STiCMAC: A MAC Protocol for Robust Space-Time Coding in Cooperative Wireless LANs

Pei Liu⋆, Chun Nie⋆, Thanasis Korakis⋆, Elza Erkip⋆, Shivendra Panwar⋆, Francesco Verde †, Anna Scaglione⋄

⋆ Polytechnic Institute of New York University, Brooklyn, NY, USA

† University of Naples, Federico II, Italy

⋄ University of California, Davis, USA

Abstract

Relay-assisted cooperative wireless communication has been shown to have significant performance gains over the legacy direct transmission scheme. Compared with single relay based cooperation schemes, utilizing multiple relays further improves the reliability and rate of transmissions. Distributed space-time coding (DSTC), as one of the schemes to utilize multiple relays, requires tight coordination between relays and does not perform well in a distributed environment with mobility. In this paper, a cooperative medium access control (MAC) layer protocol, called *STiCMAC*, is designed to allow multiple relays to transmit at the same time in an IEEE 802.11 network. The transmission is based on a novel DSTC scheme called *randomized distributed space-time coding* (*R-DSTC*), which requires minimum coordination. Unlike conventional cooperation schemes that pick nodes with good links, *STiCMAC* picks a *transmission mode* that could most improve the end-to-end data rate. Any station that correctly receives from the source can act as a relay and participate in forwarding. The MAC protocol is implemented in a fully decentralized manner and is able to opportunistically recruit relays on the fly, thus making it *robust* to channel variations and user mobility. Simulation results show that the network capacity and delay performance are greatly improved, especially in a mobile environment.

Index Terms

Space-Time Code MAC (*STiCMAC*), Randomized Distributed Space-Time Coding (R-DSTC), cooperative communications, medium access control, protocol design, IEEE 802.11

This paper is a revised version of a paper with the same name submitted to IEEE Transaction on Wireless Communications. STiCMAC protocol with RTS/CTS turned off is presented in the appendix of this draft.

I. Introduction

Cooperative wireless communication [1]–[4] techniques exploit the broadcast nature of the wireless channel by allowing stations that overhear other transmissions to relay information to the intended destination, thereby yielding higher reliability and throughput than direct transmission. While initial cooperative communication schemes [1], [2] employ a single relay, subsequent work [4] allows multiple relays to forward signals at the same time, each mimicking an antenna of a multiple antenna transmitter by using a *distributed space-time code* (DSTC). For a DSTC based transmission scheme, relays must be carefully coordinated. Before each packet transmission, a central node/controller selects and indexes all the relays it wants to recruit. This decision must be known by each of the selected relays, so that they know *who* participates in cooperation and *which* signal stream of the DSTC each of them transmits. In a distributed environment with mobility, this leads to extra signaling overhead. Furthermore, the controller needs global channel knowledge in order to optimize system performance. Another drawback of this scheme is that nodes other than those being chosen are prohibited from relaying, while at the same time, the chosen relays might fail to participate in forwarding the signal due to fading or noise. Those inherent drawbacks lead to inefficiencies in implementing a DSTC-based protocol.

The above drawbacks can be addressed by employing *randomized distributed space-time coding* (R-DSTC) [5], which eliminates the requirement of space-time code (STC) codeword assignment and reduces the coordination between the source and the relays. R-DSTC provides a robust cooperative relaying scheme in contrast to a DSTC based system, and has the potential of simplifying the protocol design, thus leading to a reduction in signaling cost.

In a cooperative environment, physical (PHY) layer cooperation needs to be integrated with a medium access control (MAC) layer in order to recruit relays as well as coordinate transmissions and receptions. *CoopMAC* [6], as one of the first MAC layer designs to support a cooperative PHY layer in a wireless LAN (WLAN), enables cooperation under the IEEE 802.11 framework. Since the low data-rate stations at the edge consume the majority of the channel time, the aggregate throughput is severely degraded [7]. *CoopMAC* alleviates this problem by allowing transmissions to take place in a two hop manner. As the transmissions over both hops are accomplished at a high rate, a considerable improvement is achieved in the aggregated throughput. The performance of CoopMAC, albeit superior to direct communication, is still limited as it only selects a single relay, which is a disadvantage when it is employed in a fading environment. While utilizing multiple relays at the PHY layer greatly improves the reliability of transmissions, it remains unclear how such techniques can be employed to deliver significant network capacity gains for a loosely synchronized network such as the IEEE 802.11.

In this paper, we design a robust MAC layer protocol called *STiCMAC* (Space-Time coding for Cooperative MAC), which is compliant with the IEEE 802.11 standard and enables R-DSTC based cooperation. *STiCMAC* allows one to harvest cooperative diversity from multiple nodes in a decentralized manner. In this scheme, if a data packet from the source needs to be relayed, all potential relays listen to the transmission from the source and try to decode. Assuming error detection mechanisms such as cyclic redundancy check (CRC) are employed at the relays, only relays that successfully decode the packet forward to the destination in *unison* using R-DSTC. In order to do so, the handshaking procedure defined by the IEEE 802.11 standard is extended to allow relays be recruited in an opportunistic manner while ensuring that the transmissions from multiple relays are collision free.

The main contribution of this paper is that it fundamentally changes the way 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 STC) that could most improve the end-to-end rate on the average. Relays decide to participate or not to participate independently based on whether they receive the packet or not. In fact, neither the source or destination station need to know who the relays are or where they are located. STiCMAC is an optimized PHY/MAC cross-layer scheme that can be implemented in a fully *decentralized* manner and is able to opportunistically recruit relays *on the fly* at minimum signaling cost for an infrastructure-based IEEE 802.11 network.

We evaluate the system performance of *STiCMAC*, and employ cross-layer optimization to find suitable transmission parameters, i.e., per-hop rates and STC dimension, that maximize the end-to-end rate. Optimization of transmission parameters is performed assuming either a complete knowledge of average channel statistics for both hops, or simply considering the number of stations in each WLAN cell. We call these two approaches *STiCMAC with channel statistics* (*STiCMAC-CS*) and *STiCMAC with user count* (*STiCMAC-UC*) respectively. We investigate the aggregated network throughput and the average delay for all stations in both a static and mobile environment. Our results suggest that both STiCMAC-CS and STiCMAC-UC have similar performance, especially for a large number of users. This outcome strongly supports our argument that the proposed scheme does not need a priori knowledge of channel conditions, as opposed to DSTC. Additionally, simulation results show that both types of *STiCMAC* significantly outperform DSTC in terms of throughput and delay, due to lower signaling cost, and also outperform *CoopMAC* and direct transmission due to increased diversity. While the performance of DSTC and *CoopMAC* significantly decreases under mobility, *STiCMAC* is more robust, and in particular *STiCMAC-UC* shows minimal performance degradation in a mobile environment. Finally, we conduct a study of the interference propagated to neighboring wireless LANs for all transmission schemes. Simulation results show that, for the same traffic load, the average interference generated by *STiCMAC* is similar to DSTC, and much less than *CoopMAC* and direct transmission.

A related work [8] proposes a MAC layer protocol that deploys DSTC in an *ad hoc* network to assist network layer routing. This allows cooperative transmissions from multiple relays, however, its performance and practicality for a mobile network are still limited due to the limitations of DSTC outlined above. Opportunistic routing [9] is a routing protocol for *ad hoc* networks that allows one node closest to the destination to forward in case multiple nodes receive from the previous hop. Compared with STiCMAC, which operates in MAC/PHY cross-layer, opportunistic routing operates in the network layer. The other difference is that STiCMAC allows an end-to-end multihop transmission within a single channel access and queuing is not necessary at the relays. STiCMAC also allows signals from multiple relays to be combined coherently in the PHY layer. Another use of the term "opportunistic" appears in the cooperative communications literature in [10], however, the notion there is to select relays based on instantaneous channel state. Generic MAC protocols for R-DSTC are designed in [11], [12], where transmission parameters are optimized given the bit error rate, assuming no channel coding is employed. Without forward error correction coding, those schemes can cause error propagation by allow relays to forward even if erroneous packets are received. These papers mostly focus on the PHY layer characteristics that enable the use of randomized codes in realistic wireless networks, and do not explicitly investigate MAC layer details. STiCMAC is the first protocol derived from the IEEE 802.11 where practical MAC layer aspects of randomized cooperation are addressed.

We note that synchronization is an important issue for all transmission schemes that allow multiple stations to transmit at the same time on the same frequency. As demonstrated in [13], symbol level synchronization in DSTC based transmission is feasible on a software defined radio platform with commercially available IEEE 802.11 components and a customized FPGA. Thus we believe necessary synchronization for R-DSTC, which is more robust to synchronization errors than DSTC [14], can also be implemented.

The rest of this paper is outlined as follows. Section II introduces the PHY layer background for R-DSTC. In Section III, we present the *STiCMAC* protocol in detail. Section IV develops two opportunistic rate adaptation schemes for *STiCMAC* to optimize the transmission parameters. Section V presents the simulation results and the performance evaluation. Finally, in Section VI, we present conclusions.

II. R-DSTC Physical Layer Description

An STC is designed to operate over several antennas at the same transmitter station. In contrast, DSTC employs an STC over multiple relays in a distributed manner. When these relays cooperatively forward a signal, each relay corresponds to a specific antenna element of the underlying STC, and transmits a predefined STC encoded stream. The advantage of DSTC lies in its capability to form a virtual MIMO system by using these relays and producing diversity gain, even if each station is only equipped with one antenna. The performance of DSTC and the diversity gain obtained has been studied in [3].

R-DSTC is introduced and examined in [5] as a novel form of DSTC. Like conventional DSTC, R-DSTC is deployed in a cooperative scenario with multiple relays along with a source and destination pair and operates over two hops. Although R-DSTC can be employed using relays with multiple antennas, we assume that each station is only equipped with a single antenna. The scenario with multiple antennas per station can be easily extended from the single-antenna case.

Fig. 1 shows a single-antenna relay that employs a regular single-input and single output (SISO) decoder to decode the information sent by the source station in the first hop. Provided the information is decoded correctly, as determined by checking the CRC field, the relay is responsible for re-encoding the information bits and passing them to an STC encoder. Suppose the underlying space-time codeword has a dimension $L \times K$, where L is the number of antennas and K is the block length transmitted by each antenna. The STC encoder generates an output of L parallel streams, each stream corresponding to an antenna. Unlike a regular DSTC where the jth relay simply transmits the stream j, in a R-DSTC system the jth relay transmits *a linear weighted combination of all L streams*. The weights of the L streams at the jth relay are denoted by a vector $\mathbf{w}_j = [w_{j1} \; w_{j2} \; \ldots \; w_{jL}]$. Each element in $\mathbf{w}_j$ is an independently generated random variable with zero mean and variance $1/L$. As described in [5], a complex Gaussian distribution is adopted for the distribution of the weights since it has desirable properties in terms of PHY layer error rates. Assuming n relays simultaneously transmit in the second hop, the vector $\mathbf{w}_j$, where $j = 1, 2, \ldots n$, represents the random weights at relay j and $\mathbf{R} = [\mathbf{w_1}, \mathbf{w_2}, \ldots, \mathbf{w_n}]^T$ is the weight matrix for all these n relays. The destination station is assumed to have one antenna and is able to decode the received signal with a conventional STC decoder.

The physical layer fundamentals of R-DSTC is described in detail in [5], where it is shown that R-DSTC comes very close to the performance of DSTC in terms of PHY layer properties and can provide the full diversity order of L with at least L relays. A major advantage of the R-DSTC technique over DSTC lies in the fact that the source station does not need to specifically select its relays as well as to assign antenna indices to each relay. In R-DSTC, the source and destination remain unaware of which stations act as relays and which random weight vector has been used in relays. These features enable R-DSTC to be a fully decentralized scheme in a cooperative environment.

III. STiC MAC: A Robust Cooperative MAC Layer Framework

While R-DSTC has been mainly studied in the PHY layer, an efficient MAC layer protocol is essential in order to enable its use in a real environment and to translate its PHY layer benefits to performance gain in the upper layers. This section presents a robust MAC layer protocol, called *Space-Time coding in Cooperative MAC* (*STiCMAC*), in support of R-DSTC in an IEEE 802.11 WLAN environment. In this paper, we consider a WLAN operating in the infrastructure mode, where an access point (AP) works as a central unit. The proposed MAC protocol is mainly composed of two parts: (1) a three-way handshake, which includes relay recruiting and acknowledgements; (2) cooperative two-hop data transmission. The three-way handshaking takes care of all signaling among the source, destination and relays. During the handshaking procedure, relays are recruited simultaneously and opportunistically according to each relay's instantaneous channel conditions, while no other stations, except for the selected relays, needs to know these channel conditions. Cooperative two-hop data transmission occurs when relays receive the necessary transmission parameters. The details of *STiCMAC* are explained in the rest of this section.

A. Wireless LAN Medium Access Control Overview

In the IEEE 802.11 WLAN standard [15], Distributed Coordination Function (DCF) is the mandatory MAC protocol. Since DCF is contention based, stations employ carrier sensing multiple access/collision avoidance (CSMA/CA) algorithm to resolve collisions. Under this scheme, each station can starts a packet transmission only if it senses the channel to be free. However, due to sensing range limitations, two stations could be sending to a common receiver simultaneously. This phenomena is referred to as the hidden node problem. In order to avoid such scenarios, virtual carrier sensing is employed, by means of the Request-to-Send (RTS) and Clear-To-Send (CTS) frames. These two control frames broadcast the duration for the upcoming data transmission so that stations that do not participate in this transmission withhold their own transmissions until the end of the ongoing packet transmission. In this paper, we focus on the DCF mode with RTS/CTS messaging and develop a cross-layer framework for a distributed cooperative system based on IEEE 802.11. STiCMAC with RTS/CTS turned off is presented in the appendix of this paper.

B. Protocol Design for R-DSTC in WLANs

In this subsection, we introduce the *STiCMAC* protocol that enables R-DSTC in an infrastructure-based WLAN under DCF mode. *STiCMAC* enables relay discovery and concurrent cooperative transmissions from all relays to the destination. Without loss of generality we consider that the source of a transmission is a station while the destination is the AP. A symmetric scheme with the same characteristics can be applied for the downlink transmission (from the AP to the stations).

In order to enable all relays to forward a packet in unison, the MAC layer needs to provide critical parameters for the cooperative transmission. The required transmission include the transmission rates for both hops, and the underlying space-time code for the second hop. Let us denote r_1 as the first-hop rate, r_2 as the second-hop rate, and L as the STC dimension. We assume that R-DSTC uses a class of underlying orthogonal STC's parameterized by the code dimension L. A proper joint selection of these parameters can optimize the MAC layer performance. Details of such an optimization will be provided in Section IV. Additionally, the MAC layer must also provide timing information for both hops, as a data packet undergoes a two-hop transmission. In *STiCMAC*, a three-way handshaking procedure is initiated by the source to disseminate these transmission parameters, followed by the data transmission. Fig. 2 illustrates how *STiCMAC* works for a single packet transmission, which consists of the following steps:

a. The Three Way Handshaking Phase

1) The source station initiates the handshaking by transmitting a RTS frame at the base rate in compliance with the IEEE 802.11 protocol. The RTS frame reserves the channel for subsequent signaling and data messages. The source continues with the transmission of the second control frame, called *Helper-Recruiting* (HR) frame, a *short inter-frame spacing* (SIFS) period after the

transmission of the RTS frame. This HR frame is transmitted at the chosen first-hop rate r_1 using a corresponding physical layer modulation level and channel coding rate. Only those stations that have a channel strong enough to decode the HR message are likely to receive the subsequent data packet correctly at the same rate. Thus, all stations receiving the HR frame correctly are recruited as relays for the current data packet forwarding. Since recruiting of the relays is conducted on the fly, this procedure is fully decentralized. The exact set of recruited relays may vary from packet to packet due to channel variations or mobility, enabling fully opportunistic use of relays. The HR frame contains the underlying STC dimension L and the hop-2 rate r_2, which is characterized by a modulation scheme and channel coding rate.

2) A SIFS time after the HR frame, the recruited relays send in unison the helper-to-send (HTS) frame using R-DSTC. The transmission is at the second-hop rate r_2, using an STC of size L. The HTS message is jointly transmitted by all relays that successfully decoded the HR message from the source station. Since a single STC is employed by all the relays, only a single HTS message is received and decoded by the destination station without causing a collision. The HTS frame is employed for the following reasons. Firstly, it is used as an acknowledgement to the source station that one or more relays have been recruited. Secondly, the destination station, as long as it receives the HTS frame correctly, can verify that those relays can indeed support a rate r_2 transmission to the destination, even though it doesn't explicitly know which stations act as relays. Thirdly, HTS frame helps to alert the hidden terminals around the relays and avoid a possible collision.
3) The destination responds with a CTS frame, which signals the end of the three-way handshaking among all participants. The above handshaking procedure reduces the likelihood of a data packet collision which is especially in the case of a long data packet.

b. Data Transmission Phase

1) In the data transmission stage, the source station proceeds with sending the data frame over the first hop, at rate r_1. We call this frame *Data-S* frame.
2) The recruited relays cooperatively transmit the data frame over the second hop, at rate r_2. We denote this frame as *Data-R*. The transmission employs an STC dimension of L.
3) The destination station finishes the procedure by sending back to the sender an *Acknowledgement (ACK)* message in order to confirm that the data packet is successfully received.

The above protocol is backward compatible with standard IEEE 802.11 WLAN protocol since RTS/CTS follows the same format as defined in standard WiFi. Legacy stations can read the *Duration* field and set their *Network Allocation Vector (NAV)*, which indicates how long the surrounding nodes must defer from accessing the channel. Thus legacy stations can co-exist with STiCMAC stations, even though they cannot participate in the cooperative transmissions. The newly introduced *HR* and *HTS* messages do lead to some additional overhead, which is evaluated in Section V.

IV. Rate Adaptation

Rate adaptation refers to the adjustment of the values of the transmission parameters, e.g., for *STiCMAC*, the first hop rate r_1, second hop rate r_2 and STC dimension L, based on the network conditions. In this section, we develop a rate adaptation mechanism to maximize the end-to-end user rate while meeting an acceptable error probability. Our rate adaptation scheme is subject to an end-to-end packet error rate (PER) threshold γ, before MAC layer retransmissions are initiated. The selection of γ affects the system performance. A high γ leads to too many retransmissions due to high packet loss at the MAC layer, while a low γ leads to an under-utilized bandwidth since the communication link could support higher modulation and coding rates. Rate adaptation also requires calibration in the physical layer [16] for a practical system. Considering that the main focus of this paper is the MAC protocol design, we do not address this issue in detail and assume that all stations have been calibrated.

We assume each station supports a set of transmission rates $r \in \{R_0, R_1, \ldots, R_p\}$, where R_0 is the base rate at which the stations exchange control information, i.e., RTS/CTS, and $R_0 < R_1 < \cdots < R_p$. A given r is identified by the modulation level M_r and the channel coding level C_r. In addition, we denote the STC code rate as R_c. We assume an additive white Gaussian noise (AWGN) channel with independent slow Rayleigh fading between each pair of stations and between the stations and the AP. Each fading level is assumed to be longer than a packet duration. All stations have a symbol energy of E_s and the power spectral density of noise signal is $N_0/2$.

In order to present our rate adaptation scheme, we first formulate the PHY layer error rates, i.e. per-hop bit error rate (BER), per-hop PER and end-to-end PER performance. Along with R-DSTC, we also calculate for comparison the PHY layer error rates for the direct transmission scheme, the two-hop single-relay (*CoopMAC*) scheme and the DSTC scheme.

The BER and PER for a direct connection between stations i and j are respectively denoted as

$P_b^{ij}(r, h_{ij})$ and $P_p^{ij}(r, h_{ij})$ for a fixed rate r and instantaneous channel gain h_{ij} between stations i and j. Let us denote $i = s$ when station i is the source and $j = d$ when station j is the destination. Assuming the instantaneous channel gain vector from all relays to the destination is denoted as $\mathbf{h^{(2)}}$, where $\mathbf{h^{(2)}} = [\ldots, h_{jd}, \ldots]$, the BER and PER between relays and the destination for DSTC with space-time codeword dimension L are denoted by $P_{b,hop2}^{DSTC}(r, L, \mathbf{h^{(2)}})$ and $P_{p,hop2}^{DSTC}(r, L, \mathbf{h^{(2)}})$, respectively. Similarly, when the instantaneous channel gain vector $\mathbf{h^{(2)}}$ weighted by the instantaneous random matrix $\mathbf{R}$ is defined as $\mathbf{h^{(2)}}\mathbf{R}$, the BER and PER between relays and the destination for R-DSTC with space-time codeword dimension L are denoted as $P_{b,hop2}^{R-DSTC}(r, L, \mathbf{h^{(2)}}, \mathbf{R})$ and $P_{p,hop2}^{R-DSTC}(r, L, \mathbf{h^{(2)}}, \mathbf{R})$, respectively, for a given r. When these instantaneous PHY layer error rates are averaged over channel fading levels, the average BER and PER rates can be obtained accordingly. Table I lists all parameters and notation used in this section. Based upon the analysis of PHY layer error rates, rate adaptation optimizes the transmission parameters for all transmission strategies with an objective to maximize the end-to-end rate for each station while ensure an end-to-end PER bounded by γ.

A. R-DSTC PHY Layer Per-hop BER Performance

In the suggested two-hop framework, note that the BER for the first hop between the source and a potential relay can be computed using the direct link formulation. We denote the second hop between all the relays and the destination as the *cooperative R-DSTC link*. This subsection formulates the BER performance for both links.

1) BER performance for a direct link: In a direct link with an instantaneous channel gain h_{ij} along with rate r (corresponding to modulation level M_r, assuming square modulation) between stations i and j, the symbol error rate is given by

$$P_s^{ij}(r, h_{ij}) = 1 - [1 - P_{\sqrt{M_r}}]^2, \tag{1}$$

with

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

where $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-z^2/2}\,\mathrm{d}z$. If Gray coding is used in the constellation, the approximate BER is

$$P_b^{ij}(r, h_{ij}) \approx \frac{1}{\log_2 M_r} P_s^{ij}(r, h_{ij}). \tag{3}$$

When station i is the source and station j is a relay, Eq. (3) describes the instantaneous BER performance from the source to a relay, since each relay decodes the source signal independently. Additionally, Eq. (3) gives the per-hop BER performance for a *CoopMAC* system [6] for both hops, when a single relay is employed without combining the first and second hop signal at the receiver.

2) BER performance for the cooperative R-DSTC link: Assuming n relays, i.e., stations $1 \ldots n$, successfully decode the source signal, each relay forwards the signal over the *cooperative R-DSTC link*. Suppose the STC used by the relays has a dimension of $L \times K$ [17]. During symbol interval m, $m = 1, 2, \cdots, K$, the forwarded signal from relay j is given by

$$z_j(m) = \sqrt{E_s}\mathbf{w}_j\mathbf{X}(m), \tag{4}$$

where $j = 1, 2, \cdots, n$, and $\mathbf{w}_j$ is the random vector at relay j, as described in Section II. Here, $\mathbf{X}(m)$ is the mth column of the STC. The received signal at the destination, during the mth symbol interval is given by,

$$y(m) = \mathbf{h^{(2)}}\mathbf{Z}(m) + w(m) = \sqrt{E_s}\mathbf{h^{(2)}}\mathbf{R}\mathbf{X}(m) + w(m), \tag{5}$$

where $w(m)$ denotes the AWGN at the mth symbol, and $\mathbf{Z}(\mathbf{m}) = [z_1(m)\ z_2(m)\ \ldots\ z_n(m)]^T$. Hence, the destination station observes a space-time coded signal with equivalent channel gain vector $\mathbf{h^{(2)}}\mathbf{R}$. The destination only needs to estimate $\mathbf{h^{(2)}}\mathbf{R}$ for STC decoding. By using the orthogonality of the underlying STC [17], the BER of the cooperative R-DSTC link using rate r, L and a fixed $\|\mathbf{h^{(2)}}\mathbf{R}\|$, denoted by $P_{b,hop2}^{R-DSTC}(r, L, \mathbf{h^{(2)}}, \mathbf{R})$, can be computed by replacing $\|h_{ij}\|$ with $\|\mathbf{h^{(2)}}\mathbf{R}\|$ in Eq. (3).

Note that for an orthogonal DSTC with a space time codeword dimension L, each of the L relays is assigned an antenna index. Hence, there is no randomization and $\mathbf{R} = \mathbf{I}$. Therefore, the BER of DSTC, denoted by $P_{b,hop2}^{DSTC}(r, L, \mathbf{h^{(2)}})$, can also be determined from Eq. (3) by replacing $\|h_{ij}\|$ with $\|\mathbf{h^{(2)}}\|$.

B. End-to-End PER Performance for R-DSTC

We derive the average PER by simulations, using the BER formulation in Section IV-A along with the channel code. Each relay adopts a convolutional code C_r for error correction, for a given rate r. In our simulation, for each hop we first produce the coded bits and then generate random errors according to the computed instantaneous BER. This bit stream is then fed into the convolutional decoder to produce the decoded bit sequence. The instantaneous PER for both hops is then obtained by comparing the output bit stream at the destination with the original bit stream.

Let us denote by $\mathcal{RS}$ the instantaneous set of relays that correctly decode the source signal in the first hop and jointly forward the signal over the second hop. In the first hop, the instantaneous channel gain vector is defined as $\mathbf{h}^{(\mathbf{1})}$ including all h_{ij}, $j \in \mathcal{RS}$. Consequently, for a given r_1, r_2, L, the end-to-end instantaneous PER between station i and the destination for the R-DSTC scheme is given by

$$P_p^{R-DSTC}(r_1, r_2, L, \mathbf{h}^{(\mathbf{1})}, \mathbf{h}^{(\mathbf{2})}, \mathbf{R}) = 1 - \sum_{\mathcal{RS} \in \mathcal{PS}(\mathcal{S}_i)} P(\mathcal{RS}) \times \Big(1 - P_{p,hop2}^{R-DSTC}(r_2, L, \mathbf{h}^{(\mathbf{2})}, \mathbf{R})\Big), \tag{6}$$

where

$$P(\mathcal{RS}) = \prod_{j \in \mathcal{RS}} (1 - P_p^{ij}(r_1, h_{ij})) \times \prod_{j \notin \mathcal{RS}} P_p^{ij}(r_1, h_{ij}), \tag{7}$$

In Eq. (6), S_i denotes all stations excluding the source station i, and $\mathcal{PS}(\mathcal{S}_i)$ is the power set of $\mathcal{S}_i$. $P(\mathcal{RS})$ is the probability that an instantaneous relay set $\mathcal{RS}$ is recruited. $P_p^{ij}(r_1, h_{ij})$ denotes the instantaneous PER between station i and relay j over the first hop, while $P_{p,hop2}^{R-DSTC}(r_2, L, \mathbf{h}^{(\mathbf{2})}, \mathbf{R})$ denotes the instantaneous PER from all relays in $\mathcal{RS}$ to the destination, over the second hop.

Following Eq. (6) for instantaneous end-to-end PER, the average end-to-end PER can be obtained by averaging over all first and second hop channel gains and the random weight vector $\mathbf{R}$, and is given by

$$P_p^{R-DSTC}(r_1, r_2, L) = \mathbb{E}_{\mathbf{h}^{(\mathbf{1})}, \mathbf{h}^{(\mathbf{2})}, \mathbf{R}} \left\{ P_p^{R-DSTC}(r_1, r_2, L, \mathbf{h}^{(\mathbf{1})}, \mathbf{h}^{(\mathbf{2})}, \mathbf{R}) \right\}. \tag{8}$$

C. End-to-End PER Performance for Other Schemes

Below we formulate the end-to-end PER performance for the other schemes in order to provide comparison with the proposed R-DSTC scheme. For the direct transmission scheme, the average end-to-end PER between the source station i and the destination can be found using the direct-link instantaneous PER, and is given by

$$P_p^{direct}(r) = \mathbb{E}_{h_{id}} \left\{ P_p^{id}(r, h_{id}) \right\}, \tag{9}$$

where the direct rate is r and $P_p^{id}(r, h_{id})$ denotes the instantaneous PER between source station i and the destination for a given h_{id} and r.

For *CoopMAC* scheme, the average end-to-end PER performance of source station i also depends on the chosen single relay j, $j \in \mathcal{S}_i$ and is given by

$$P_p^{coop}(r_1, r_2, j) = \mathbb{E}_{h_{ij}, h_{jd}} \left\{ 1 - \left(1 - P_p^{ij}(r_1, h_{ij})\right) \times \left(1 - P_p^{jd}(r_2, h_{jd})\right) \right\}, \tag{10}$$

where h_{ij} and h_{jd} denote the instantaneous channel gain for the first and second hops, respectively. $P_p^{ij}(r_1, h_{ij})$ and $P_p^{jd}(r_2, h_{jd})$ denote the instantaneous PER for the two hops, for a given h_{ij} and h_{jd}.

For DSTC, the instantaneous end-to-end PER between source i and destination d depends on a fixed and predefined relay set, denoted as $\mathcal{RS}_i$, and is formulated as

$$P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i) = \mathbb{E}_{\mathbf{h^{(1)}}, \mathbf{h^{(2)}}} \left\{ P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i, \mathbf{h^{(1)}}, \mathbf{h^{(2)}}) \right\}. \tag{11}$$

In Eq. (11), $P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i, \mathbf{h^{(1)}}, \mathbf{h^{(2)}})$ denotes the instantaneous end-to-end PER and is given by

$$P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i, \mathbf{h^{(1)}}, \mathbf{h^{(2)}}) = 1 - \sum_{\mathcal{RS}' \in \mathcal{PS}(\mathcal{RS}_i)} (1 - P_{p,hop2}^{DSTC}(r_2, L, \mathbf{h^{(2)}})) \times P(\mathcal{RS}'), \tag{12}$$

where

$$P(\mathcal{RS}') = \prod_{j \in \mathcal{RS}'} (1 - P_p^{ij}(r_1, h_{ij})) \times \prod_{j \notin \mathcal{RS}'} P_p^{ij}(r_1, h_{ij}), \tag{13}$$

$\mathcal{RS}'$ is an instantaneous subset of relays from $\mathcal{RS}_i$ that participate in relaying and $P_{p,hop2}^{DSTC}(r_2, L, \mathbf{h^{(2)}})$ denotes the instantaneous PER between relays and the destination for fixed rate r_2, STC dimension L and channel gains $\mathbf{h^{(2)}}$ based on relays in $\mathcal{RS}'$.

D. Optimizing end-to-end rate and the choice of transmission parameters

We now describe how to choose the optimal transmission parameters in order to maximize the end-to-end transmission rate for each station, while ensuring the end-to-end average PER is bounded by γ. Even though our emphasis is on R-DSTC, we also discuss direct transmission, *CoopMAC* and DSTC schemes. In our rate adaptation, every scheme relies on knowledge of the average channel statistics rather than the instantaneous channel gains, thus making it suitable for a WLAN where the average channel statistics change slowly. Assuming the WLAN channel is reciprocal, the source station can estimate the average channel statistics for direct transmission and relayed transmission by listening beacons from AP and overhearing transmissions of other stations. For WLAN systems are typically a stationary or low-mobility environment, the average channel statistics are measured and reported every few seconds, producing only negligible performance loss in throughput. We also discuss rate adaptation based only on number of users in the network.

The set of transmission parameters is different for each scheme and is discussed below. In this paper, all transmission parameters are computed at the source station, as opposed to the protocol in [12] that conducts the computation at the destination station. The maximum end-to-end rate of station i is achieved by minimizing the end-to-end transmission time for each scheme. In addition, we will also discuss the channel information assumed by each scheme for rate adaptation.

1) Direct transmission scheme: When the source station i transmits to the destination directly, assuming the source station knows the channel statistics to the destination, the optimal transmission parameter is the transmission rate r and the optimum rate r^* is given by

$$r^* = \max r \qquad s.t. \;\; P_p^{direct}(r) \leq \gamma, \tag{14}$$

where $P_p^{direct}(r)$ is given by Eq. (9). Note that the optimal transmission rate r is modified whenever the source or destination move to a new location, since the average channel gain for the direct link changes.

2) Two-hop single-relay (CoopMAC) scheme: We assume there is no signal combining at the destination. A practical MAC protocol for this scheme is *CoopMAC* [6]. Assuming the source knows the channel statistics between itself and all other stations and between other stations and the destination, the transmission parameters include r_1, r_2 and the selected relay j. In *CoopMAC* [6], the optimum relay information is stored in a *CoopTable* at each source station. The optimum rates r_1^*, r_2^* and the best relay j^* are selected by minimizing the end-to-end transmission time over two hops, and is formulated by

$$(r_1^*, r_2^*, j^*) = \arg\min_{r_1, r_2, j} \frac{1}{r_1} + \frac{1}{r_2} \qquad s.t. \;\; P_p^{coop}(r_1, r_2, j) \leq \gamma, \tag{15}$$

where $P_p^{coop}(r_1, r_2, j)$ is given by Eq.(10). When the network topology changes, e.g., the source, destination or any other station move to new locations, the optimal parameters are reselected using Eq. (15). Hence, *CoopMAC* is more suitable for a stationary environment with low mobility. When the stations move rapidly, the demand for collecting the global channel knowledge leads to a large overhead for the system. An inaccurate estimation of the channel results in a non-optimal rate adaptation scheme and thus degrades the system performance, as further illustrated in Section V.

3) DSTC scheme: Assuming the available space-time codewords have dimensions denoted by $T = \{L_1, L_2, \ldots, L_{max}\}$, DSTC needs to select its relay set $\mathcal{RS}_i$ consisting of L relays, where $L \in T$ and $L = |\mathcal{RS}_i|$. Thus, the transmission parameters are rates r_1, r_2, L and $\mathcal{RS}_i$. Similar to *CoopMAC*, the source station is assumed to know the average channel statistics between itself and each stations and between other stations and the destination. The optimum transmission parameters can be obtained by,

$$(r_1^*, r_2^*, L^*, \mathcal{RS}_i^*) = \arg\min_{r_1, r_2, L, \mathcal{RS}} \frac{1}{r_1} + \frac{1}{R_c r_2} \qquad s.t. \;\; P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i) \leq \gamma, \tag{16}$$

where $P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i)$ is given by Eq.(11), and R_c is the rate of the orthogonal STC with dimension L. It is known that it is only possible to have full rate (R_c = 1) orthogonal STC for L = 2, otherwise $R_c < 1$ [17]. With N stations in the single-cell WLAN excluding the destination AP, there are $\sum_{L \in T} \binom{N-1}{L}$ possible relay sets $\mathcal{RS}_i$ containing L relays. An exhaustive search for all possible relays in $\mathcal{RS}_i$ leads to a combinatorial complexity, it is prohibitively expensive to solve online.

In order to reduce the complexity of relay selection, we propose a greedy algorithm and use it to evaluate DSTC performance in Section V. The basic idea is to sequentially add L relays to the optimal relay set. For each step, we find a single relay that, when combined with the relays selected in the previous steps, will maximize the end-to-end throughput if DSTC is used to assist transmissions from the source. For the first relay, we choose the best relay from the N-1 stations that maximizes the end-to-end rate in a two-hop manner (single relay based CoopMAC [6]) and add it into the relay set. Then, the second relay is chosen from the remaining N-2 stations in such a way that it can achieve the maximal end-to-end rate along with the first selected relay, using DSTC. Such a selection is iterated until all L relays are picked and added to the relay set. Our simulation shows only 5% throughput difference between this greedy algorithm and exhaustive search when L=2 and N=10.

Like *CoopMAC*, DSTC need to reselect the transmission parameters whenever the network topology changes and incurs a large amount of channel estimation overhead especially in a mobile environment.

4) STiCMAC scheme: One difficulty of the *CoopMAC* and *DSTC* strategies is in choosing the optimal L^* ($L^* = 1$ for *CoopMAC* and $L^* > 1$ for *DSTC*) relays out of the $N - 1$ other stations. In contrast, the R-DSTC based *STiCMAC* eliminates such a requirement, and thus the transmission parameters only include rates r_1, r_2, and the STC size L, and not the relay set. For the *STiCMAC* strategy, we develop two classes of rate adaptation algorithms based upon different channel knowledge:

- The *STiCMAC-CS* scheme is assumed to have the same channel knowledge of channel statistics as in DSTC and *CoopMAC*. That is, the source station i is assumed to know the channel statistics between itself and other stations and between other stations and the destination. The optimal transmission parameters r_1^*, r_2^*, L^* are given by

$$(r_1^*, r_2^*, L^*) = \arg\min_{r_1, r_2, L} \frac{1}{r_1} + \frac{1}{R_c r_2} \qquad s.t.\;\; P_p^{R-DSTC}(r_1, r_2, L) \leq \gamma, \tag{17}$$

  where the end-to-end PEP for R-DSTC is given by Eq. (8) and R_c is the rate of the orthogonal STC of dimension L. The rate adaptation scheme for *STiCMAC-CS* is described in Algorithm. 1. The optimal set (r_1^*, r_2^*, L^*) is exhaustively searched over all possible combinations. Each source station executes this algorithm to find the optimum transmission parameters whenever any of channel gains change. Similar to the limitation of *CoopMAC* and DSTC, *STiCMAC-CS* requires a global channel knowledge and thus is relatively costly in a mobile scenario.
- *STiCMAC-UC* scheme provides rate adaptation with minimal channel information. Unlike *STiCMAC-CS*, *CoopMAC* and DSTC, the source station i is only assumed to know the channel statistics between itself and the destination, together with N, the number of stations in the WLAN. [1] *STiCMAC-UC* determines its optimal rate parameters by simply ensuring the average PER over all possible spatial locations of stations, is bounded by γ, assuming all stations are uniformly located using a random spatial distribution χ, as shown in the following equation,

$$(r_1^*, r_2^*, L^*) = \arg\min_{r_1, r_2, L} \frac{1}{r_1} + \frac{1}{R_c r_2} \qquad s.t.\;\; \mathbb{E}_\chi\Big(P_p^{R-DSTC}(r_1, r_2, L)\Big) \leq \gamma. \tag{18}$$

  STiCMAC-UC scheme is described in detail in Algorithm 2 and only depends on the number of stations in the WLAN without the need for their specific locations. Since *STiCMAC-UC* requires less information, for a specific location of users, it yields suboptimal operating parameters compared to *STiCMAC-CS*. However, *STiCMAC-UC* eliminates extra signaling for channel measurements and is suitable for a mobile environment where collecting global channel statistics is hard and costly. Note that DSTC and *CoopMAC* need to pre-determine the relays before a transmission can be initiated, hence cannot be based on merely the number of users.

[1] Alternatively, a reasonable assumption is for the source to estimate the statistics of the relays' links towards itself, while being unaware of relays-destination average channel qualities. The performance of such a scheme would be between *STiCMAC-CS* and *STiCMAC-UC*.

For all rate adaptation schemes with full channel statistics, namely *direct*, *CoopMAC*, *DSTC* and *STiCMAC-CS*, we assume optimal parameters are recomputed whenever the channel statistics change. For *STiCMAC-UC*, a two-dimensional look-up table can be pre-computed for the optimal transmission parameters and saved at each source, corresponding to the total number of stations, N, and the distance from the source to the AP in each cell. Once a station enters or leaves the WLAN cell, the BS will broadcast such user count information in its beacon frame to all stations and each station can update its optimal transmission parameters. Thus, *STiCMAC-UC* does not need real-time computation during network operation. Obviously, in all the relay-assisted schemes, if the end-to-end rate derived by the used rate adaptation scheme is lower than the direct transmission rate, the source station chooses the direct transmission mode instead of cooperation.

V. Performance Evaluation

In order to evaluate the performance of the proposed *STiCMAC* scheme, we developed a detailed simulation model using OPNET modeler. We compare *STiCMAC* with direct transmission, *CoopMAC* and DSTC MAC for both stationary and mobile environments. Additionally, all schemes use the rate adaptation algorithm described in Section IV. The comparison and evaluation was done on a typical single-cell WLAN.

A. Network Topology and Configuration

We assume that the considered wireless LAN complies with the IEEE 802.11g standard and the cell radius is 100 meters. Independent Rayleigh slow 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 of a cell and N mobile stations. According to [17], both for DSTC and R-DSTC, a full-rate orthogonal STC is employed for $L = 2$ with R_c = 1, while a R_c = 3/4 rate orthogonal STC is employed for $L = 3, 4$. Each AP or mobile station is equipped with a single omnidirectional antenna. Our simulations are conducted on the uplink from the mobile stations to the AP, with the parameters shown in Table. II. The simulation results display 90% confidence intervals.

B. Mobility Model

Our simulations are performed for both stationary and mobile scenarios. In the stationary scenario, all stations are uniformly distributed within the cell coverage. In the mobile scenario, the stations are assumed to move across the cell using the *random walk with reflection* (*RWkRlc*) model [18]. The *RWkRlc* model is widely adopted to characterize the movement of mobile stations. The *RWkRlc* model initially deploys stations randomly according to a uniform distribution over the cell. Then, it assigns a random speed to each station that is uniformly distributed in the range [V_{min}, V_{max}]. Each station picks a random travel duration uniformly distributed in the range [T_{min}, T_{max}] and a uniformly distributed random direction. Once a station has walked for the selected duration of time, it may dwell for a random amount of time T_d based upon a uniform distribution before it reselects a new travel duration, speed and direction. In contrast to the classic *Random Walk* model [19], the *RWkRlc*-governed model includes *reflection* as an additional feature. Namely, whenever a station reaches the cell boundary during its walk, it will be reflected by the boundary in a similar way that a ray of light reflects off a mirror. This reflection functionality will ensure that the random walk is bounded within a given cell coverage. Accordingly, the *RWkRlc* model produces a uniform spatial distribution of all stations across the cell and thus enables us to make a fair comparison with the static scenario. The typical parameters of the *RWkRlc* model we used are shown in Table II.

C. Simulation Results

Fig. 3 depicts the MAC layer throughput performance of a single station as a function of its distance to the AP, assuming N=48 stations are uniformly distributed in a static wireless LAN. When the station is close to the AP, all schemes fall back to direct transmission and thus achieve the same throughput. As the distance to the AP grows, all the two-hop schemes outperform the direct transmission, since two high-speed hops provide a higher end-to-end throughput than a low-speed direct transmission, especially as the stations get closer to the cell edge. For large distances, *STiCMAC-CS* and *STiCMAC-UC* schemes show the highest per-station throughput gains, followed by the *DSTC* and *CoopMAC*.

Fig. 4 displays the comparison of the aggregate throughput in a stationary environment as a function of N, the number of stations. When the number of stations is less than 16, the two *STiCMAC* schemes, *STiCMAC-CS* and *STiCMAC-UC*, provide throughput performance comparable to *CoopMAC* and *DSTC*, while all the cooperative schemes provide a higher throughput than direct transmission. Note that for a small number of stations, *DSTC* performs worse than the other two-hop schemes, due to the increased overhead for relay recruitment. Compared to *CoopMAC*, the extra overhead needed by *DSTC* includes the pilot tones (1 time slot for each pilot which is 9 μseconds) and relay indices (1 byte for each relay) sent by the source to the selected relays, as well as the acknowledgements (1 time slot which is 9 μseconds for each relay) from all these relays before every packet transmission is initiated, as is described in [8]. The more relays are recruited by *DSTC*, the higher the overhead. As the number of stations increases, *STiCMAC* shows a significant throughput gain over the other schemes (up to 50% gain over direct) due to the following reasons: a) A large number of stations lead to a larger probability of finding more relays, which results in higher diversity and power gain over the second hop. b) Compared to the DSTC MAC [8], *STiCMAC* needs substantially reduced signaling overhead and handshaking. Also, the overhead of *STiCMAC* is constant and independent of the number of relays, while the DSTC overhead increases as the number of relays increases. It is also noted that the aggregate throughput of *STiCMAC-UC* is only slightly lower than *STiCMAC-CS*. This is because a sufficiently large number of stations supplies enough potential relays and thus eliminates the need for a global knowledge of node locations. This validates our argument that *STiCMAC* operates efficiently without a global knowledge of channel statistics.

Fig. 5 depicts the throughput performance of all schemes in a mobile environment where each station moves according to the *RWkRlc* model. Under mobility, we assume channel statistics are updated every 2 seconds. Hence each source station can only perform rate adaptation with 2 second intervals. In contrast to the stationary scenario, the throughput of all schemes except *STiCMAC-UC* degrade relative to the static case as mobility leads to an inaccurate estimation of channel information, resulting in sub-optimal rate adaptation. For example, in *CoopMAC* and *DSTC*, the selected relay stations may move away due to mobility and become unavailable in the forwarding phase. From Fig. 5, it is clear that *STiCMAC* schemes outperform the others in terms of throughput. Under mobility, *STiCMAC-UC* performance is superior to that of *STiCMAC-CS*. Therefore in a mobile environment, *STiCMAC-UC* scheme is preferable since it does not rely on the instantaneous spatial distribution of all stations for rate adaptation, and thus leads to more robust throughput performance.

Fig. 6 and Fig. 7 demonstrate the medium access delay for a stationary and mobile environment respectively under full load. This delay is measured from the moment that a packet becomes the head-of-line packet in the MAC transmission buffer to the moment that that packet is successfully received at the MAC layer of the receiver. The figures reveal that a large number of stations leads to an increase in medium access delay for all schemes due to the increased delay before successful access to the channel. However, *STiCMAC* achieves the lowest delay compared to direct transmission, *CoopMAC* and the *DSTC*, since R-DSTC supports a higher end-to-end rate for each connection, and therefore decreases the end-to-end transmission time.

In addition to throughput and delay performance, *STiCMAC* also reduces the interference generated to neighboring cells when loaded with traffic at the same level. This is because *STiCMAC* supports a higher average data rate per packet transmission and thus needs reduced air time to deliver the same amount of data on an end-to-end basis, as compared to the other schemes. Consequently, the average transmission power emanating from the reference cell is reduced, even though more relays have been recruited. Fig. 8 shows the interference in a mobile scenario where the average interference power generated by a cell is calculated assuming N=24 users in each cell. The average interference power is illustrated in Fig. 8 and measured in units of dBm at a distance of (100 - 300 m) away from the AP of the reference cell. We observe that both *STiCMAC* schemes generate less interference compared to *DSTC*, *CoopMAC* and direct transmission. In conclusion, *STiCMAC* generates less interference at the same MAC layer traffic load compared to the other schemes.

VI. Conclusion

In this paper, we develop a PHY/MAC cross-layer protocol we call *STiCMAC* by employing R-DSTC in a WLAN system. The *STiCMAC* protocol incorporates randomized cooperative PHY layer into the operation of the mandatory DCF MAC of a WLAN to provide robust cooperative communications using multiple relays. The proposed protocol is simple and it realizes a significant performance gains in terms of throughput, delay and interference reduction over various other single-hop and multi-hop mechanisms (e.g., *CoopMAC* and *DSTC*). The new MAC is backward compatible with IEEE 802.11. Although only the infrastructure mode is discussed in this paper, similar ideas also apply to ad hoc WLANs. Compared to previously known two-hop schemes [6], [8], STiCMAC enables a fully *distributed* yet *robust* cooperation using multiple relays. The signaling and channel feedback overhead is reduced due to randomized cooperation, resulting in a significant MAC layer throughput improvement. The robustness of *STiCMAC* translates to high gains, even in the more challenging mobile environment. Indeed, the relative gains are higher for *STiCMAC* in the mobile environment.

Appendix

The operation of IEEE 802.11 MAC is based on carrier sensing, and it also employs virtual carrier sensing (RTS/CTS) to minimize the hidden terminal problem. In order to keep backward compatibility with the legacy system, the design of STiCMAC works with RTS/CTS.

STiCMAC also works without using RTS/CTS frames. In such a scenario, the source can directly starts a data packet transmission and embed transmission parameters necessary for the second hop transmission (using R-DSTC) in a separate shim header field of the first hop data packet. Any relays that decode it would be able to forward the packet to the destination using R-DSTC.

We conducted simulations to show how STiCMAC performs without RTS/CTS protection, and the results demonstrate that STiCMAC still outperforms other transmission schemes. The following figures illustrate the throughput and delay without using the RTS/CTS mechanism. It is shown in Fig. 9 that all schemes display degraded performance as compared to the performance using RTS/CTS. This is because our simulations assume all stations are heavily loaded to show saturated throughput. Therefore, a large number of packet collisions occur because of CSMA/CA based channel access. Additionally, the packet size of the simulation is 1500 bytes, and thus the system performance degrades when not protected by RTS/CTS. While RTS/CTS could be less efficient when the traffic load is light, STiMAC continues to work well without RTS/CTS.

For a network with moderate mobility (1-2 meters/second), as shown in in Fig. 10, the throughput of all schemes is affected. However, STiCMAC is still superior to all other schemes including direct transmission, CoopMAC and DSTC.

References

[1] 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.

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

[3] J. N. Laneman and G. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. on Info. Theory*, vol. 49, no. 10, Oct 2003.

[4] J. N. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. on Info. Theory*, vol. 50, no. 12, December 2004.

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

[6] 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.

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

[8] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. V. Krishnamurthy, and O. Ercetin, “A framework for distributed spatio-temporal communications in mobile ad hoc metworks,” in *Proc., IEEE INFOCOM*, Barcelona, Spain, April 2006.

[9] S. Biswas and R. Morris, “Opportunistic routing in multi-hop wireless networks,” *ACM SIGCOMM Computer Communication Review*, vol. 34, no. 1, January 2004.

[10] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, “A simple cooperative diversity method based on network path selection,” *IEEE Journal on Sel. Areas in Communications*, vol. 24, no. 3, 2006.

[11] 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.

[12] F. Verde, T. Korakis, E. Erkip, and A. Scaglione, “A simple recruitment scheme of multiple nodes for cooperative MAC,” *IEEE Trans. on Communications*, vol. 58, no. 9, September 2010.

[13] P. Murphy and A. Sabharwal, “Design, Implementation and Characterization of a Cooperative Communications System,” *IEEE Trans. on Veh. Technology*, vol. 60, no. 6, July 2011.

[14] M. Sharp, A. Scaglione, and B. Sirkeci-Mergen, “Randomized Cooperation in Asynchronous Dispersive Links,” *IEEE Trans. on Communications*, vol. 57, no. 1, pp. 64–68, Jan 2009.

[15] IEEE Std 802.11-2007, “Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” *IEEE Standard*, June 2007.

[16] G. Judd, X. Wang, and P. Steenkiste, “Efficient Channel-aware Rate Adaptation in Dynamic Environments,” in *ACM MobiSys Conf.*, Breckenridge, CO, June 2008.

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

[18] M. McGuire, “Stationary Distributions of Random Walk Mobility Models for Wireless Ad Hoc Networks,” in *Proc., ACM International Symposium on Mobile Ad hoc Networking and Computing*, Urbana-Champaign, IL, May 2005.

[19] T. Camp, J. Boleng, and V. Davies, “A survey of mobility models for ad hoc network research,” *Wireless Communications and Mobile Computing*, vol. 2, no. 5, pp. 483–502, 2002.

TABLE I: Notation Used in the Paper

Notation	Description
N	Number of stations in a WLAN excluding the AP
r_1, r_2	The first and second hop rates
L	STC dimension for the underlying space-time code
γ	End-to-end PER threshold
M_r, C_r	Modulation, channel coding for rate r
E_s	Symbol energy
$N_0/2$	Power spectral density of AWGN
h_{ij}	Instantaneous channel gain between stations i and j
$\mathbf{h^{(1)}}$	Instantaneous channel gain vector between source and relays
$\mathbf{h^{(2)}}$	Instantaneous channel gain vector between relays and destination
$\mathcal{RS}_i$	Deterministic relay set of source station i for DSTC
$\mathcal{RS}$	Instantaneous relay set of source station i for R-DSTC
$P_b^{ij}(r, h_{ij})$ $P_p^{ij}(r, h_{ij})$	BER for a direct connection between stations i and j for given r and h_{ij}. PER for a direct connection between stations i and j for given r and h_{ij}.
$P_{b,hop2}^{R-DSTC}(r, L, \mathbf{h^{(2)}}, \mathbf{R})$ $P_{p,hop2}^{R-DSTC}(r, L, \mathbf{h^{(2)}}, \mathbf{R})$	BER for R-DSTC between relays and destination for given r, L, $\mathbf{h^{(2)}}$ and $\mathbf{R}$. PER for R-DSTC between relays and destination for given r, L, $\mathbf{h^{(2)}}$ and $\mathbf{R}$.
$P_{b,hop2}^{DSTC}(r, L, \mathbf{h^{(2)}})$ $P_{p,hop2}^{DSTC}(r, L, \mathbf{h^{(2)}})$	BER for DSTC between relays and destination for given r, L and $\mathbf{h^{(2)}}$. PER for DSTC between relays and destination for given r, L and $\mathbf{h^{(2)}}$.
$P_p^{id}(r, h_{id})$	End-to-end PER for a direct transmission for given r and h_{id}.
$P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i, \mathbf{h^{(1)}}, \mathbf{h^{(2)}})$	End-to-end PER for DSTC for given r_1, r_2, L, $\mathcal{RS}_i$, $\mathbf{h^{(1)}}$ and $\mathbf{h^{(2)}}$.
$P_p^{R-DSTC}(r_1, r_2, L, \mathbf{h^{(1)}}, \mathbf{h^{(2)}}, \mathbf{R})$	End-to-end PER for R-DSTC for given r_1, r_2, L, $\mathbf{h^{(1)}}$, $\mathbf{h^{(2)}}$ and $\mathbf{R}$.
$P_p^{direct}(r)$	Average end-to-end PER for a direct transmission for given r.
$P_p^{coop}(r_1, r_2, j)$	Average end-to-end PER for CoopMAC for given r_2, r_2 and relay j.
$P_p^{R-DSTC}(r_1, r_2, L)$	Average end-to-end PER for R-DSTC for given r_1, r_2 and L.
$P_p^{DSTC}(r_1, r_2, L, \mathcal{RS}_i)$	Average end-to-end PER for DSTC for given r_1, r_2, L and $\mathcal{RS}_i$.

TABLE II: Simulation Configuration and Mobility Modeling

Parameters	Value
Received E_s/N_0 at edge	1.4
Path loss exponent	3.0
Propagation Model	ITU-T Indoor Model and Rayleigh fading
Spectrum bandwidth	20 MHz
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 [15]
Acceptable MAC Layer PER γ	5%
MAC Layer PDU size	1500 bytes
Contention window size	0 - 1023
Underlying orthogonal STC dimension, L,	2,3,4
Achievable STC code rates, R_c	1 ($L = 2$), 3/4 ($L = 3, 4$)
Min Speed (V_{min})	1 meter/second
Max Speed (V_{max})	2 meter/second
Dwell Time during Walk (T_d)	1 second
Min Travel Duration per Step (T_{min})	2 second
Max Travel Duration per Step (T_{max})	5 second

Algorithm 1 Rate Adaptation for STiCMAC Channel Statistics

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 orthogonal STC dimensions for R-DSTC is L, where $L \in \{L_1, L_2, ..., L_{max}\}$. Initialize $R^* = 0$.

for Each possible set of transmission parameters $\{r_1,\ r_2,\ L\}$ **do**

  Find $P_p^{R-DSTC}(r_1, r_2, L)$ for R-DSTC using Eq.(8).

  if $P_p^{R-DSTC}(r_1, r_2, L) < \gamma$ and $\frac{1}{1/r_1+1/r_2} > R^*$ **then**

    $R^* \leftarrow \frac{1}{1/r_1+1/r_2}$, $L^* \leftarrow L$, $r_1^* \leftarrow r_1$, $r_2^* \leftarrow r_2$

  end if

end for

Algorithm 2 Rate Adaptation for STiCMAC User Count

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 orthogonal STC dimensions for R-DSTC is L, where $L \in \{L_1, L_2, ..., L_{max}\}$. Suppose all stations are located in the WLAN cell based on a random distribution function χ. Initialize $R^* = 0$.

for Each possible set of transmission parameters $\{r_1,\ r_2,\ L\}$ **do**

  for All possible locations of other stations **do**

    Find $P_p^{R-DSTC}(r_1, r_2, L)$ for R-DSTC transmission using Eq. (8) and average over all these locations using χ.

  end for

  if $\mathbb{E}_\chi\big(P_p^{R-DSTC}(r_1, r_2, L)\big) < \gamma$ and $\frac{1}{1/r_1+1/r_2} > R^*$ **then**

    $R^* \leftarrow \frac{1}{1/r_1+1/r_2}$, $L^* \leftarrow L$, $r_1^* \leftarrow r_1$, $r_2^* \leftarrow r_2$

  end if

end for

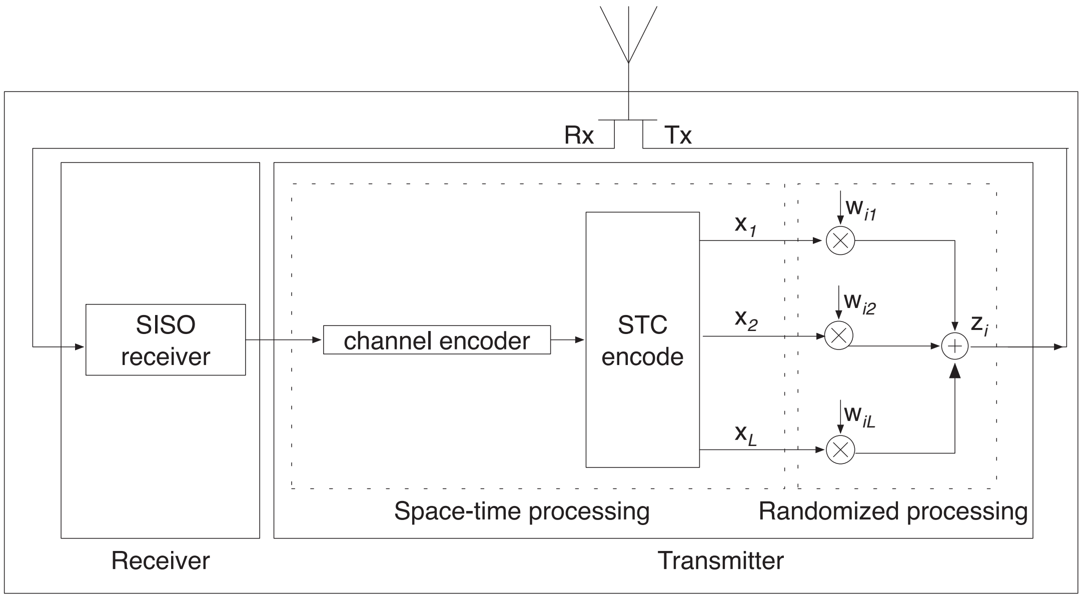

Fig. 1: R-DSTC signal processing in a relay.

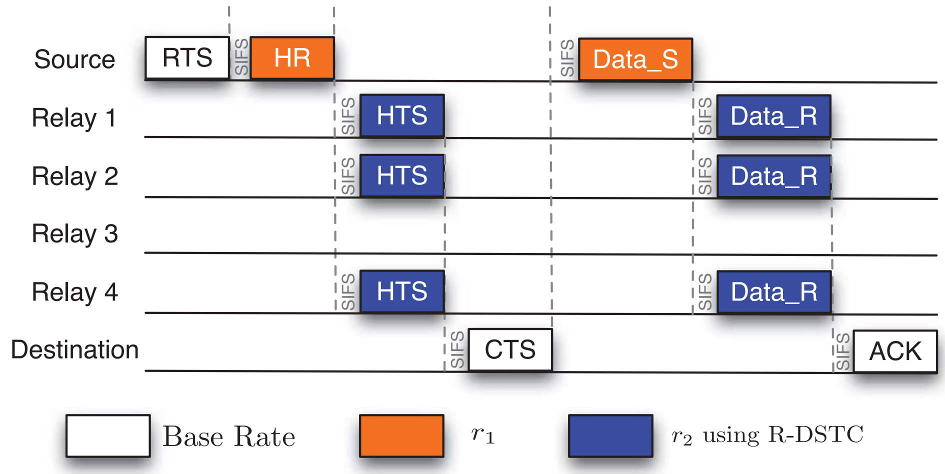

Fig. 2: Signaling procedure for *STiCMAC* based cooperation.

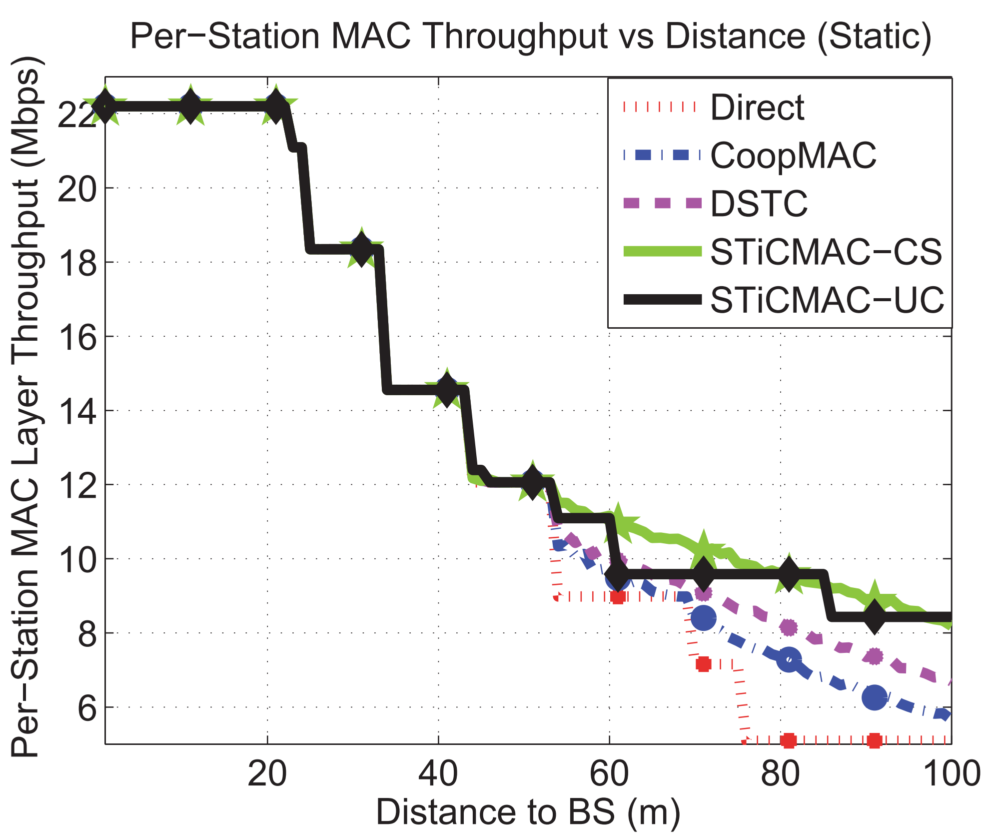

Fig. 3: Per station MAC layer throughput vs distance (meters) to AP

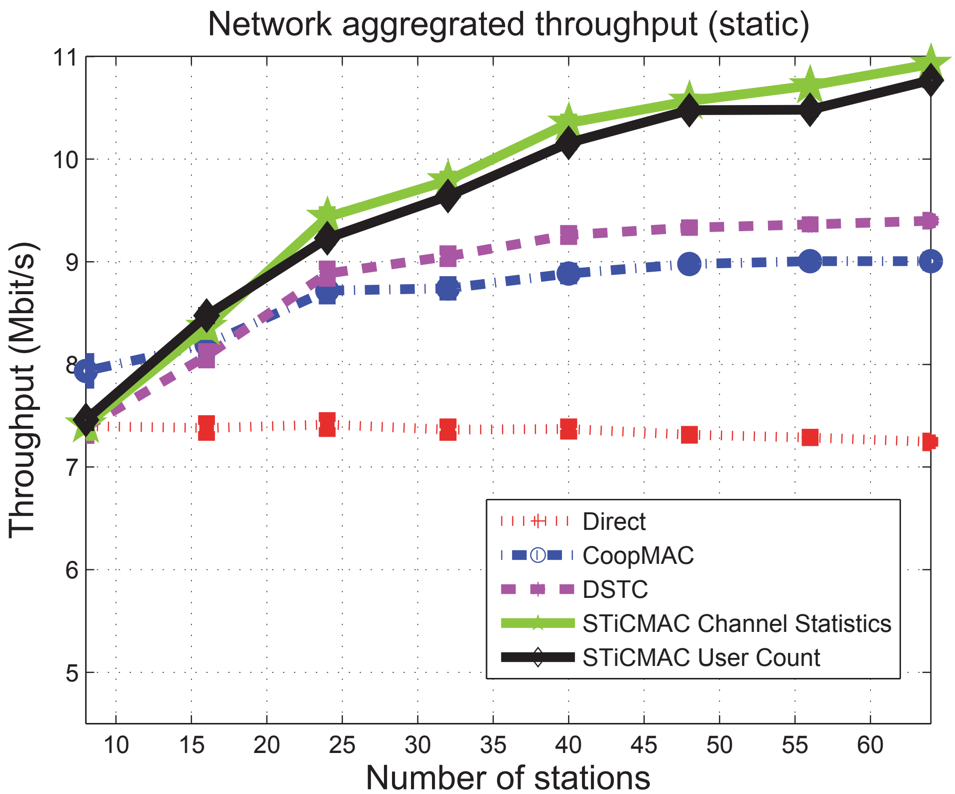

Fig. 4: Throughput comparison for the static environment.

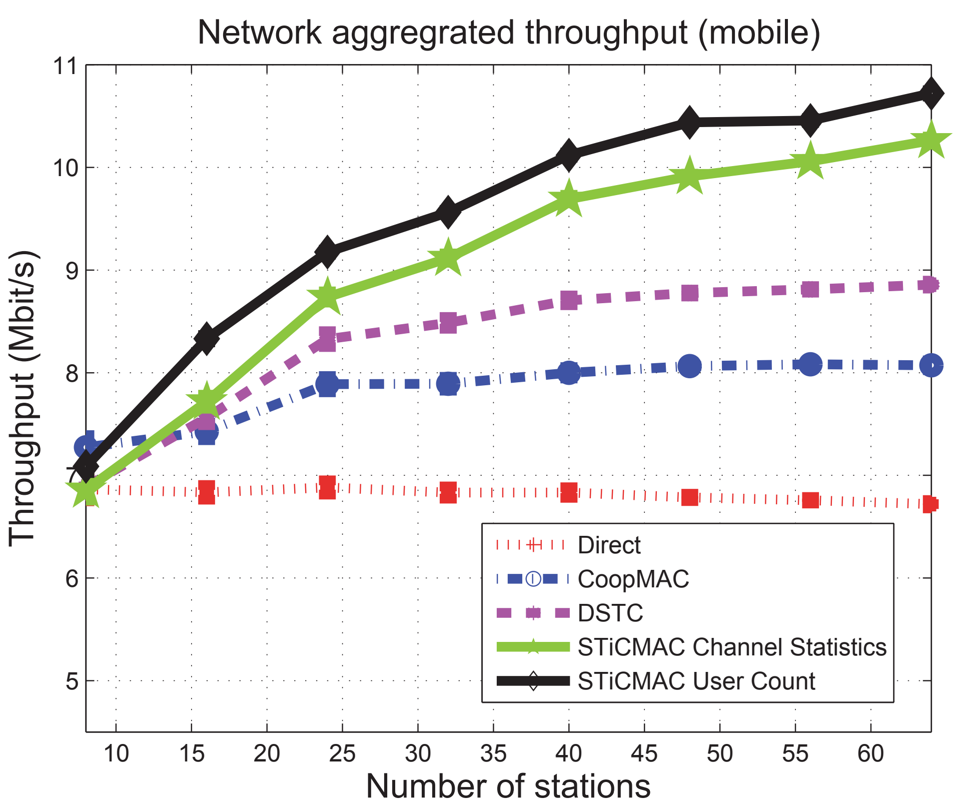

Fig. 5: Throughput comparison for the mobile environment.

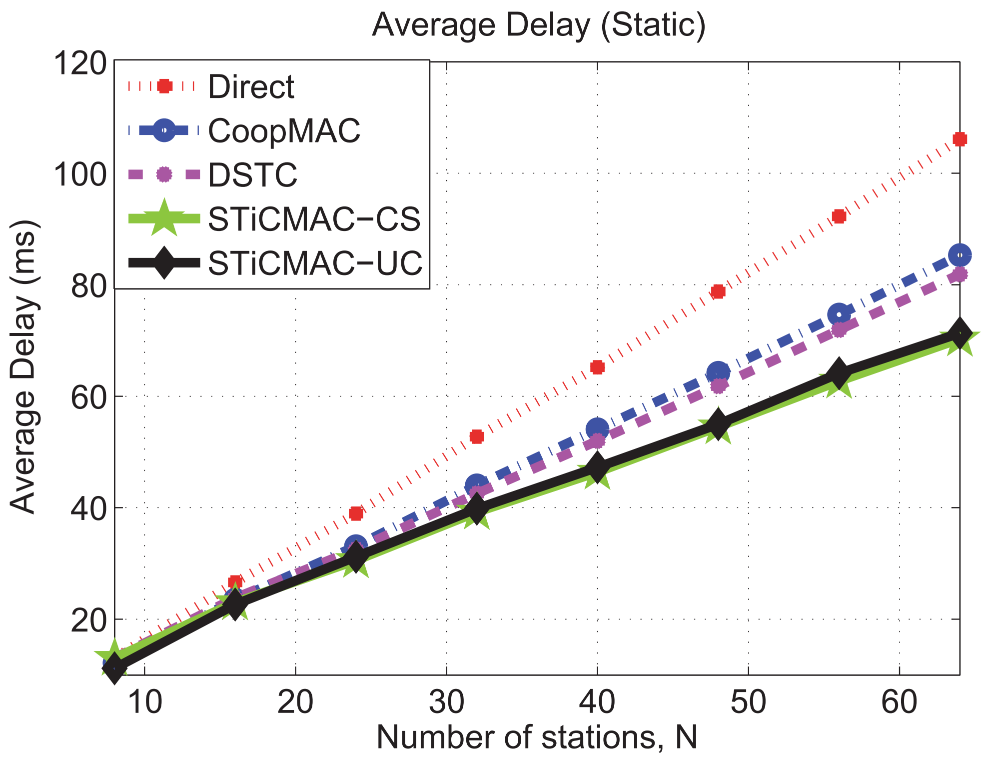

Fig. 6: Medium access delay in a static environment.

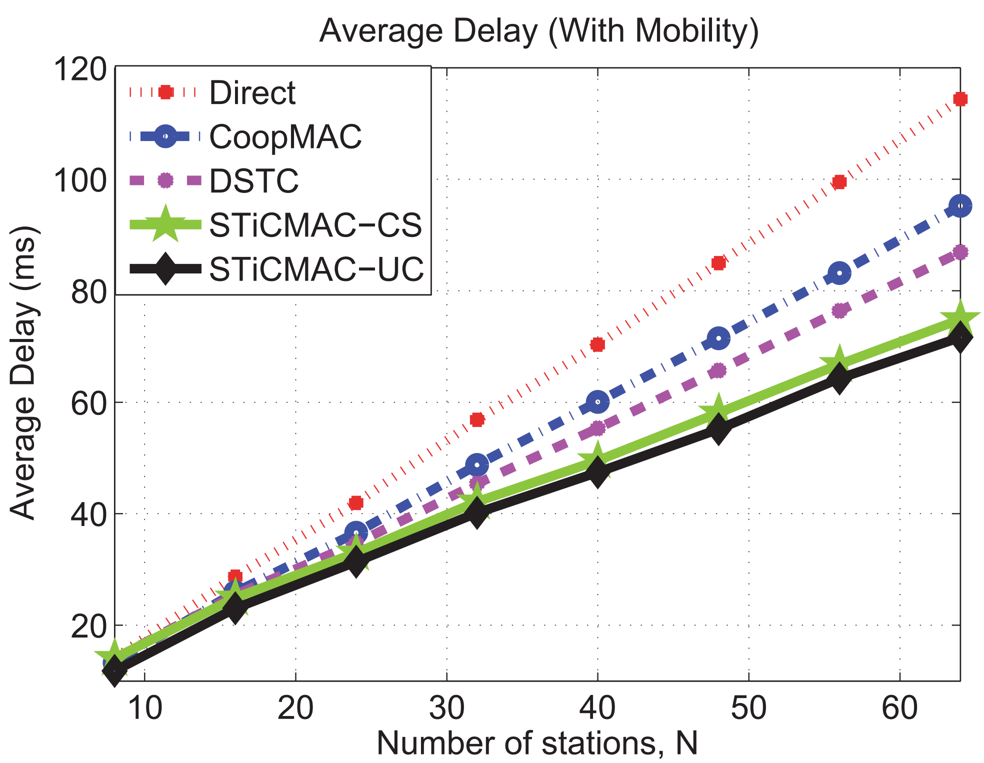

Fig. 7: Medium access delay in a mobile environment.

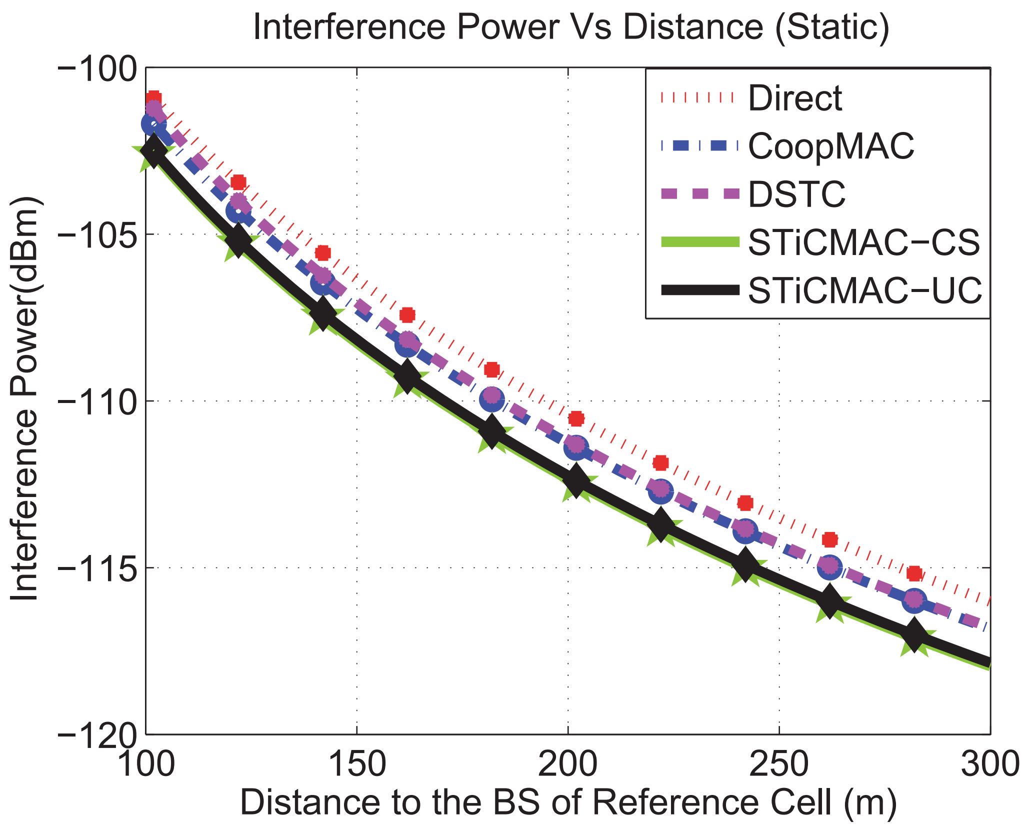

Fig. 8: Interference power vs distance (meters) to reference cell.

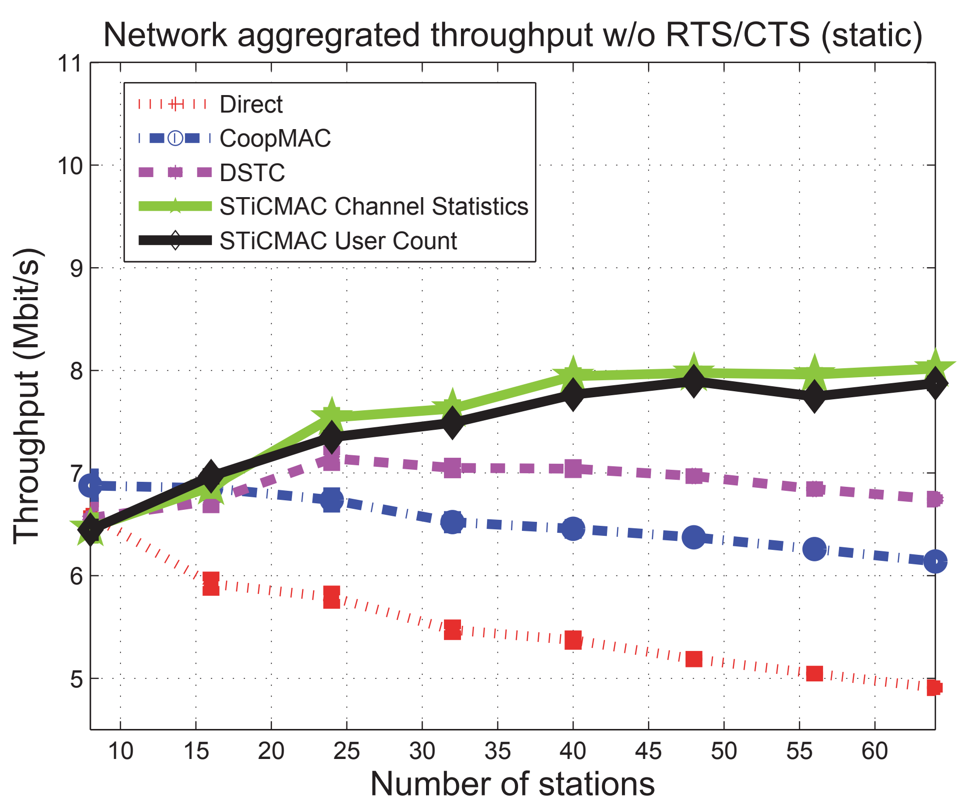

Fig. 9: Throughput comparison without RTS/CTS.

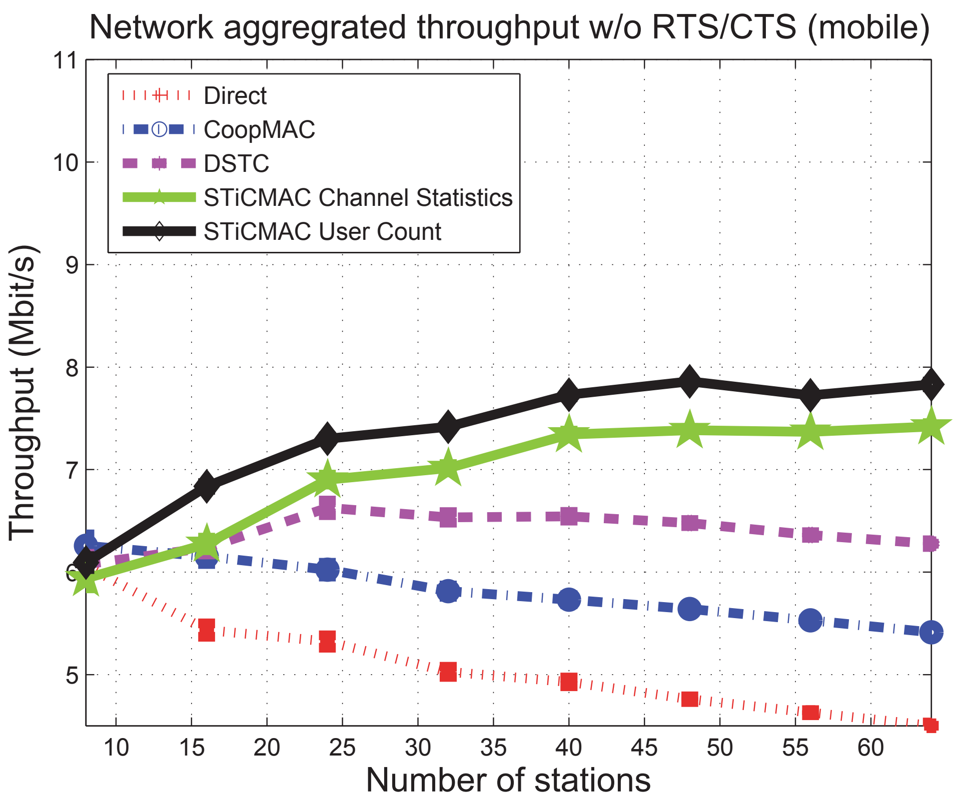

Fig. 10: Throughput comparison for mobile network without RTS/CTS.