
Spectrum bandwidth	20 MHz
PHY layer data rates (Mbps)	6, 9, 12, 18, 24, 36, 48, 54
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Channel coding	Convolutional 1/2, 2/3, 3/4
Packet size	1500 (bytes)
Contention window size	0 - 1023

In our simulation model, we compare R-DSTC with the direct transmission and CoopMAC schemes in terms of throughput and delay metrics. Direct transmission is the legacy method in an IEEE 802.11 system that connects the source and destination pair in a single-hop transmission. In the CoopMAC scheme, only one relay station is chosen to maximize the end-to-end throughput as described in Section III-C. The R-DSTC mechanism is evaluated by two approaches: 1) *R-DSTC channel statistics* and 2) *R-DSTC user count*. *R-DSTC channel statistics* assumes that the station-to-station channel statistics, such as average SNR, is known by the source station and is used to jointly optimize per-hop rate of the source adaptively, while *R-DSTC user count* only needs to know the number of stations in the network and the average received SNR of the source station at the AP. By using this information, *R-DSTC user count* then jointly optimizes per-hop rate and L of the source station by averaging over all possible locations of other stations. Hence, *R-DSTC user count* allows the source station to determine its transmission rates for two hops and L without knowing the deployment of other stations.

Fig. 2 depicts the aggregated throughput performance of a WLAN cell. It shows that the two R-DSTC approaches are significantly superior to the direct transmission and CoopMAC schemes. As the number of stations increases, throughput for direct transmission decreases due to increased collision probability. The performance for CoopMAC increases with the number of stations, since the probability of finding a better relay increases with node density, which offsets the performance loss due to collisions. However, the improvement is limited. In contrast, R-DSTC throughput increases greatly when the number of stations is large. The reason is that R-DSTC can substantially boost the end-to-end transmission rate for each station and thus results in a high system throughput gain even if the collisions occur more frequently.

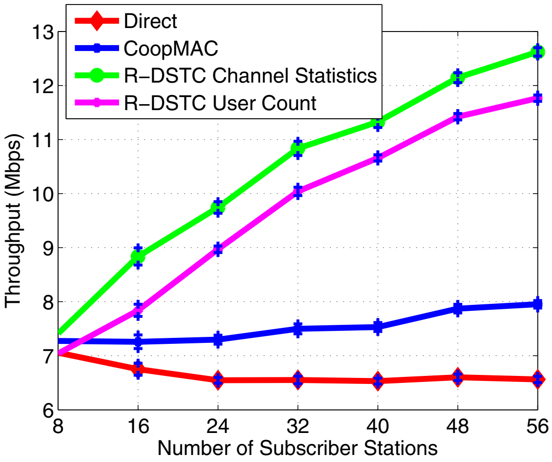

Fig. 2: Aggregated Cell Throughput Performance.

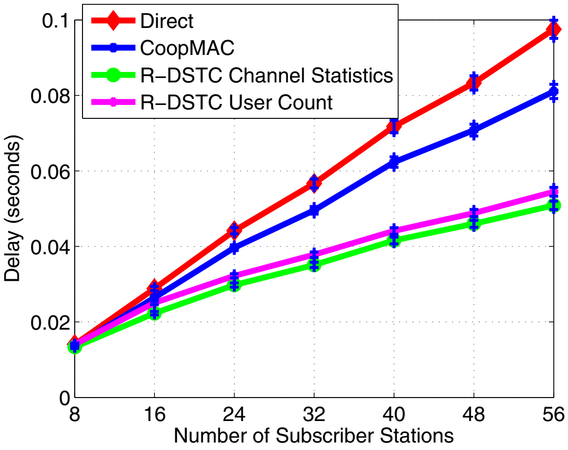

Fig. 3: Average Delay Performance.

Fig. 3 demonstrates the average head-of-line delay in a WLAN cell. This delay is measured from the moment when a packet becomes the head-of-line packet to the moment when that packet is successfully received. It reveals an increase in the number of stations in the WLAN system leads to increasing delay for all schemes. However, R-DSTC achieves the lowest delay performance compared to direct transmission and CoopMAC transmission, since R-DSTC supports a higher end-to-end rate for each connection.

An important insight from in Fig. 2 and Fig. 3 is that the *R-DSTC User Count* scheme achieves a throughput and delay performance comparable to *R-DSTC Channel Statistics* does, even for a moderate number of stations. Since *R-DSTC User Count* does not need to collect the station-to-station channel statistics, the measurement and bandwidth overhead is reduced. Thus, our proposed MAC protocol, especially *User Count*, can translate the R-DSTC PHY layer advantages to upper layer gains with its minimal channel estimation requirements. This suggests that our protocol can be easily applied in a practical WLAN system.

V. CONCLUSION

In this paper, we develop a cross-layer framework with R-DSTC in a WLAN system. The PHY-MAC protocol incorporates R-DSTC into the operation of the mandatory DCF MAC of a WLAN network and provides a framework for robust cooperative communications. The proposed protocol is simple and backward compatible, yet it realizes a significant performance gain over the legacy system and single relay based CoopMAC. It works for both the infrastructure mode and ad hoc mode of WLAN. Compared with [5] and [7], it enables a fully *distributed* yet *robust* cooperation using multiple relays. The signaling and channel feedback overhead is reduced significantly. In our future work, we will analyze the performance of our R-DSTC based MAC protocol in a mobile environment.

REFERENCES

[1] “Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” *ANSI/IEEE Std 802.11, 1999 Edition*, 1999.

[2] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, “Performance Anomaly of 802.11b,” in *Proc., IEEE INFOCOM*, San Francisco, CA, April 2003.

[3] A. Sendonaris, E. Erkip, and B. Aazhang, “User Cooperation Diversity - Part I: System Description,” *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1938, November 2003.

[4] ——, “User Cooperation Diversity - Part II: Implementation Aspects and Performance Analysis,” *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, November 2003.

[5] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, “CoopMAC: A Cooperative MAC for Wireless LANs,” *IEEE Journal on Sel. Areas in Communications*, vol. 25, no. 2, pp. 340 – 354, February 2007.

[6] P. Liu, Z. Tao, Z. Lin, E. Erkip, and S. Panwar, “Cooperative Wireless Communications: A Cross-Layer Approach,” *IEEE Communications Magazine, Special Issue on MIMO Systems*, August 2006.

[7] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. V. Krishnamurthy, and O. Ercetin, “A Framework for Distributed Spatio-Temporal Communications in Mobile Ad hoc Networks,” in *Proc., IEEE INFOCOM*, Barcelona, Spain, April 2006.

[8] B. S. Mergen and A. Scaglione, “Randomized space-time coding for distributed cooperative communication,” *IEEE Transactions on Signal Processing*, pp. 5003–5017, October 2007.

[9] P. Liu, Y. Liu, T. Korakis, A. Scaglione, E. Erkip, and S. Panwar, “Cooperative MAC for rate adaptive randomized distributed space-time coding,” in *Proc., IEEE Globecom*, Nov 2008.

[10] B. Sirkeci-Mergen and A. Scaglione, “Randomized space-time coding for distributed cooperative communication,” in *ICC*, 2006.

[11] J. G. Proakis, *Digital Communications (Fourth edition)*. McGraw Hill, 2000.

[12] H. Jafarkhani, *Space-Time Coding: Theory and Practice, Page. 55*. Cambridge University Press, 2005.

[13] IEEE P802.11g, “Further Higher-Speed Physical Layer Extension in the 2.4 GHz Band,” *IEEE Standard*, 2003.