A Cross-layer Multi-hop Cooperative Network Architecture for Wireless Ad hoc Networks

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Abstract

In this paper, a novel decentralized cross-layer multi-hop cooperative network architecture is presented. Our architecture involves the design of a simple yet efficient cooperative flooding scheme, two decentralized opportunistic cooperative forwarding mechanisms as well as the design of Routing Enabled Cooperative Medium Access Control (RECOMAC) protocol that spans and incorporates the physical, medium access control (MAC) and routing layers for improving the performance of multi-hop communication. The proposed architecture exploits randomized coding at the physical layer to realize cooperative diversity. Randomized coding alleviates relay selection and actuation mechanisms, and therefore reduces the coordination among the relays. The coded packets are forwarded via opportunistically formed cooperative sets within a region, without communication among the relays and without establishing a prior route. In our architecture, routing layer functionality is submerged into the MAC layer to provide seamless cooperative communication while the messaging overhead to set up routes, select and actuate relays is minimized. RECOMAC is shown to provide dramatic performance improvements, such as eight times higher throughput and ten times lower end-to-end delay as well as reduced overhead, as compared to networks based on well-known IEEE 802.11 and Ad hoc On Demand Distance Vector (AODV) protocols.

Index Terms

Cooperative communications, wireless ad hoc networks, cooperative routing.

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I. Introduction

Wireless ad hoc networking paradigm has emerged as a powerful platform for applications, such as wireless mesh networks, wireless sensor networks and mobile ad hoc networks, owing to their attributes such as, minimal configuration requirements, quick deployment and decentralized operation. Different from centralized wireless networks, where nodes communicate with a base station or an access point via single hop links, in wireless ad hoc networks, the end-to-end communication is carried over multiple hops, realized through intermediate nodes.

Despite many potential applications as exemplified above, the performance of wireless ad hoc networks is still limited because: i) The end-to-end path consists of multiple concatenated unicast links along specified nodes on a predetermined path. Those unicast links suffer from errors due to channel impairments, caused by fading, and failure of even a single link can make the entire end-to-end path inoperable, requiring route rediscovery and maintenance procedures. In case of harsh environmental conditions, the route discovery phase may need to be repeated several times causing heavy messaging burden, thereby leading to wasted network bandwidth and degraded throughput. ii) Routing messages are delivered by contending for the available medium. In addition to the burden for rediscovery, the contention avoidance and resolution mechanisms also steal from the network bandwidth that could otherwise be used for data communication. Moreover, as the network size is increased, the message overhead of routing strategies is also increased, resulting in further degradation in throughput and delay performance.

The use of multiple-input-multiple-output (MIMO) systems can provide robustness against channel impairments by utilizing diversity gain. Cooperative diversity has emerged as an efficient method to realize diversity gains offered by multiple input single output (MISO) systems without the need for employing multiple antennas on wireless nodes [1]. Cooperative diversity exploits the wireless broadcast advantage. Nodes which overhear a transmission emulate an antenna array, for example employing space-time codes [2], and they provide the receiver with multiple copies of the original signal through independent channels, thereby forming a virtual MISO (v-MISO) link. There is vast amount of literature on cooperation in the physical layer [2]–[6], and there is increasing interest on network layer architectures supporting cooperative diversity [7]–[16]. Although improvements in single hop networks due to cooperative diversity has been studied, with many diverse examples [7]–[11] showing significant performance improvements,

the literature on multi-hop cooperative protocols is still limited.

A common approach in the literature to incorporate cooperative diversity in multi-hop networks is to employ cooperation on already discovered and 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. As opposed to the schemes that consider single link improvements within non-cooperative routes, in [15] and [16], the objective is to improve the end-to-end performance of a route by utilizing cooperative (v-MISO) links in lieu of multiple links, and obtain a route with v-MISO links based on a non-cooperative route.

The aforementioned schemes restrict packet forwarding to be completed on a prior non-cooperative route, hence they 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 space-time code (DSTC) or for reducing the computational complexity. Since realization of cooperative diversity requires extra messaging for cooperative set selection and actuation, under realistic wireless network scenarios, the throughput of the aforementioned systems will further degrade. This automatically raises the problem of how to select and actuate the relays in a decentralized, distributed fashion without obliterating the benefits of cooperation.

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]. OLA relies on the idea that each node accumulates energy from multiple transmissions of a packet, and relays this packet when the accumulated energy is above a predetermined threshold. However, the authors of [18] consider a perfect MAC protocol, which provides flawless coordination among the nodes, while packets are routed through the network. Furthermore, although OLA can be favorable for network flooding, its operation for unicast routing is problematic without an appropriately designed MAC protocol. If transmissions are not coordinated via a MAC protocol, OLA can result in multiple nodes to transmit different packets at overlapping periods, resulting in significantly degraded system performance.

The proper design of multi-hop cooperative protocols with cooperative diversity involves optimizing the behavior and performance of various layers jointly. In this paper, we propose

a cross-layer cooperative network architecture that involves *cooperative flooding* and *cooperative forwarding* mechanisms for packet forwarding, and Routing-Enabled Cooperative Medium Access Control (RECOMAC) protocol, which facilitates these mechanisms by incorporating physical, MAC and routing layers. Our cooperative architecture exploits randomized coding, namely, Randomized Distributed Space-Time Codes (RDSTC) [19], at the physical layer. Randomized coding alleviates relay selection and actuation mechanisms, as a specific antenna index is not allocated per relay, and therefore the coordination among the relays is reduced. In our cooperative forwarding mechanisms, the coded packets are forwarded from a cooperative set to a consecutive cooperative set in the direction towards the final destination, while no messaging is required among the relays of a cooperative set.

In RECOMAC, the routing layer functionality is submerged into the MAC layer such that the MAC packet exchanges are exploited for route formation. Our RECOMAC architecture facilitates formation of cooperative sets on the fly in a decentralized and distributed fashion without the need for extra messaging overhead for relay selection and actuation, resulting in opportunistically formed cooperative links that provide robust and reliable end-to-end communication. RECOMAC does not require establishing a prior non-cooperative route before cooperative transmissions, as opposed to the schemes [15], [16]. This reduces the messaging overhead for route discovery and establishment phases. Furthermore, in our architecture, the end-to-end route is defined as series of *regions* in which the relays reside, as opposed to a string of predetermined nodes used in existing methods [15], [16], [18]. Our architecture allows and enables cooperative transmission of multiple nodes in the routing region. Cooperative forwarding within a region enables progress of the packets towards the direction of the final destination even for sparse networks, where the routing schemes with non-cooperative transmissions can not guarantee source-destination connectivity.

Via realistic implementation of RECOMAC in a network simulator environment, ns-2, and detailed simulations, we evaluate and compare the performance of our architecture in terms of end-to-end throughput and end-to-end delay, to those of non-cooperative networks using well known MAC and ad hoc routing protocols, IEEE 802.11 and AODV, respectively. The routing and MAC overhead is an important cost of end-to-end communication, appropriate quantification of which helps solid comparison between various proposed protocols in the literature. In our analysis, we also quantify the overhead of realizing our cooperative architecture in comparison

to the considered non-cooperative architecture. It is shown that RECOMAC provides eight times higher average end-to-end throughput and ten times lower end-to-end delay, as compared to non-cooperative networks based on IEEE 802.11 and AODV protocols, while requiring reduced overhead.

The rest of the paper is organized as follows. In Section II, we describe the system model, consisting of the network model and the physical layer model, specifically RDSTC. In Section III, we present our cooperative forwarding strategies with RDSTC that form the framework for our cross-layer architecture. Next, we introduce our cooperative cross-layer architecture, RECOMAC, in Section IV. In Section V, we provide the performance analysis, followed by our conclusions in Section VI.

II. SYSTEM MODEL

We consider a wireless ad hoc network with uniformly and 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, namely its coordinates (x_i, y_i), via a positioning system, such as Global Positioning System (GPS) [20], [21]. We assume that there are N nodes in the network, and the nodes are assumed to know the node density, ρ, of the network.

In this network, a source node, S, generates packets to be delivered to a destination node, D. We assume that S and D are located in the network such that multiple wireless hops are required for the end-to-end communication.

We assume that transmission of node i is attenuated by a path-loss exponent of α, and the instantaneous channel gain between nodes i and j, namely h_{ij}, is affected by slow, flat Rayleigh fading, which is independent from other channels. The fading coefficients remain the same during one frame exchange duration (including MAC messaging and packet duration). It is also assumed that the additive white Gaussian noise at all receivers have equal power spectral density, $N_0/2$. Below, we describe the physical layer relations describing non-cooperative (direct) and cooperative transmissions.

1) Non-cooperative Transmission: In non-cooperative transmission, the transmit power is fixed as P. The 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 depends on modulation and

channel coding used, and corresponds to an SNR level for correct reception of a packet with a certain level of reliability. Alternately, we can consider this threshold as arising from the outage probability formulation for fixed transmission rate [22].

2) Cooperative Transmission with Randomized Distributed Space-Time Codes: In this paper, cooperative transmissions are realized via Randomized Distributed Space-Time Codes (RDSTC). Here, we provide a brief description of RDTSC and their application in cooperation. For a comprehensive description, the reader is referred to [19].

Let $\mathbf{z} = [z_0 \ z_1 \ldots z_{n-1}]$ 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. In the following, we describe the processing at each cooperating node and analyze the decoding at 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: $\mathbf{z} \to \mathcal{G}(\mathbf{z})$, 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 kth node in the set $\mathcal{C}$. Then RDSTC can be expressed as the following mapping: $\mathbf{z} \to \mathcal{G}(\mathbf{z}) \mathcal{R}$, where $\mathcal{R} = [\mathbf{r}_1 \ \mathbf{r}_2 \ldots \mathbf{r}_C]$ 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 chosen identically and independently distributed, i.i.d., according to a given distribution. In [19], distributions which provide maximal diversity are identified.

We denote the vector that represents the channel coefficients between the nodes in $\mathcal{C}$ and the receiver node j as $\mathbf{h}_{\mathcal{C}j} = [h_{1j} \ h_{2j} \ \ldots \ h_{Cj}]$. 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 $\mathbf{h} \sim \mathcal{N}_c(\mathbf{0}, (N_0/2)\mathbf{\Sigma}_{h_{\mathcal{C}j}})$. We assume that node j employs coherent detection which requires channel estimation. Note that the received signal can be interpreted to have passed through an effective channel of $\tilde{\mathbf{h}}_{\mathcal{C}j} \triangleq \mathcal{R}_{\mathcal{C}} \, \mathbf{h}_{\mathcal{C}j}$. Thus, instead of estimating the channel vector $\mathbf{h}_{\mathcal{C}j}$ and the randomization matrix, $\mathcal{R}_{\mathcal{C}}$, separately, the receiver can estimate the effective channel coefficients of $\tilde{\mathbf{h}}_{\mathcal{C}j}$ [19], and does not need to know the identity of the nodes in $\mathcal{C}$. For orthogonal space-time codes, $\mathcal{G}(\mathbf{z})$, the instantaneous SNR

of the cooperatively transmitted signal received at node j is given as $\gamma_{\mathcal{C}j} = \frac{P||\mathcal{R}_{\mathcal{C}}\,\mathbf{h}_{\mathcal{C}j}||^2}{N_0}$. Hence, the cooperative transmission can be successfully decoded by node j, if $\gamma_{\mathcal{C}j} \geq \gamma_0$.

Note that unlike regular distributed space-time coding (DSTC) [23], RDSTC does not allocate an antenna index to each relay, which means relay selection and actuation mechanisms can be totally alleviated. This reduces the coordination requirement among the source and the relays, which leads to potential reduction in the signaling overhead for initiation of cooperative transmission. Furthermore, in DSTC, the number of cooperating nodes is constrained by the dimension of the underlying space-time code. However, in RDSTC, addition of more relays is possible without a bound on the total number of nodes in the cooperative set, which naturally can improve the overall signal quality. Therefore, RDSTC is favorable for cooperative networks due to its flexibility and decentralized operation. However, although RDSTC has been shown to provide significant improvements in two hop infrastructured networks [24]–[26], the end-to-end performance of cooperative transmissions with RDSTC in multi-hop scenarios has not been investigated to this date.

III. Cooperative Packet Forwarding using RDSTC

In this section, we present three cooperative packet forwarding mechanisms for ad hoc networks that exploit RDSTC. The proposed cooperative forwarding schemes form the basis for our cooperative cross-layer architecture, RECOMAC, discussed in detail in Section IV. For the cooperative transmissions, we require that each node in the cooperative set uses a normalized power level. The power normalization ensures that the average transmit power of a cooperative set and a non-cooperative transmission is the same. This way, we are able to observe the signal quality improvement due to cooperative diversity, while maintaining the total interference power approximately the same as a non-cooperative scheme. The details on power normalization is provided in Section III-B.

A. Cooperative Forwarding Strategies

1) Cooperative Flooding (CF): In CF, the source node, S, initiates flooding by non-cooperative transmission, and then successive packet forwarding is carried out using cooperative transmissions with RDSTC. The transmission of the source node is in broadcast mode and it is received by multiple neighboring nodes. Let $\mathcal{C}_1 = \{j|\gamma_0 \leq \gamma_{Sj}\}$ denote the set of first hop nodes that receive

the source transmission and cooperatively transmit the packet. The set of nodes that successfully receive the packet transmitted by $\mathcal{C}_1$ form the second hop cooperative set, represented by $\mathcal{C}_2$. Each node in $\mathcal{C}_2$ re-encodes the information using RDSTC and forwards it cooperatively. 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, each node only knows whether it belongs to $\mathcal{C}_k$ or not, but it is unaware of the other nodes. The cooperative sets at each hop depend on the instantaneous channel states and node locations. Hence, each packet may be flooded by a different set of relays. For brevity of notation, we omit to represent the dependency of cooperative sets on instantaneous channel conditions and node locations.

CF policy is similar to the opportunistic large arrays (OLA) approach of [17], as both schemes flood the network by cooperative transmissions. However, different from OLA and conventional flooding, in CF, the total transmit power is kept approximately normalized at each hop. Furthermore, in OLA, the cooperative transmissions are actuated as energy is accumulated at a node, while in CF, nodes only decode based on their reception from the previous cooperative set. Note that when energy accumulation is considered, the transmission synchronization can become challenging, unless an appropriate MAC is designed for handling firing times. However, none of these have been addressed in [17], [18].

CF can be used for dissemination of common information throughout the network, such as dissemination of query packets. Due to RDSTC, CF does not require contention resolution mechanisms as conventional flooding or extra overhead to synchronize cooperative transmissions. CF floods the network faster than conventional flooding, thanks to cooperative diversity gain. This will be further illustrated in Fig. 2. Within the context of our RECOMAC architecture, CF will be utilized for location discovery of the destination node as described in Section IV-A.

2) Cooperative Forwarding within Progress Region (CFPR): In this scheme, the main idea is to progressively forward data from S to D, while exploiting cooperative transmissions with randomized coding. Different than CF, we envision cooperative forwarding within a specified region. Suppose that S has acquired the location information of D via a flooding algorithm, for example via CF. We propose the use of this destination location information to set up a regional route between S and D such that the progress of packets towards D is enhanced. We define forward progress as the progress made by a packet in a direction towards D at each hop, and we define the forward progress region (FPR) as the area between S and D, in which the

forwarders for the source packets, i.e., the cooperative sets, are required to reside in. The nodes inside the FPR are candidate relays for cooperative packet forwarding with RDSTC. The use of FPR prevents loops and assures that the packet moves closer to D at every traversed hop, resulting in improved throughput and delay performance, as will be shown in Section III-C.

Limiting packet forwarding to a specific region has been considered previously in [27] and [28]. However, in these works, the main reason for constraining packet forwarding to a region is to reduce the amount of flooded messages in the network and to avoid long unicast routes to the destination. Moreover, these works do not consider cooperative transmissions. Our aim in defining FPR is to improve the signal strength of the cooperative transmissions using RDSTC with normalized transmit power levels. Due to power normalization, the transmission range of nodes in a cooperative set concentrated in a small region close to the destination, can achieve higher average SNR levels at the next hop receivers, as compared to the range of nodes in cooperative sets with dispersed nodes in a large region, which is the case in CF.

In our preliminary studies, we have observed that the size and shape of the FPR affects the end-to-end performance of cooperative packet forwarding. Although arbitrary FPR shapes are possible, here, we aim to use a simple FPR controlled via a few parameters, which can be adjusted to obtain a desired system performance depending on the node density. While sparse networks call for large FPR to guarantee end-to-end connectivity, dense networks may benefit from small FPR. In particular, FPR should be such that in order to guarantee the commence and 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, even though 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. In this paper, we propose to use an elliptical FPR, as it satisfies the requirements stated above. The elliptical FPR has S and D located at its two foci, and its denoted by $\mathcal{F}(\delta_1, \delta_2)$, where δ_1 and δ_2 are semi minor and semi major axis of the elliptical region, respectively. The size and shape of the FPR can be controlled, and δ_1 and δ_2 can be chosen for optimizing the performance. The use of an elliptical region for routing has been previously studied in [28] without the cooperation perspective, and the region is used for improving the performance of conventional routing schemes, achieved only

with non-cooperative transmissions. In this work, our setting and purpose is different: We use a completely different physical layer setting, randomized coding with RDSTC, and we propose to use elliptical FPR for enhancing cooperative forwarding.

In CFPR, nodes participate in cooperative forwarding if they can successfully decode the packet, and if they are in the FPR. Each relay autonomously decides whether to cooperatively forward the packet or not based on its location (x, y). For the time being, we assume that the location information of S and D, and the δ_1, δ_2 values are forwarded within the packet (in the packet header), so a node that can successfully decode the packet obtains sufficient information for computing the FPR boundaries and decides whether it belongs to the FPR or not. We provide detailed packet structures including required fields, as we describe our cooperative cross-layer protocol in Section IV.

In this scheme, the cooperative set at hop k is given as:

$$\mathcal{C}_k = \{j | \gamma_0 \leq \gamma_{\mathcal{C}_{k-1}j}, j \notin \cup_{i=1}^{k-1} \mathcal{C}_i, (x_j, y_j) \subseteq \mathcal{F}(\delta_1, \delta_2)\},$$

with $\mathcal{C}_0 = \{S\}$. Each node only knows whether it belongs to $\mathcal{C}_k$ or not, but it is unaware of the other nodes. Cooperative sets at each hop are again formed on the fly in an opportunistic manner based on the instantaneous values of the channel states, node locations and FPR parameters.

As compared to CF, CFPR reduces the number of cooperating nodes at each hop, by restraining the inclusion of a node in the cooperative set via the FPR test. Since cooperative transmissions are normalized in power and the transmitters are concentrated in a region towards D, CFPR results in longer transmission ranges, leading to fewer hops as compared to CF, as illustrated in the numerical results of Section III-C.

3) CFPR with Dual Threshold (CFPR-DT): Owing to the observation that cooperative sets concentrated in a small region provide high average received SNR levels, the forward progress of a packet can be further improved by constraining the size of the cooperative sets. This can be achieved by activating a relay node based on a second, upper threshold, so that the total signal strength in the direction of D is improved.

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. Consider two consecutive cooperative hops of CFPR formed as $\mathcal{C}_{k-1} \rightarrow \mathcal{C}_k \rightarrow \mathcal{C}_{k+1}$. $\mathcal{C}_k$ consists of the nodes that receive

the cooperatively transmitted signal from $\mathcal{C}_{k-1}$ at varying SNR levels (all certainly are above γ_0). Due to the effect of path-loss, the nodes that are close to $\mathcal{C}_{k-1}$ receive the signal with large SNR levels with high probability; likewise the nodes that are far away from $\mathcal{C}_{k-1}$ receive the signal with lower, yet still sufficient, SNR levels to decode the packet. This suggests that the transmission range of $\mathcal{C}_k$ can be further improved by preventing the nodes that receive the signal with high SNR levels from participating in cooperative packet forwarding.

For CFPR-DT, the cooperative set at hop k is given as

$$\mathcal{C}_k = \{j | \gamma_0 \leq \gamma_{\mathcal{C}_{k-1}j} \leq \gamma_1, j \notin \cup_{i=1}^{k-1} \mathcal{C}_i, (x_j, y_j) \subseteq \mathcal{F}(\delta_1, \delta_2)\}, \tag{1}$$

where γ_1 is the upper threshold value for the received instantaneous SNR. It is assumed that all FPR parameters, particularly δ_1, δ_2 and γ_1 values, are forwarded within the packet (in the packet header). As in CF and CFPR, in CFPR-DT each node only knows whether it belongs to $\mathcal{C}_k$ or not, but it is unaware of the other nodes.

CFPR-DT limits the number of cooperating nodes at each hop, by restraining the inclusion of a node in the cooperative set via γ_1. Cooperating nodes concentrated towards D provide longer transmission ranges, which leads to fewer hops in comparison with CFPR, as shown later in Section III-C.

B. Power Normalization and FPR Parameter Selection

The performance of CF, CFPR and CFPR-DT strategies depend on power normalization and the selected FPR parameters, namely δ_1, δ_2 and γ_1. In this subsection, we address criteria for power normalization and FPR parameter selection.

1) Power Normalization: The purpose of power normalization is to limit the total transmit power of a cooperative set, $\mathcal{C}_k$, such that robust cooperative transmission is attained without consuming more transmit power than a system employing non-cooperative transmissions.

Power normalization of the cooperating nodes is carried out by equally dividing the available power budget, which is set equal to the non-cooperative transmit power level, P, among the cooperating nodes. In order to realize power normalization in a decentralized fashion, it is necessary that each node in the cooperative set knows the number of actuated nodes in the set. However, acquiring this information instantaneously is impractical. Even if it can be realized

under some oversimplified network and channel assumptions, e.g. via immediate feedbacks, this requires substantial messaging overhead, which may reduce the benefits obtained by cooperation.

In this paper, due to the implementation difficulties of obtaining instantaneous (exact) number of nodes in a cooperative set, we propose to use the average number of actuated relays in a cooperative set for power normalization. The opportunistic nature of our cooperative forwarding strategies suggest that the nodes which are actuated at hop k, i.e., $\mathcal{C}_k$, depend on the previous cooperative set, $\mathcal{C}_{k-1}$. Thus, the average number of relays at the kth hop, $\bar{C}_k = E[E[C_k | \mathcal{C}_{k-1}]]$, can first be calculated conditioned on previous relay set, and then obtained by averaging over all possible $\mathcal{C}_{k-1}$ realizations and randomization matrices as well as fading.

The average number of nodes that participate in cooperative forwarding of the packet at the first hop of CFPR-DT, or equivalently, the average number of nodes that successfully receive the source transmission and that satisfy the FPR conditions and the upper threshold, γ_1, can be computed via $\bar{C}_1 \triangleq E[E[C_1]]$, which is given as

$$\bar{C}_1 = \iint_{(x,y) \in \mathcal{F}(\delta_1, \delta_2)} \rho[e^{-\gamma_0 \Gamma_s(x,y)} - e^{-\gamma_1 \Gamma_s(x,y)}] dx dy, \tag{2}$$

where $1/\Gamma_s(x,y)$ is the received average SNR at location (x,y) such that $\Gamma_s(x,y) = (N_0/P)[(x - x_s)^2 + (y - y_s)^2]^{(\alpha/2)}$. Here, $C_1 = |\mathcal{C}_1|$, ρ is the node density of the network, which is assumed to be uniform, and exponential terms represent the probability of the received SNR at location (x,y) to remain between the two thresholds, γ_0 and γ_1. Note that, for CF, (2) is updated such that FPR is the entire network and the upper threshold is set as infinity, $\gamma_1 \to \infty$; for CFPR, (2) is updated such that $\gamma_1 \to \infty$.

Computation of the average number of relays for $k \geq 2$ is intricate not only due to randomized coding, which does not yield a closed form probability density function for the cooperatively transmitted signal [29], but also due to the dependency of each cooperative set on the previous set. Due to this fact, in this work, we obtain $\bar{C}_k$ ($k \geq 2$) via extensive simulations.

In the simulations, we consider a network of N nodes randomly and uniformly distributed in a rectangular region with width and length equal to 100 m, and with the lower left corner at (0,0). In order to avoid edge effects, S and D are assumed to be located inside the network, where S is at $(20, 50)$ and D is at $(80, 50)$. Path-loss exponent is set as $\alpha = 4$, and each packet and each link undergoes independent flat, slow Rayleigh fading. 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.

In Fig. 1, we present the simulation results depicting the average number of cooperating nodes at the first four hops after the source node, namely $\bar{C}_1$, $\bar{C}_2$, $\bar{C}_3$, $\bar{C}_4$, when $N = 100$, δ_2 is varied from 4 to 48 m and δ_1 is selected such that S-D connectivity is assured. It is observed in the results of CF that although the number of relays at the first hop can be smaller than the ones' at the other hops, due to non-cooperative transmission, the average number of relays tends to be similar as the hop count is increased, which is a consequence of the power normalization and uniform node distribution. For CFPR and CFPR-DT schemes, $\bar{C}_2$, $\bar{C}_3$ and $\bar{C}_4$ are approximately the same for relatively small δ_2.

Since computing the average number of relays for every hop can be time consuming and may not be practical, we assume that the nodes which receive the packet from the source node, $\mathcal{C}_1$, normalize their transmit power levels with $\bar{C}_1$, furthermore, the nodes at the following hops, i.e., the nodes that receive the packet through cooperative transmission, normalize their transmit power levels using $\bar{C}_2$. Note that the source node can compute the $\bar{C}_1$ and $\bar{C}_2$ based on the node density and the FPR parameters prior to communication and tabulate the results. Then, this information can be forwarded within the source initiated packet (in the packet header).

2) FPR parameter selection for CFPR and CFPR-DT: The FPR parameters, δ_1, δ_2 and γ_1 can be selected for optimizing the system performance. In this paper, the FPR parameters are selected such that the average end-to-end throughput between S and D is maximized. Let $\mathcal{T}_{SD}(\delta_1, \delta_2, \gamma_1)$ denote the end-to-end throughput for S-D communication for a single network realization. Furthermore, let $\overline{\mathcal{T}}_{SD}(\delta_1, \delta_2, \gamma_1)$ represent the average end-to-end throughput, where averaging is done over node distributions.

Thus, the optimal FPR parameters are found via the following optimization problem:

$$\max_{\delta_1, \delta_2, \gamma_1} \overline{\mathcal{T}}_{SD}(\delta_1, \delta_2, \gamma_1) \tag{3a}$$

$$s.t. \quad D \notin \cup_{k=1}^{K(\delta_1, \delta_2, \gamma_1)-1} \mathcal{C}_k, \ D \in \mathcal{C}_{K(\delta_1, \delta_2, \gamma_1)}, \tag{3b}$$

$$\gamma_0 < \gamma_1, \tag{3c}$$

where $K(\delta_1, \delta_2, \gamma_1)$ is the total number of hops between S and D for single realization of the network (fading, node distribution and randomization matrix realization). Constraint (3b) represents that the destination, D, does not belong to an active cooperative transmission set, but belongs to the last relay set, i.e., $\mathcal{C}_{K(\delta_1, \delta_2, \gamma_1)}$. Note that in (3a), the objective is to maximize the throughput averaged over multiple network simulations, while the constraint (3b) represents the cooperative sets for single realization of the network. Furthermore, note that the optimization problem is given for CFPR-DT. The optimal FPR parameters for CFPR can be obtained using (3a) via setting $\gamma_1 \to \infty$. We compute $\overline{\mathcal{T}}_{SD}$ and obtain the optimal parameters via extensive simulations carried out prior to actual communication. The optimal choice of $(\delta_1, \delta_2, \gamma_1)$ as a function of the node density and network size can then be stored in a look-up table.

C. Performance Evaluation

Here, we investigate and compare the performance of our cooperative forwarding strategies. In the simulations, we consider the same network set up and settings as described in Section III.B-1. The FPR parameters, δ_1 and δ_2, for CFPR and CFPR-DT are optimized such that for a given network size the total number of hops is minimized, which also translates into maximizing the throughput for constant rate systems. In our preliminary studies, we have observed that the upper threshold value affects the total number of hops of CFPR-DT in the same amount for the considered network sizes. The results depict the optimal upper threshold value, which is found as $\gamma_1 = 15$ dB, that minimizes the total number of hops for all considered network sizes. In Fig. 2, we depict how fast the packet originated at S reaches D, in terms of the number of hops.

For comparison, we also include the results for the conventional non-cooperative flooding (F). These results show that to reach D, cooperative forwarding (CF) requires much smaller number of hops than flooding, resulting in faster information dissemination. Note that, the above results do not take into account the MAC overhead for node coordination, collisions and contention resolution, which are expected to cause degradation on the performance of non-cooperative flooding significantly, as compared to our proposed cooperative forwarding schemes (CF, CFPR, CFPR-DT). This is because with the help of RDSTC, proposed cooperative schemes are collision-free and do not require any contention resolution mechanisms. Further details on the overhead as well as RECOMAC protocol are described in the next section. Of all the cooperative schemes, since CFPR-DT results in the lowest number of hops, it will be used for data delivery in the

RECOMAC protocol.

IV. Routing Enabled Cooperative MAC Protocol: RECOMAC

In conventional wireless networks that are 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 whom 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, since the wireless medium is shared, and simultaneously transmitted packets have a high chance of collision. Once a collision occurs, it should be resolved as the packets are retransmitted. 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, as they are forwarded to their next destinations.

Our proposed cooperative cross-layer architecture, Routing Enabled Cooperative MAC, RECO-MAC, 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. Our architecture achieves this by incorporating the routing layer functions into the MAC layer. RECOMAC builds on our cooperative forwarding strategies presented in Section III, and it employs a modified version of IEEE 802.11 protocol [31] for medium access and data delivery. In particular, we introduce new functionalities to IEEE 802.11 MAC, such as cooperative packet transmission and routing for realizing CFPR-DT for data delivery. We introduce new modified packet structures for RECOMAC with additional fields to support our cooperative forwarding strategies as depicted in Fig. 3 and detailed below. Furthermore, RECOMAC makes use of the reserved bit in the Frame Control Field of the MAC header to allow the nodes to differentiate between the cooperative and non-cooperative transmissions[1].

In RECOMAC, end-to-end communication is realized in two phases. In the destination location discovery phase, S obtains the location information of D. Then, in the data delivery phase, S uses the location information of D for data delivery via a multi-hop cooperative protocol that relies on CFPR-DT strategy. We describe the destination location discovery phase and the data delivery phase as follows.

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[1]In the original IEEE 802.11 standard, if a node receives a packet that is not destined to itself, it ignores the packet and sets its network allocation vector (NAV) according to the duration specified in the packet header.

A. Destination Location Discovery Phase

Destination location discovery is pursued by S before data delivery to 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 described in Section III-A1. Note that when destination location is not known, CFPR or CFPR-DT cannot be used. Fig. 3a depicts the structure of the LREQ packet, including the source and the final destination (D) addresses, the source location, the hop count field that designates how many hops this LREQ message has traversed, and the sequence control field which is used to avoid dissemination of stale LREQ messages. The hop count is initialized to 0 at S and 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. The FPR parameters and the upper threshold, γ_1, are set based on the density of the network and the source and the destination locations according to the optimization problem given in (3a). LREP message involves address and location information, as well as FPR parameters, hop count and sequence control as given in Fig. 3b. The LREP message is forwarded through the selected FPR by D. When S receives this LREP message, it obtains the location information of D, which concludes the destination location discovery phase.

B. Data Delivery Phase

Having completed the destination discovery phase successfully, the cooperative forwarding for data delivery can be initiated. A data packet is sent after a successful routing-enabled-request-to-send (R-RTS) and routing-enabled-clear-to-send (R-CTS) message exchange between the sender and the receiver nodes, which are in fact cooperative sets or the source, S. Following a successful data delivery, a routing-enabled acknowledgement (R-ACK) is sent by D. We differentiate between the cooperative and non-cooperative acknowledgements, as R-CACK and R-ACK, respectively, due to their different functions as described below. In the following, we present the protocol operation by describing the operation of S, intermediate cooperating nodes and D.

1) Source node: The source node computes the optimal FPR parameters via the optimization problem given in 3a. The operation of S is depicted in the flow chart given in Fig. 4, and

summarized below.

(i) Whenever there is a packet in the source node's buffer, it initiates 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. 3c, 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, including $\bar{C}_1$ and $\bar{C}_2$) and the number of hops that the message has traversed.

The source node broadcasts the R-RTS message, with FPR parameters, the upper threshold, γ_1, and location information set, the cooperation bit turned off and the hop count field set to 0. 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 and 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, and stay silent during this period, thereby avoiding possible collisions.

(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).

(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: The operation of the cooperating nodes is depicted in Fig. 5, and summarized below.

Whenever a node receives a R-RTS message, it checks whether it satisfies the FPR and upper threshold criteria, as given in (1). 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 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 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. 6. Furthermore, in Fig. 7, we depict the cooperative forwarding and cooperative set formation within the packet exchanges of RECOMAC.

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 the cooperative set receive the packet in 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, such that the SIFS specified in IEEE 802.11 standard is extended by an amount of maximum propagation delay, T_{prop}. Each node obtains the propagation delay between the sender and itself, then subtracts this value from the total updated SIFS length. This way, the nodes that receive the packet at different times can have timers that fire at the same time instant.

V. PERFORMANCE ANALYSIS

In this section, we present the performance analysis of our RECOMAC architecture in comparison to conventional layered architecture employing regular IEEE 802.11 protocol at the MAC layer and AODV at the routing layer.

AODV is an on-demand route acquisition system, where a route is created when desired by the source node. AODV uses a metric to select the best path between the source and the destination node. In our performance comparisons, we consider two metrics for AODV, the hop count and airtime metrics. When AODV uses the hop count metric, an end-to-end path is established based on the minimum hop count, when airtime metric is used, the end-to-end path is established based on the end-to-end link reliability. Since the airtime metric is link aware, it has been defined as the AODV routing metric in wireless mesh network standard, IEEE 802.11s [32].

We consider the same network set up and settings as described in Section III.B-1. The system parameters used in our simulations are 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 simulate networks with varying number of nodes. For each data point, we create and simulate 20 different network realizations, and the results are averaged.

We have implemented RECOMAC in ns-2 environment, to carry out simulations for performance analysis of RECOMAC in comparison to non-cooperative architecture with IEEE 802.11 and AODV with hop count and airtime metrics. In the implementation of non-cooperative network based on IEEE 802.11 and 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 initiates repeated

route discovery without establishing a valid end-to-end route, and thereby leading to zero end-to-end throughput. Because of this, in our simulations, AODV routing packets and MAC packets are assumed to be error-free, i.e., they are not affected by fading, whereas data packets undergo Rayleigh fading. However, in RECOMAC, all control packets (R-RTS, R-CTS, R-CACK, R-ACK) and 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, whereas AODV cannot even find a valid path between S and D especially when the network is sparse. AODV can operate when the network is sufficiently dense, i.e., when the number of route alternatives is high. However, as we show in the sequel, this results in dramatically increased routing overhead. In the following experiments, the average results are obtained over the cases where the end-to-end connection is established. Due this fact, we do not have data for AODV with airtime metric when $N = 60$.

In Fig 8, we depict the average end-to-end throughput of RECOMAC, IEEE 802.11/AODV with hop count and airtime metrics. It is observed that RECOMAC improves the throughput performance significantly for all networks sizes. The performance of IEEE 802.11/AODV with airtime metric is better than IEEE 802.11/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 based on layered architecture with IEEE 802.11 and AODV.

In Fig. 9, we depict the average number of total hops between S and D. It is observed that 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. 10, we depict the average end-to-end delay per 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 with IEEE 802.11 and AODV. In our simulations, we observed that AODV schemes may drop packets at the MAC layer due to numerous unsuccessful transmission attempts. In our results, we measure only the delay of successfully delivered packets.

In Figures 11 and 12, we provide the amount of MAC and routing overheads caused by the routing protocols. It is observed in Fig. 11 that RECOMAC reduces the MAC messaging overhead significantly as compared to IEEE 802.11/AODV with hop count and airtime metrics. The fraction of required MAC messaging to the obtained throughput is around 0.0023% for all considered network sizes for RECOMAC, whereas it ranges between 14% and 27% for 802.11/AODV with airtime, and it ranges between 60% and 80% for 802.11/AODV with hop count. This is because of the fact that 802.11/AODV schemes require larger number of hops to reach the destination, and at each hop, these schemes require multiple retransmissions in case of channel impairments. Furthermore, 802.11/AODV schemes make 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, thereby causing reduced MAC messaging.

In Fig. 12, we depict the routing message overhead of RECOMAC and 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 AODV with hop count is incomparably poorer than the RECOMAC and AODV with airtime metric and it is not shown. It is observed that the fraction of required route discovery messaging to the obtained throughput is 0.000012% for all considered network sizes for RECOMAC, whereas it ranges between 0.014% and 0.031% for 802.11/AODV with airtime metric, and it ranges between 4% and 18% for 802.11/AODV with hop count.

In this paper, we only provide performance comparisons with conventional layered architectures, as the protocols are readily available in network simulators. It is difficult to make meaningful performance comparisons with other cooperative protocols in the literature [12], [14]–[16], [18], because these protocols either do not consider an explicit MAC protocol and they

assume perfect coordination among the nodes [16], [18], or they consider flawless relay selection and actuation procedures [12], [14], [15], which obscure the effect of messaging overhead on the overall system performance.

VI. CONCLUSIONS

In this paper, a novel cooperative routing framework and a cross-layer cooperative network architecture are presented for wireless ad hoc networks. The cooperative architecture spans the physical, MAC and routing layers. 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 architecture 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 cooperative forwarding framework and our cross-layer architecture, RECOMAC, significantly improve the system performance, with eight times higher throughput and ten times lower delay, as compared to non-cooperative layered architecture with IEEE 802.11 and AODV routing. RECOMAC stands out as a promising architecture that can fully exploit cooperative diversity by enabling cooperative transmissions with RDSTC.

REFERENCES

[1] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity — part I: System description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[2] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 32, no. 10, pp. 74–80, Oct. 2004.

[3] F. H. P. Fitzek and M. D. Katz, *Cooperation in Wireless Networks: Principles and Applications.* Springer, 2006.

[4] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[5] V. Stankovic, A. Host-Madsen, and Z. Xiong, "Cooperative diversity for wireless ad hoc networks," *IEEE Signal Process. Mag.*, vol. 23, no. 5, pp. 37–49, Sep. 2006.

[6] J. Luo, R. S. Blum, L. J. Cimini, Greenstein, and A. M. Haimovich, "Decode-and-forward cooperative diversity with power allocation in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 793–799, Mar. 2007.

[7] L. Badia, M. Levorato, F. Librino, and M. Zorzi, "Cooperation techniques for wireless systems from a networking perspective," *IEEE Wireless Commun.*, vol. 17, no. 2, pp. 89–96, Apr. 2010.

[8] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 340–354, Feb. 2007.

[9] M. S. Gokturk and O. Gurbuz, "Cooperation in wireless sensor networks: Design and performance analysis of a mac protocol," in *IEEE ICC '08.*, May 2008, pp. 4284–4289.

[10] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in wireless networks," in *Allerton Conf. on Communications, Control and Computing*, Oct. 2003.

[11] M. S. Gokturk and O. Gurbuz, "Cooperative mac protocol with distributed relay actuation," in *Wireless Communications and Networking Conference, 2009. WCNC 2009. IEEE*, April 2009, pp. 1–6.

[12] B. Zhao and M. C. Valenti, "Practical relay networks: A generalization of hybrid-ARQ," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 7–18, Jan. 2005.

[13] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[14] F. Librino, M. Levorato, and M. Zorzi, "Distributed cooperative routing and hybrid arq in mimo-blast ad hoc networks," in *Proc. of IEEE GLOBECOM*, Nov. 2007, pp. 657–662.

[15] G. Jakllari, S. V. Krishnamurthy, M. Faloutsos, P. V. Krishnamurthy, and O. Ercetin, "A framework for distributed spatio-temporal communications in mobile ad hoc networks," in *Proc. of IEEE INFOCOM*, April 2006, pp. 1–13.

[16] M. Dehghan, M. Ghaderi, and D. Goeckel, "Cooperative diversity routing in wireless networks," in *Proc. of WiOpt*, June 2010.

[17] A. Scaglione and Y.-W. Hong, "Opportunistic large arrays: Cooperative transmission in wireless multihop ad hoc networks to reach far distances," *IEEE Trans. Signal Process.*, vol. 51, no. 8, pp. 2082–2092, Aug. 2003.

[18] L. V. Thanayankizil and M. A. Ingram, "Reactive routing for multi-hop dynamic ad hoc networks based on opportunistic large arrays," in *Proc. of Wireless Mesh and Sensor Networks Workshop, IEEE GLOBECOM*, Dec. 2008.

[19] B. Sirkeci-Mergen and A. Scaglione, "Randomized space-time coding for distributed cooperative communication," *IEEE Trans. Signal Process.*, vol. 55, no. 10, pp. 5003–5017, Oct. 2007.

[20] E. D. Kaplan, *Understanding GPS: principles and applications*. Artech House, Boston, MA, 1996.

[21] G. Dommety and R. Jain, *Potential networking applications of global positioning systems (GPS)*. Technical report TR-24, The Ohio State University, 1996.

[22] J. Proakis, E. Biglieri, and S. Shamai, "Fading channels: information-theoretic and communication aspects," *IEEE Trans. Inf. Theory*, vol. 44, no. 6, pp. 2619–2692, Oct. 1998.

[23] J. Laneman and G. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[24] C. Nie, P. Lie, T. Korakis, E. Erkip, and E. Panwar, "Coopmax: A cooperative mac with randomized distributed space-time coding for an ieee 802.16 network," in *Proc. of IEEE ICC*, June 2009.

[25] P. Liu, C. Nie, E. Erkip, and S. Panwar, "Robust cooperative relaying in a wireless lan: Cross-layer design and performance analysis," in *Proc. of IEEE GLOBECOM*, 2009, pp. 4107–4112.

[26] F. Verde, T. Korakis, E. Erkip, and A. Scaglione, "A Simple Recruitment Scheme of Multiple Nodes for Cooperative MAC," *IEEE Trans. Commun.*, vol. 58, no. 9, pp. 2667–2682, Sep. 2010.

[27] X.-Y. Li, K. Moaveninejad, and O. Frieder, "Regional gossip routing for wireless ad hoc networks," *Mobile Networks and Applications*, vol. 10, no. 1-2, pp. 61–77, 2005.

[28] C. Saad, A. Benslimane, J. Champ, and J.-C. Konig, "Ellipse routing: A geographic routing protocol for mobile sensor networks with uncertain positions," in *IEEE GLOBECOM*, Dec. 2008, pp. 1–5.

[29] T. Q. Duong, O. Alay, E. Erkip, and H.-J. Zepernick, "End-to-end performance of randomized distributed space-time codes," in *Proc. of IEEE PIMRC*, Sept. 2010.

[30] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[31] "IEEE Standard 802.11-1997, Wireless Lan medium access control (MAC) and physical layer (PHY) specifications."

[32] J. D. Camp and E. W. Knightly, "The IEEE 802.11s extended service set mesh networking standard," *IEEE Commun. Mag.*, vol. 46, no. 8, pp. 120–126, Aug. 2008.
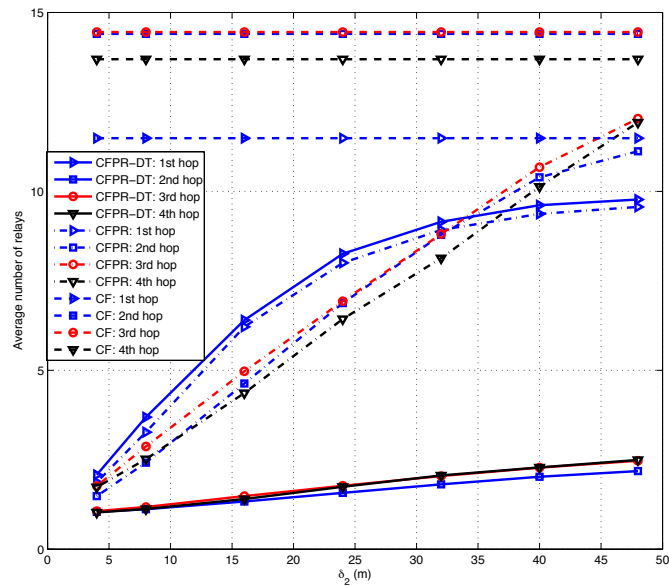
Fig. 1. Average number of relays at the first, second, third and the fourth hops for CF, CFPR and CFPR-DT schemes, when $N = 100$.
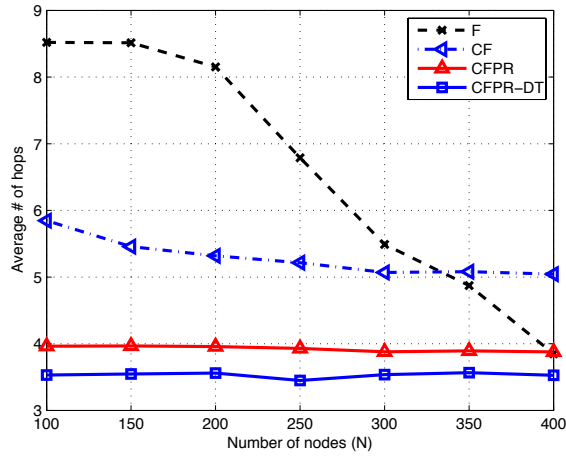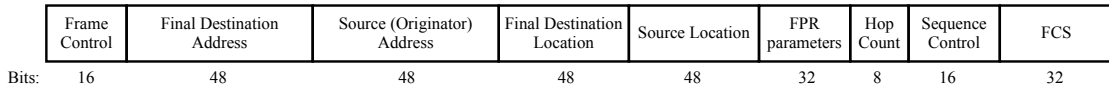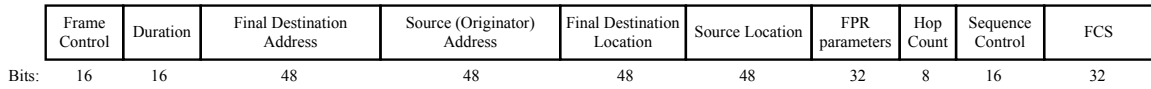
Fig. 2.   Average number of hops to reach the destination node for conventional flooding (F), CF, CFPR and CFPR-DT schemes.

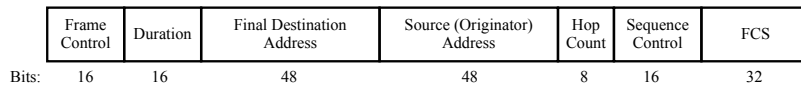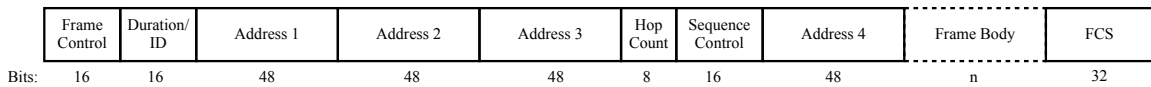| Frame Control	Final Destination Address	Source (Originator) Address	Source Location	Hop Count	Sequence Control	FCS
Bits: 16	48	48	48	8	16	32

(a) LREQ message format

Frame Control	Final Destination Address	Source (Originator) Address	Final Destination Location	Source Location	FPR parameters	Hop Count	Sequence Control	FCS
Bits: 16	48	48	48	48	32	8	16	32

(b) LREP message format

Frame Control	Duration	Final Destination Address	Source (Originator) Address	Final Destination Location	Source Location	FPR parameters	Hop Count	Sequence Control	FCS
Bits: 16	16	48	48	48	48	32	8	16	32

(c) R-RTS message format

Frame Control	Duration	Final Destination Address	Source (Originator) Address	Hop Count	Sequence Control	FCS
Bits: 16	16	48	48	8	16	32

(d) R-CTS, R-ACK and R-CACK message formats

Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Hop Count	Sequence Control	Address 4	Frame Body	FCS
Bits: 16	16	48	48	48	8	16	48	n	32

(e) DATA packet format

Fig. 3.   RECOMAC packet structures. FPR parameters field is reserved for δ_1, δ_2, γ_1, $\bar{C}_1$ and $\bar{C}_2$ information.
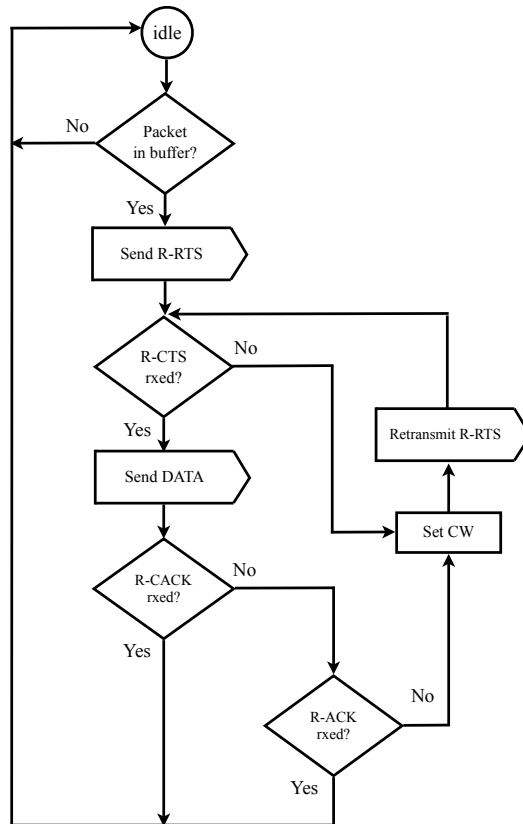
Fig. 4. Flow chart for the source node.

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
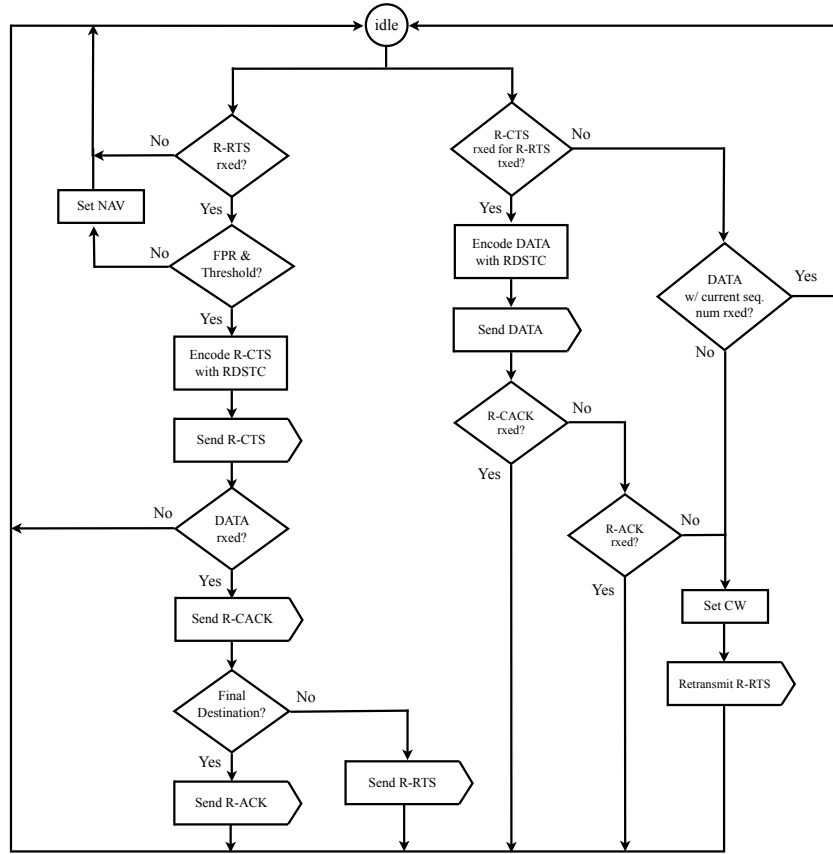
Fig. 5. Flow chart for the intermediate cooperating nodes and the final destination node.
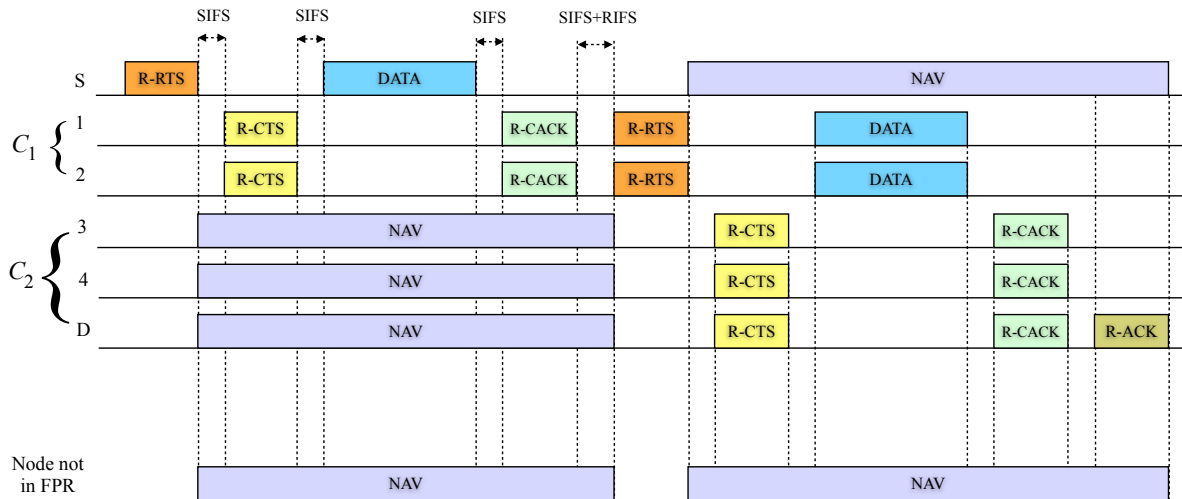
Fig. 6. RECOMAC packet exchange procedure: For the transmission of S, cooperation bit of the frame control field is set as 0, while it is set as 1 for all other transmissions which carried out in cooperative mode.
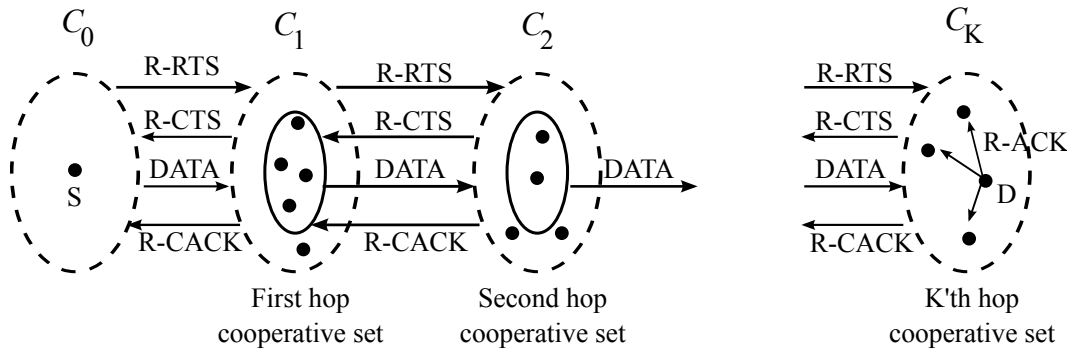
Fig. 7. Cooperative forwarding and cooperative set formation within packet exchanges of RECOMAC.

TABLE II

SOURCE-DESTINATION CONNECTIVITY

N	60	80	100	120	140	160	180
AODV-hop count	0.15	0.25	0.70	0.80	1	1	1
AODV-airtime	0	0.45	0.65	0.95	0.95	0.95	1
RECOMAC	1	1	1	1	1	1	1
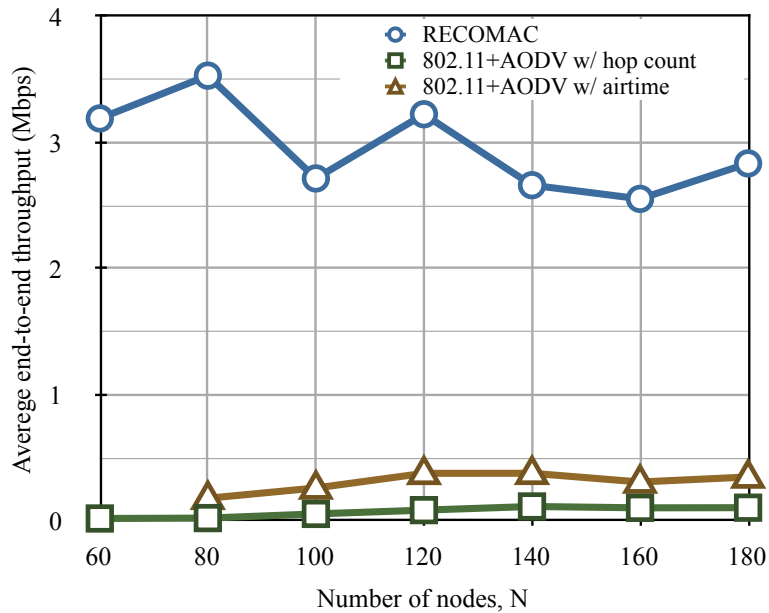
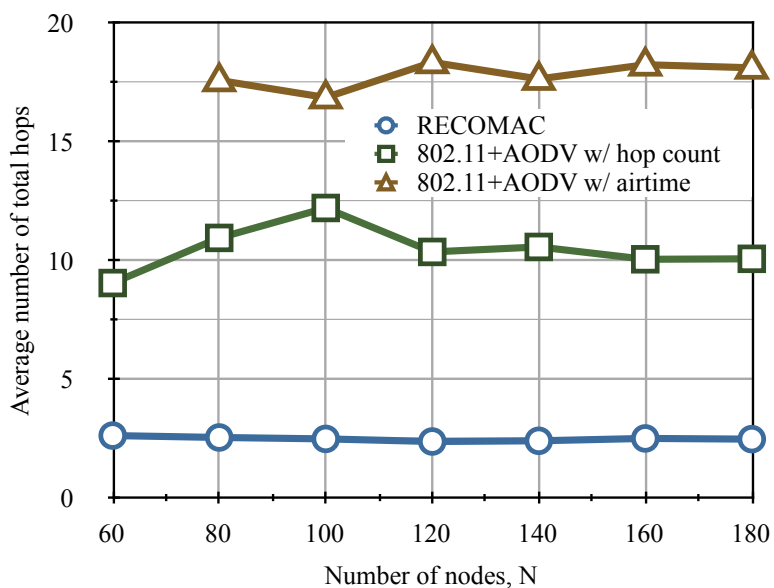Fig. 8. The average end-to-end throughput for RECOMAC, 802.11+AODV with hop count and 802.11+AODV with airtime metric.

Fig. 9.   The average total number of hops for RECOMAC, 802.11+AODV with hop count and 802.11+AODV with airtime metric.
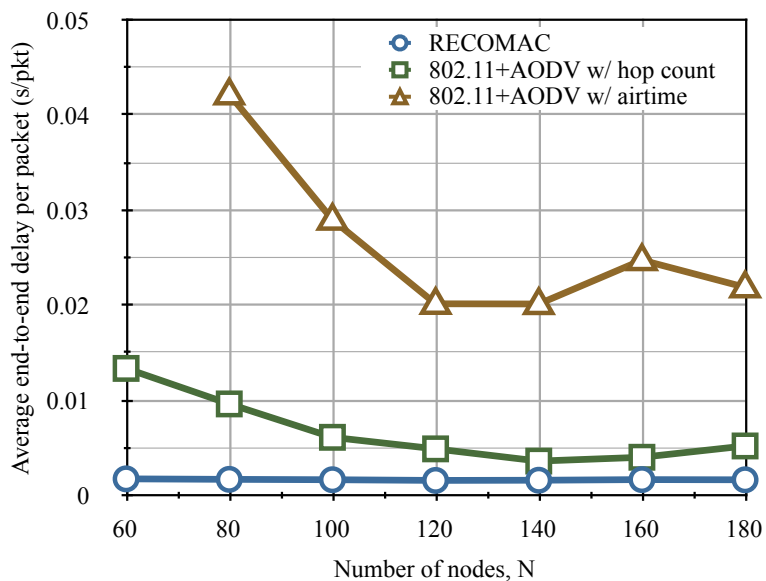

Fig. 10.   The average end-to-end delay per delivered data packet for RECOMAC, 802.11+AODV with hop count and 802.11+AODV with airtime metric.
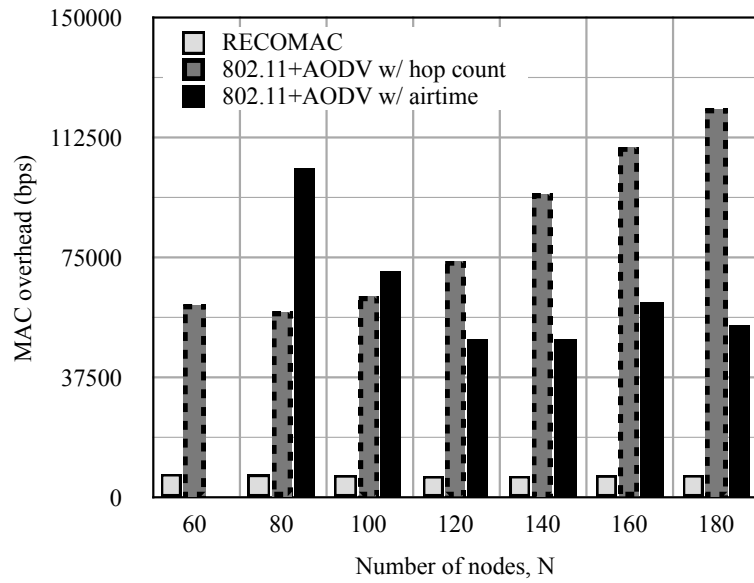
Fig. 11. The average MAC overhead for RECOMAC, 802.11+AODV with hop count and 802.11+AODV with airtime metric.
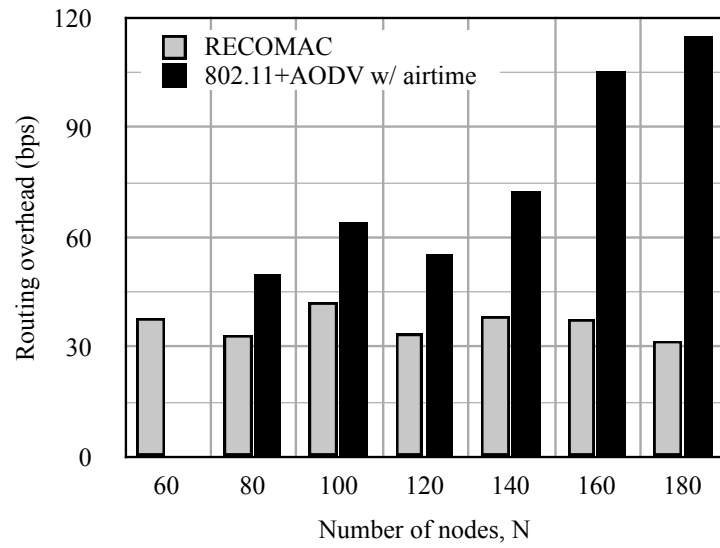

Fig. 12. The average routing overhead for RECOMAC, 802.11+AODV with hop count and 802.11+AODV with airtime metric. Note that for $N = 60$, 802.11+AODV with airtime does not establish S-D connection.