

RECOMAC: A Cross-layer Cooperative Network Protocol for Wireless Ad hoc Networks

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Abstract—A novel decentralized cross-layer multi-hop cooperative protocol, namely, Routing Enabled Cooperative Medium Access Control (RECOMAC) is proposed for wireless ad hoc networks. The protocol architecture makes use of cooperative forwarding methods, in which coded packets are forwarded via opportunistically formed cooperative sets within a region, as RECOMAC spans the physical, medium access control (MAC) and routing layers. Randomized coding is exploited at the physical layer to realize cooperative transmissions, and cooperative forwarding is implemented for routing functionality, which is submerged into the MAC layer, while the overhead for MAC and route set up is minimized. RECOMAC is shown to provide dramatic performance improvements of eight times higher throughput and one tenth of end-to-end delay than that of the conventional architecture in practical wireless mesh networks.

Index Terms—Cooperative communications, wireless ad hoc networks, cooperative routing.

I. INTRODUCTION

Wireless ad hoc networks have been considered in various different applications such as wireless mesh networks, wireless sensor networks and mobile ad hoc networks, owing to expectations, such as minimal configuration requirements, quick deployment and decentralized operation. However, the performance of wireless ad hoc networks is still limited since the end-to-end path consists of multiple concatenated unicast links, which suffer from errors due to wireless channel impairments, and failure of even a single link can make an end-to-end path inoperable, requiring route re-discovery and maintenance procedures. In practical scenarios, channel conditions change frequently due to fading and/or mobility, and recurrent route discoveries can cause heavy messaging burden, i.e., wasted network bandwidth. Furthermore, such routing messages are delivered over the shared wireless medium, so they are subject to collisions, which result in further degradation in throughput and delay performance.

Cooperative diversity has recently emerged as an efficient method to realize diversity gains offered by multiple input single output (MISO) systems, without employing multiple antennas on wireless nodes [1]. Nodes which overhear a transmission emulate an antenna array, e.g., by using space-time codes (STCs) [2], provide the receiver with multiple

copies of the original signal through independent channels to form a virtual MISO (v-MISO) link. There is vast amount of literature on implementing cooperation in the physical layer [2]–[6], and increasing interest on higher layer functions that support cooperative diversity [7]–[16]. Cooperative diversity over single hop networks has been studied with diverse examples [7]–[11]; however, the literature on multi-hop cooperative protocols is still limited. A common approach for incorporating cooperative diversity in multi-hop networks is to employ cooperation on already established routes. For example, in [2] and [12], cooperation is exploited to mediate an unreliable single hop link on the non-cooperative route, such that the original link is kept but its quality is improved by cooperative transmissions of the neighbors. On the other hand, in [13] and [14], an opportunistic v-MISO link is formed only when a link fails. Hence, the existing schemes do not make use of all the route alternatives that can be realized for end-to-end communication between a source-destination pair. Furthermore, in these schemes, the number of relays participating in cooperation is fixed due to the fixed dimension of the underlying distributed STC (DSTC). Moreover, realization of such cooperation requires extra messaging for cooperative set selection and actuation functions to be implemented at the MAC level. Recently, a cooperative routing scheme that circumvents the relay selection and actuation problem by use of opportunistic large arrays (OLA) [17] at the physical layer has been presented in [18]. In [18], the authors consider a perfect MAC protocol, which provides flawless coordination among the nodes, as the packets are routed through the network. Although OLA can be favorable for network flooding, its operation for unicast routing requires an appropriately designed MAC protocol. Hence, the problem of how to select and actuate the relays, and the design of a MAC layer which enables these functions for cooperative routing without obliterating the benefits of cooperation remains open. In fact, the proper design of multi-hop cooperative protocols with cooperative diversity involves optimizing the performance of physical, MAC and routing functions jointly.

In this paper, we propose Routing-Enabled Cooperative Medium Access Control (RECOMAC) as a cross-layer cooperative protocol, where the very recent ideas of cooperation with Randomized DSTC (RDSTC) [19] and cooperative forwarding [20] are realized in jointly designed MAC and routing functions. RECOMAC architecture exploits RDSTC together with cooperative forwarding, in such a way that the coded packets are forwarded from a cooperative set to a consecutive cooperative set in the direction towards the

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final destination, without any need for selecting and activating relays. This way, the end-to-end route is defined as a series of *regions* in which the relays reside, as opposed to a string of predetermined nodes used in existing methods [15], [16], [18]. In the RECOMAC protocol, thanks to RDSTC, the relay selection and actuation steps, as well as MAC collisions, avoidance/resolution mechanisms are totally alleviated, and the routing layer functionality is submerged into the MAC layer, as MAC packet exchanges are exploited for route formation. We provide the detailed performance analysis of the RECOMAC protocol through extensive simulations in ns-2 tool, and we demonstrate that RECOMAC provides significant performance improvements, eight times higher average end-to-end throughput and one tenth of the end-to-end delay, than that of the conventional architecture of wireless mesh networks, employing IEEE 802.11 for MAC and ad hoc on demand distance vector (AODV) for routing, all achieved at almost zero overhead cost.

The rest of the paper is organized as follows: In Section II, we provide the preliminaries with the system model, RDSTC basics and summary of cooperative forwarding strategies. In Section III, we present our cooperative cross-layer protocol RECOMAC, including packet structures and protocol operation. In Section IV, we provide the performance analysis of RECOMAC, and in Section V, we present our conclusions.

II. PRELIMINARIES

A. System Model

We consider a wireless ad hoc network with N randomly distributed nodes, each of which is equipped with a single antenna. It is assumed that each node, i , has the capability to acquire its location information, (x_i, y_i) , via a positioning system, such as Global Positioning System (GPS) [21], [22]. Uniform distribution is assumed with node density, ρ , available to all nodes. A source node, S , generates packets to be delivered to a destination node, D over multiple wireless hops. Transmitted signal from node i to node j is attenuated by free space path loss model with exponent α , which corresponds to the average channel statistics, and the instantaneous channel gain, h_{ij} is subject to flat Rayleigh fading. The fading coefficients are assumed independent across channels and constant during one frame. Additive white Gaussian noise is assumed at all receivers with equal power spectral density, $N_0/2$.

B. Non-cooperative Transmission

Given that the transmit power is fixed as P , the non-cooperative (direct) transmission of node i results in an instantaneous SNR of $\gamma_{ij} = \frac{P|h_{ij}|^2}{N_0}$ at node j . It is assumed that the packet transmitted by node i can be successfully decoded by node j if $\gamma_{ij} \geq \gamma_0$, where γ_0 is the decoding threshold which corresponds to an SNR level for correct reception of a packet with a certain level of reliability.

C. Cooperative Transmission with RDSTC

RDSTC has been shown to provide significant improvements in single hop, infrastructured networks [23]–[25]. Unlike DSTC [26], in RDSTC an antenna index is not allocated

to each relay, which means relay selection and actuation mechanisms can be totally alleviated. Furthermore, the number of cooperating nodes in DSTC is constrained by the dimension of the space-time code, while in RDSTC the total number of nodes in the cooperative set is unbounded. Therefore, application of RDSTC in cooperative networks is promising due to flexibility and decentralized operation. Here, we briefly describe cooperation via RDSTC; further details can be found in [19].

Let $\mathbf{z} = [z_0 \ z_1 \ \dots \ z_{n-1}]$ be the block of symbols to be transmitted from node i to node j via cooperation of multiple intermediate nodes. We denote the node set that has successfully decoded the symbols, \mathbf{z} , as \mathcal{C} , and $C \triangleq |\mathcal{C}|$ represents the number of nodes in this set. The main idea is that the nodes in \mathcal{C} can form a cooperative set to forward data towards node j . At each node, in \mathcal{C} , \mathbf{z} is mapped onto a matrix $\mathcal{G}(\mathbf{z})$, as in standard space-time coding: $\mathbf{z} \rightarrow \mathcal{G}(\mathbf{z})$, where $\mathcal{G}(\mathbf{z})$ is an $n \times L$ space-time code matrix, L denotes the number of antennas in the underlying space-time code. Then, each node in \mathcal{C} transmits a random linear combination of columns of $\mathcal{G}(\mathbf{z})$. Let \mathbf{r}_k be the $L \times 1$ random vector that contains the linear combination of coefficients for the k^{th} node in the set \mathcal{C} . Then RDSTC can be expressed as the following mapping: $\mathbf{z} \rightarrow \mathcal{G}(\mathbf{z})\mathcal{R}$, where $\mathcal{R} = [\mathbf{r}_1 \ \mathbf{r}_2 \ \dots \ \mathbf{r}_C]$ is an $L \times C$ matrix, named as *the randomization matrix*. Since node processing is intended to be local, \mathbf{r}_k 's should be independently assigned for each $k \in \mathcal{C}$. This property allows RDSTC to be implemented in a decentralized fashion. We assume that entries of \mathcal{R} are independently and identically distributed, i.i.d., according to a given distribution as in [19]. The vector that represents the channel coefficients between the nodes in \mathcal{C} and the receiver node j is denoted as $\mathbf{h}_{\mathcal{C}j} = [h_{1j} \ h_{2j} \ \dots \ h_{Cj}]$. The signal received by node j is given as $\mathbf{y} = \mathcal{G}(\mathbf{z})\mathcal{R}\mathbf{h}_{\mathcal{C}j} + \mathbf{w}$, where $\mathbf{w} \sim \mathcal{N}_c(\mathbf{0}, (N_0/2)\mathbf{I})$, and $\mathbf{h} \sim \mathcal{N}_c(\mathbf{0}, (N_0/2)\Sigma_{\mathbf{h}_{\mathcal{C}j}})$. Assuming that node j employs coherent detection, the received signal can be interpreted to have passed through an effective channel of $\tilde{\mathbf{h}}_{\mathcal{C}j} \triangleq \mathcal{R}\mathbf{h}_{\mathcal{C}j}$. Thus, the receiver can estimate the effective channel coefficients of $\tilde{\mathbf{h}}_{\mathcal{C}j}$ [19]; hence it does not need to know the identity of the nodes in \mathcal{C} . Considering orthogonal space-time codes, $\mathcal{G}(\mathbf{z})$, the instantaneous SNR of the cooperatively transmitted signal received at node j is given as $\gamma_{\mathcal{C}j} = \frac{P\|\tilde{\mathbf{h}}_{\mathcal{C}j}\|^2}{N_0}$, and if $\gamma_{\mathcal{C}j} \geq \gamma_0$, the cooperative transmission can be successfully decoded by node j .

D. Cooperative Forwarding Strategies

In this section, we briefly summarize our two cooperative packet forwarding mechanisms, both of which utilize cooperative transmissions via RDSTC as presented in [20]. These cooperative forwarding schemes are employed in the proposed cooperative cross-layer RECOMAC protocol as presented in Section III.

1) *Cooperative Flooding (CF)*: In CF, the source node, S , initiates flooding by non-cooperative transmission. The nodes in set, \mathcal{C}_1 successfully receive the source's transmission and cooperatively transmit the packet via RDSTC. Next, \mathcal{C}_2 indicates the set of nodes that successfully receive \mathcal{C}_1 's transmis-

sion, forming the second hop cooperative set, re-encoding the information and forwarding it cooperatively, using RDSTC. In general, the cooperative set at hop k can be written as: $\mathcal{C}_k = \{j | \gamma_0 \leq \gamma_{\mathcal{C}_{k-1}j}, j \notin \cup_{i=1}^{k-1} \mathcal{C}_i\}$, where $\mathcal{C}_0 = \{S\}$. Note that, at each hop, each node only needs to know whether it belongs to \mathcal{C}_k , so due to changes in channel conditions each packet may be flooded by a different set of relays. Unlike conventional flooding, contention resolution is not required in CF, thanks to RDSTC, and CF floods the network faster than conventional flooding, owing to the cooperative diversity gain, [20]. CF is suitable for dissemination or query of common network information; likewise, in the proposed RECOMAC protocol, CF is employed for the discovery of the location of the destination node.

2) *Cooperative Forwarding within Progress Region with Dual Threshold (CFPR-DT)*: In this scheme, the main idea is to progressively forward data from S to D , within a specified region, while exploiting cooperative transmissions with RDSTC. Supposing that S has acquired the location information of D (for example via CF), this information is utilized to set up a regional route between S and D , such that the progress of packets towards D is enhanced. Defining Forward Progress Region (FPR) as the area between S and D , the nodes inside the FPR are candidate relays for cooperative packet forwarding with RDSTC. FPR should be such that in order to guarantee the sustained progress of forwarding, at each hop, sufficient number of cooperating nodes providing the maximum possible diversity gain is included in the FPR. This calls for a sufficiently large region around S and between S and D . Moreover, in some cases, D may not be able to decode a packet due to a deep fade in its channel, while its neighbors may have decoded it. Hence, a sufficiently large region around D is also required to be included in the FPR, so that the nodes around D can cooperatively transmit the packet when necessary. Both of these requirements for cooperative routing can be satisfied by an elliptical FPR, which has S and D located at its two foci. Denoting δ_1 and δ_2 as the semi minor and semi major axis of the elliptical FPR, the nodes can participate in cooperative forwarding if they can successfully decode the packet, and if they are in the FPR.

The forward progress of a packet can be further improved by constraining the size of the cooperative sets based on a second SNR threshold as discussed in [20]. By preventing the nodes that receive the signal with high SNR levels from participating in cooperative packet forwarding, the total signal strength in the direction of D is improved. Therefore, in CFPR-DT, we propose that the nodes autonomously decide whether to participate in cooperative forwarding by checking whether the received SNR is under a predetermined upper threshold value, γ_1 , in addition to checking if they are in the FPR. For this purpose, the location information of S and D , and the δ_1 , δ_2 values are to be forwarded within the packet. Hence, the cooperative set at hop k is given as: $\mathcal{C}_k = \{j | \gamma_0 \leq \gamma_{\mathcal{C}_{k-1}j} \leq \gamma_1, j \notin \cup_{i=1}^{k-1} \mathcal{C}_i, (x_j, y_j) \subseteq \mathcal{F}(\delta_1, \delta_2)\}$, where γ_1 is the upper threshold value for the received instantaneous SNR and $\mathcal{C}_0 = \{S\}$. Cooperative sets at each hop are formed on the fly, in an

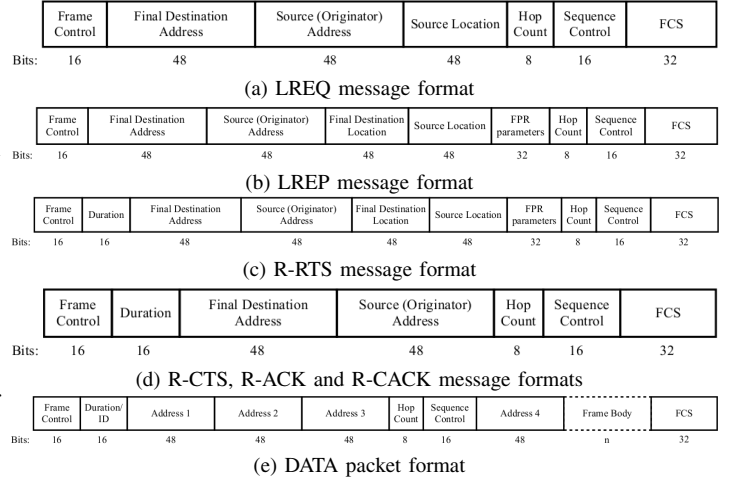


Fig. 1. RECOMAC packet structures.

opportunistic manner, independently at each node, based on the instantaneous values of the channel states, individual node locations, FPR parameters and SNR threshold γ_1 .

For the cooperative transmission in CF and CFPR-DT schemes, power normalization is required to ensure that the average transmit power of a cooperative set and a non-cooperative transmission are the same. Hence, we have assumed and realized equal power allocation among cooperating nodes, as explained in [27]. For selecting FPR parameters, (δ_1, δ_2) , and γ_1 , we have considered the objectives for minimizing the hop count and minimizing the spatial footprint of the path between S and D , so that the optimal choice of $(\delta_1, \delta_2, \gamma_1)$ can be computed as a function of the node density and network size and then stored in a look-up table at the source node [20], [27]. Since cooperative transmissions are normalized in power and the transmitters are concentrated in a region towards D , CFPR-DT results in longer transmission ranges, leading to fewer hops as compared to CF.

III. ROUTING ENABLED COOPERATIVE MAC (RECOMAC) PROTOCOL

In conventional wireless networks based on a layered architecture, the job of the routing layer is to discover the best set of nodes for delivering packets to a specific destination, and to configure and maintain the nodes so that each node is informed about the next node to forward incoming packets to reach their destinations. Routed packets need to be delivered over the physical link with the help and coordination of the MAC layer. The job of the MAC layer is to coordinate the transmissions from multiple nodes and successfully deliver all the packets on each link along the path. Our proposed cooperative cross-layer protocol, RECOMAC, on the other hand, spans and combines the functions of physical, MAC and routing layers to provide seamless cooperative communication while the the messaging overhead to set up routes, select and actuate relays is minimized. RECOMAC achieves this by incorporating the routing layer functions into the MAC layer. RECOMAC builds on our cooperative forwarding strategies from [20], summarized in Section II.D, while employing a

modified version of IEEE 802.11 protocol [28] for MAC. Specifically, new functions and new packet structures (Fig. 1) are introduced to implement cooperative flooding and cooperative forwarding algorithms and realizing CFPR-DT. Next, we describe the RECOMAC protocol operation, as well as the destination location discovery and the data delivery phases in detail.

A. Destination Location Discovery Phase

Destination location discovery is pursued by the source node, S before data delivery to destination, D starts. The goal in this phase is to obtain the location information for D . S first inquires the location of D with a Location Request (LREQ) message that is carried across the network via CF scheme, described in Section II-D1. Note that, when the destination location is not known, CFPR-DT cannot be used. Fig. 1a depicts the structure of the LREQ packet, including the source and the final destination (D) addresses, the source location, the hop count and the sequence control field, which is used to avoid dissemination of stale LREQ messages. The hop count field is initialized to 0 at S and it is incremented by one at each hop.

When D receives the LREQ message, it obtains the location information of S . In response to LREQ, D initiates the cooperative forwarding of the Location Reply (LREP) message, via CFPR-DT scheme. The FPR parameters (δ_1 , δ_2), and the SNR threshold, γ_1 , are calculated based on the density of the network and the source and the destination locations according to minimum hop count or minimum spatial footprint criterion defined in [20]. LREP message, which involves those FPR parameters, address and location information, hop count and sequence control fields as given in Fig. 1b, is created by D and forwarded to S through the selected FPR. Receiving this LREP message, S obtains the location information of D .

B. Data Delivery Phase

Having completed the destination discovery phase, the cooperative forwarding for data delivery can be initiated. For delivery of a data packet across each hop, a successful routing-enabled-request-to-send (R-RTS) and routing-enabled-clear-to-send (R-CTS) message exchange is required between the sender node and the receiver node (or cooperative sets), so that the medium is reserved for each transmission. After a successful delivery, a routing-enabled cooperative acknowledgement (R-CACK) packet is sent by the receiver node (or set), and after a successful end-to-end delivery, a routing-enabled acknowledgement (R-ACK) packet is sent by D . In the following, we present the protocol by describing the operation of source, intermediate (cooperating) and destination nodes. The packet exchanges for all steps can also be viewed from Fig. 2.

1) *Source node*: The source node initially computes the optimal FPR parameters according to a desired criterion as in [20]. Then;

(i) Whenever there is a packet in the source node's buffer, it starts the data transmission by broadcasting an R-RTS

message. The R-RTS packet structure is consistent with IEEE 802.11 RTS structure, but here we introduce additional fields to realize RECOMAC. As depicted in Fig. 1c, the R-RTS message includes fields that hold the location information of S and D , and the FPR parameters (δ_1 , δ_2 , γ_1) and the number of hops that the message has traversed. The R-RTS message informs the neighboring nodes about the expected duration of the single-hop transmission as specified in the duration field. The duration field of RTS is set to a value \mathcal{D}_{R-RTS} , which is calculated as $\mathcal{D}_{R-RTS} = 4T_{SIFS} + 4T_{R-CTS} + T_{DATA} + T_{R-CACK} + T_{R-ACK} + 5T_{prop} + T_{RIFS}$, where T_{SIFS} is the duration of one short interframe spacing (SIFS), T_{RIFS} is the duration of one reduced interframe spacing (RIFS), T_{R-CTS} , T_{R-CACK} , T_{R-ACK} , T_{DATA} denote the duration of R-CTS, R-CACK, R-ACK and DATA frames, respectively, and T_{prop} designates the maximum propagation delay. The nodes which receive the R-RTS but do not belong to the FPR or do not satisfy the upper threshold, set their network allocation vectors (NAV) to \mathcal{D}_{R-RTS} provided in R-RTS.

(ii) If R-CTS is received after SIFS period, the source node sends the data packet. If R-CTS is not received after SIFS period, the source node updates its contention window (CW), backs off and restarts from step (i). R-RTS/R-CTS exchange ensures to reserve the medium for the NAV duration, also preventing collisions and the hidden terminal problems.

(iii) If R-CACK is received after DATA transmission, S deduces that the data packet has progressed one hop towards D . If a R-ACK message is received following the R-CACK message, S deduces that the packet is successfully delivered at D in one hop. If R-ACK is received, but R-CACK is not received, S again deduces that D has been reached in single hop. If neither R-CACK nor R-ACK is received, S initiates retransmission with updated CW and returns to step (i).

2) *Intermediate Cooperating Nodes*: Whenever a node receives a R-RTS message, it checks whether it satisfies the FPR and upper SNR threshold criteria according to CFPR-DT, as explained in section II-D3. If it does, it cooperatively sends the R-CTS message, which is encoded with RDSTC. If the node does not satisfy the FPR conditions, it sets its NAV according to the duration specified in R-RTS header indicating that the medium is busy and this node will remain silent within this duration. Note that here multiple nodes cooperatively, simultaneously and autonomously transmit the R-CTS packet which is encoded with RDSTC.

When a node receives the DATA packet, it sends a R-CACK message cooperatively declaring the forward progress of the DATA packet. Following the R-CACK transmission, the node waits for an SIFS + RIFS period for an R-ACK message from D . If the node does not receive an R-ACK, it deduces that the DATA has not been delivered to D , and it initiates the cooperative transmission of R-RTS for the next hop progress of the DATA packet. If a node does not receive a DATA packet after SIFS period following R-CTS transmission, it sets its NAV to the duration from the R-RTS packet and returns to the idle state. If the node does not receive a DATA packet, but receives a R-CACK for the data packet

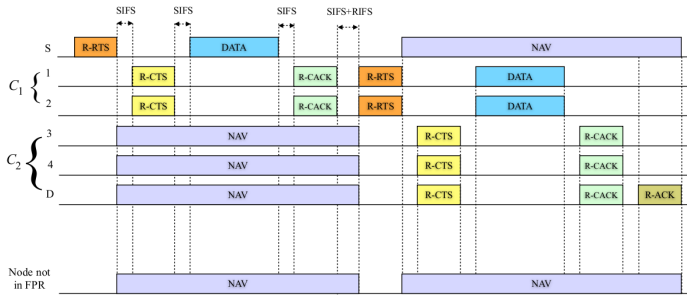


Fig. 2. RECOMAC packet exchange procedure: For the transmission of S , cooperation bit of the frame control field is set as 0, while it is set as 1 for all other transmissions which carried out in cooperative mode.

with the same sequence number it was expecting, it infers that the cooperative transmission has been carried out successfully without its participation. In this case, the node updates its NAV according to the duration from the R-CACK packet and returns to the idle state. When the node receives an R-CTS message in response to an R-RTS message it has transmitted, it encodes the DATA with RDSTC and sends the DATA cooperatively. If the node receives R-CACK following the DATA transmission, it deduces that the DATA has progressed one hop towards D , and returns to the idle state.

3) *Final destination node*: The final destination node operates like an intermediate node during the exchange of R-RTS - R-CTS - DATA - R-CACK messages. When this node receives the packet destined to itself, it sends a R-ACK message following an SIFS period after its R-CACK transmission, to declare that the packet is delivered successfully at the destination, so as to prevent further forwarding of the data packet. The packet exchanges and NAV settings are depicted in Fig. 2.

Note that, all the nodes that receive a packet and autonomously decide to participate in cooperative transmission, initiate their timers based on the time instant they receive the packet. However, due to different propagation delays, the nodes in a cooperative set can receive the packet at different time instants, resulting in different firing times for their timers and yielding asynchronous transmissions. In order to circumvent this problem, we use an extended SIFS period, which is standard SIFS period plus the amount of maximum propagation delay, T_{prop} . Each node can obtain the propagation delay between the sender and itself, then subtract this value from the total extended SIFS period. This way, the nodes that receive the packet at different times can all have their timers set to transmit synchronously, at the same time instant.

IV. RECOMAC PERFORMANCE ANALYSIS

In this section, we present the performance analysis of RECOMAC protocol and architecture in comparison to conventional layered architecture of wireless mesh networks that employ IEEE 802.11 protocol at the MAC layer and AODV at the routing layer. We consider two metrics for AODV, the hop count and airtime metrics, where the end-to-end path is established according to shortest path and reliability constraints. Since the airtime metric is link aware, it has been

TABLE I
SYSTEM PARAMETERS USED IN SIMULATIONS

DATA	8192 bits	PLCP header	144 bits
RTS	168 bits	Short preamble	432 bits
CTS, ACK	112 bits	Basic rate (used for MAC, PHY headers and control messages)	6 Mbps
R-RTS	304 bits	Data rate	54 Mbps
R-CTS, R-CACK, R-ACK	184 bits	MAC header	272 bits
AODV-hop count RREQ	192 bits	CW min / max	15 / 1023
AODV-hop count RREP	160 bits	Slot time	9 μs
AODV-airtime RREQ	368 bits	SIFS	10 μs
AODV-airtime RREP	344 bits	RIFS	2 μs
RECOMAC LREQ	216 bits	RECOMAC SIFS	12 μs
RECOMAC LREP	296 bits	Max. Transmit power	100 mW

TABLE II
SOURCE-DESTINATION CONNECTIVITY

N	60	80	100	120	140	160	180
AODV w/ hop count	0.15	0.25	0.70	0.80	1	1	1
AODV w/ airtime	0	0.45	0.65	0.95	0.95	0.95	1
RECOMAC	1	1	1	1	1	1	1

defined as the AODV routing metric in wireless mesh network standard, IEEE 802.11s [29].

We have implemented RECOMAC in ns-2 environment, to carry out simulations for performance analysis, in comparison to non-cooperative, conventional architecture with IEEE 802.11 and AODV (abbreviated as IEEE802.11+AODV) with hop count and airtime metrics. In the simulations, we have considered a network of N nodes randomly and uniformly distributed in a rectangular region, whose lower left corner is located at coordinates (0,0) and width and length are set as 100 m. In order to avoid edge effects, S and D are assumed to be placed at coordinates (20, 50) and (80, 50), respectively. Path-loss exponent is set as $\alpha = 4$, and each packet and each link undergoes independent flat and slow Rayleigh fading (so that the channel gain remains constant during a frame exchange period). Each node forms its randomization matrix, \mathcal{R} , with the coefficients drawn from complex Gaussian distribution. It is assumed that each node uses Alamouti scheme [30] for the underlying space-time code of the RDSTC. Furthermore, the transmit power, P , is selected such that average non-cooperative transmission range is 15 m. The SNR threshold for successful packet decoding is set as $\gamma_0 = 10$ dB, and for CFPR-DT, upper SNR threshold is set as $\gamma_1 = 15$ dB, which has been found as the best upper threshold value that minimizes the total number of hops for all considered network sizes in the experiments. The protocol parameters are set according to values provided in Table I. We use the transmission rates of IEEE 802.11g standard, where control messages (R-RTS, R-CTS, R-CACK, R-ACK, RTS and CTS) and packet headers are transmitted at 6 Mbps and data packets are transmitted at 54 Mbps. We have run our simulations on networks with varying number of nodes, N , and for each data point, we provide the average result obtained from 20 different network realizations.

In the implementation of the conventional architecture, IEEE802.11+AODV, we assume that RTS-CTS exchange is enabled. It is assumed that during one frame exchange fading levels do not change. We observed in our simulations that when the routing messages of AODV are subject to Rayleigh fading, AODV has to repeatedly initiate route discovery and cannot establish a valid end-to-end route, leading to zero end-to-end throughput. Because of this, in our simulations

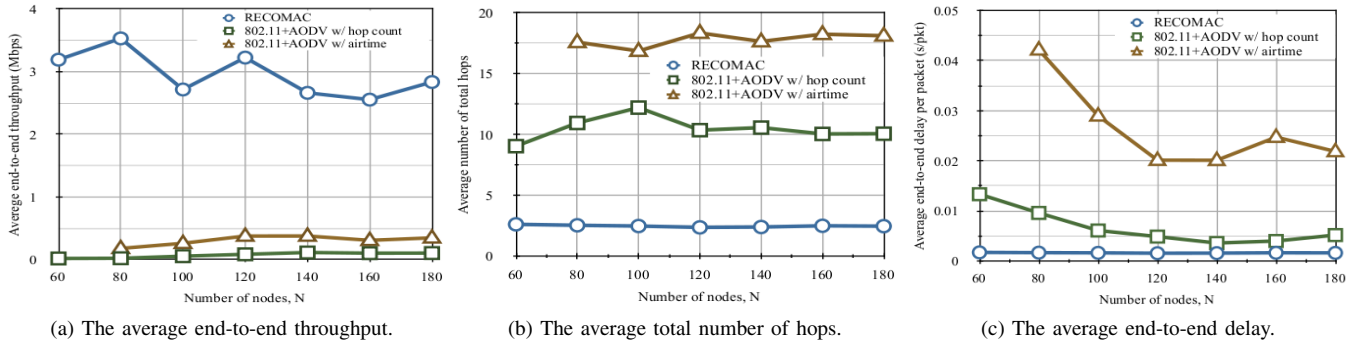


Fig. 3. Comparison of RECOMAC, IEEE802.11+AODV with hop count and IEEE802.11+AODV with airtime metric.

to test the performance of IEEE802.11+AODV under fading, the routing and MAC packets are assumed to be error-free, i.e., they are not affected by fading, while data packets do undergo Rayleigh fading. However, in RECOMAC, all control packets (R-RTS, R-CTS, R-CAK, R-ACK) as well as DATA packets undergo Rayleigh fading. Under these assumptions, in Table II, we provide the fraction of the network realizations in which S and D could establish an end-to-end connection. It is observed that RECOMAC assures S - D connectivity for all cases, despite the fact that control packets undergo fading, while IEEE802.11+AODV can operate only when the network is sufficiently dense, i.e., when the number of route alternatives is high. In our experiments, the average results are provided for the cases when the end-to-end connection is established. Due to this fact, we do not present results for IEEE802.11+AODV with airtime metric when $N = 60$.

In Fig 3a, we depict the average end-to-end throughput of RECOMAC and IEEE802.11+AODV with hop count and airtime metrics. It is observed that RECOMAC improves the throughput performance significantly for all network sizes. The performance of IEEE802.11+AODV with airtime metric is better than IEEE802.11+AODV with hop count, as it updates the path depending on the link quality. The throughput enhancement of RECOMAC is due to robust cooperative transmissions, which prevent packet retransmissions even under channel impairments and avoid collisions by nature. It is observed that RECOMAC can provide eight times higher end-to-end throughput as compared to a non-cooperative network with IEEE802.11 and AODV.

In Fig. 3b, we depict the average number of total hops between S and D . It is observed that IEEE802.11+AODV with airtime metric can result in longer routes in search for more reliable ones, while AODV with hop count minimizes the hop count for the end-to-end communication. RECOMAC provides the smallest number of total hops, owing to the long haul transmissions enabled by cooperative diversity.

In Fig. 3c, we depict the average end-to-end delay per successfully delivered packet. It is seen that RECOMAC improves the delay performance significantly, because it takes smaller number of hops to reach the destination, packet collisions are avoided by randomized coding and the retransmissions due to channel errors are avoided due to improved signal quality as a result of cooperative diversity gain. Even when retransmissions

are required, this does not call for reestablishment of the end-to-end route, unlike the conventional layered architecture, IEEE 802.11+AODV. Also, in our simulations, we have observed that IEEE802.11+AODV architecture may drop packets at the MAC layer due to numerous unsuccessful transmission attempts.

In Figure 4, we present the amount of MAC and routing overhead measured in the experiments. It is observed in Fig. 4a that RECOMAC reduces the MAC messaging overhead significantly as compared to IEEE802.11+AODV with hop count and airtime metrics. The fraction of required MAC messaging to the obtained throughput is around 0.0023% for RECOMAC for all considered network sizes, whereas it ranges between 14% and 27% for IEEE802.11+AODV with airtime, and from 60% to 80% for IEEE802.11+AODV with hop count. This is because of the fact that IEEE802.11+AODV architecture requires larger number of hops to reach the destination, and at each hop multiple retransmissions are required in case of channel failures. Furthermore, IEEE802.11+AODV makes many unsuccessful data delivery attempts, requiring repeated route rediscovery phases for which MAC packets are used to coordinate the routing packets. On the other hand, RECOMAC makes use of robust long-haul cooperative transmissions that avoid retransmissions due to channel errors and collisions, while reducing the total number of hops to reach the destination, causing reduced MAC messaging. In Fig. 4b, we depict the overhead of routing messages for RECOMAC and IEEE802.11+AODV with airtime metric. The routing message overhead for RECOMAC represents the total messaging (LREP and LREQ) carried out during the destination location discovery phase. The performance of IEEE802.11+AODV with hop count is incomparably poorer than IEEE802.11+AODV with airtime metric, so it is not shown on the plot. It is observed that the fraction of required route discovery messaging to the obtained throughput is 0.000012% for RECOMAC for all considered network sizes, whereas it ranges between 0.014% and 0.031% for IEEE802.11+AODV with airtime metric, and from 4% to 18% for IEEE802.11+AODV with hop count.

It is worthwhile to note that, here the performance of RECOMAC is compared to the conventional IEEE802.11+AODV architecture, since it is a realistic benchmark as the architecture of wireless mesh networks. Furthermore, it is not possible to

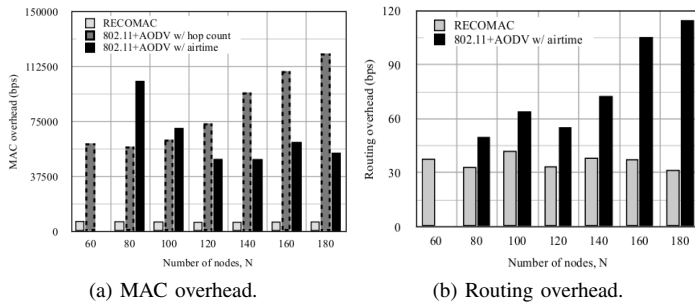


Fig. 4. MAC and routing overhead comparison of RECOMAC, IEEE802.11+AODV with hop count and airtime metrics. Note that, for $N = 60$, IEEE802.11+AODV with airtime does not establish S - D connection.

make meaningful performance comparisons with other cooperative routing protocols in the literature, since those protocols do not provide the MAC layer functionality, as they assume either perfect coordination among the nodes (e.g., [16], [18]), or flawless relay selection and actuation procedures (e.g., [12], [14], [15]).

V. CONCLUSIONS

In this paper, a cross-layer cooperative protocol architecture is presented for wireless ad hoc networks. Different from existing works in literature, in our proposed framework, end-to-end communication is realized through the opportunistically formed cooperative sets that are formed on the fly with minimal MAC overhead and without the need for establishing a prior non-cooperative route. Our cooperative architecture spans the physical, MAC and routing layers, while it enables recruiting multiple relays without messaging burden, eliminates relay selection and actuation procedures, causing minimal overhead. The results demonstrate that under Rayleigh fading and path loss, our cross-layer architecture, RECOMAC, significantly improves the system performance, with eight times higher throughput and one tenth of the delay of conventional wireless mesh networks with non-cooperative transmissions, at almost zero overhead cost. Therefore, RECOMAC stands out as a promising protocol and architecture for realizing cooperation with RDSTC in wireless ad hoc networks.

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