CoopGeo: A Beaconless Geographic Cross-Layer Protocol for Cooperative Wireless Ad Hoc Networks

Teck Aguilar, Syue-Ju Syue, Vincent Gauthier, Hossam Afifi and Chin-Liang Wang

***Abstract*—Cooperative relaying has been proposed as a promising transmission technique that effectively creates spatial diversity through the cooperation among spatially distributed nodes. However, to achieve efficient communications while gaining full benefits from nodes cooperation, more interactions at higher layers of the protocol stack, particularly the MAC (Medium Access Control) and network layers, are indispensably required. This is ignored in most existing articles that mainly focus on physical-layer relaying techniques. In this paper, we propose a novel cross-layer framework involving two levels of joint design—a MAC-network cross-layer design for forwarder selection (also termed routing) and a MAC-physical for relay selection—over symbol-wise varying channels. Based on location knowledge and contention processes, the proposed cross-layer protocol, CoopGeo, aims at providing an efficient, distributed approach to select next hops and optimal relays along a communication path. Simulation results demonstrate that CoopGeo not only operates properly with varying densities of nodes, but also performs significantly better than the existing protocol BOSS in terms of packet error rate, transmission error probability, and saturated throughput.**

***Index Terms*—Cooperative networks; wireless ad hoc networks; cross-layer; beaconless geographic routing; relay selection**

I. Introduction

OVER the last decade, there has been a tremendous wave of interest in the study of cooperative communications for wireless networks. By taking advantage of the broadcast nature of the wireless medium, neighbors overhearing data packets are allowed to assist in the ongoing transmission. Such resource sharing (e.g., power, antennas, etc.) achieved by nodes cooperation is a fundamental idea of cooperative communications. In other words, the number of degrees of freedom (as introduced in [1]) in wireless systems can be effectively increased by enabling collaboration between network nodes. Most attractively, without the requirement of equipping wireless terminals with multiple antennas to construct a multiple-input multiple-output (MIMO) system, cooperative techniques break the limitations of the physical size and hardware complexity and, dramatically, are capable to provide spatial diversity as well.

Most existing work on cooperative techniques focuses on physical-layer cooperative relaying schemes, where various diversity-oriented signaling strategies have been proposed and further demonstrated on the basis of information theory [2]–[7]. However, to achieve efficient communications while gaining full benefits from nodes cooperation, more interactions at higher layers of the protocol stack, in particular the MAC (Medium Access Control) and network layers, are indispensably required. Furthermore, an efficient cooperation-based MAC (or cooperative MAC) scheme should be not only payload-oriented but also channel-adaptive to improve the network throughput and diversity gain simultaneously; otherwise, an inefficient MAC scheme may even make cooperation gain disappear [8].

Two major questions related to cooperative MAC design need to be answered: 1) when to cooperate? 2) whom to cooperate with and how to do selection? For the first question, intuitively there is no need to do cooperation if the direct link is of high quality. In addition, cooperation inevitably introduces inefficiency in some degree due to extra protocol overhead and limited payload length. Therefore a cooperative MAC protocol should be carefully designed to prevent unnecessary cooperation [8]. In [9], the authors proposed a cooperation metric that is related to the instantaneous source-relay and relay-destination channel measurements to decide if cooperation is needed. The use of automatic repeat request (ARQ) and hybrid-ARQ schemes in cooperative networks has been discussed in [10], [11]. In [3], an incremental relaying protocol using limited feedback from the destination was proposed, and it can be viewed as an extension of ARQ in the relaying context. The second question about cooperative MAC design addresses the typical relay selection problem. There may exist a group of available relays around the source; however, some are beneficial and some not. How to find the optimal one(s) efficiently and effectively is of vital importance to a practical MAC protocol.

§This paper was accepted in part at the 2010 IEEE 71st Vehicular Technology Conference (VTC 2010-Spring), Taipei, Taiwan, May 2010.

Recent years have seen growing interest in the subject of relay selection [8]–[10], [12]–[25]. Some focus on the design of enhancing system reliability in a centralized manner [9], [12]–[14], neglectful of the needs of overhead produced by nodes coordination, unmindful of the feasibility of capturing a lot of channel state information (CSI) among nodes, unsuitable for being used in resource-constrained networks. To make relay selection more efficient, the authors of [15] described how physical-layer cooperation can be integrated with the MAC layer to improve network performances. Other cross-layer issues are also included in [15]. In [16], the authors presented the concept of selection diversity and demonstrated that the single best-relay selection can outperform distributed space-time coded relaying schemes in terms of outage probability. In [17]–[19], distributed relay selection schemes based on the knowledge of local instantaneous channel conditions without requiring topology information are proposed. CoopMAC [20] and rDCF [21] are similar cooperative MAC protocols, which alleviate the throughput hindrance caused by low-data-rate nodes. The main idea is to select a high-data-rate node helping the data delivery through two-hop transmission. In [10], a generalized concept of hybrid automatic repeat request scheme (hybrid-ARQ) is applied to relay networks, allowing that packet retransmissions could be performed at any relay that overhears and decodes earlier transmitted blocks when the negative acknowledgment (NACK) is received. In [22], the authors proposed a busy-tone-based cross-layer cooperative MAC (CTBTMA) protocol, where busy tones are utilized to solve collisions in a cooperation scenario and address the optimal relay selection problem. In [23], the authors introduced an adaptive relay selection based on random access relay advertisements, by which each relay decides whether to participate in the cooperation. In [24], the authors studied a fully opportunistic relay selection scheme under partial CSI for cellular networks, where macro and micro diversities are jointly considered. Considering the time-varying characteristic of some mobile environments in which the widely used memoryless channel assumption becomes unrealistic, [25] addressed a relay selection problem under finite-state Markov channels. In [14], we have proposed a geographic relay selection scheme based on the knowledge of location information of nodes. By jointly combining the source-relay and relay-destination distances, the optimal relay offering the best cooperative link can be efficiently determined. However, the selection process proposed by [14] requires a central controller to decide which relay is most helpful, leading to more overhead and power consumption. One goal of this paper is to present a distributed relay selection protocol based on [14], with MAC-physical cross-layer design.

Likewise, in view of the interaction between the MAC and network layers, we also incorporate routing issues in this paper as a properly designed MAC protocol can facilitate routing process at the network layer, in particular the beaconless geographic routing[1] (BLGR) [28]–[33]. BLGR is one of the most efficient and scalable routing solutions for wireless ad hoc and sensor networks. The key advantage of BLGR is that it needs neither prior knowledge of network topology for making a route decision nor the periodic exchange of control messages (i.e., beacons) for acquiring neighbors' geographic locations. A current node can make its own routing decisions by using local information. In general, a BLGR protocol comprises two operating phases: forwarding phase and recovery phase. In the forwarding phase, routing decisions are made according to the greedy mechanism, a neighbor closest to the destination is chosen as the next hop of a current node. Greedy forwarding, however, fails when reaching a local minimum, i.e., a current node that has no neighbor closer to the destination. In this case, the recovery mode based on the well-known face routing algorithm is triggered to find another path to the destination.

It is worth noting that BLGR at the network layer is usually coupled with MAC protocols to offer better network throughput and preserve advantageous properties such as localized operation and high scalability. A paradigm of network-MAC cross-layered BLGR protocol is as follows: through a contention process at the MAC layer, each candidate forwarder sets a contention timer depending on the progress to the destination such that the optimal candidate (closest to the destination in greedy sense) responds first, as a result of time-out. Hence, cross-layer design between the network and MAC layers is quite significant. In [33], Sanchez et al proposed a cross-layered BLGR protocol called BOSS, which uses a three-way (DATA/RESPONSE/SELECTION) handshake and an area-based timer-assignment function to reduce collisions among responses during the forwarder selection phase. However, when operating in recovery mode, BOSS performs face routing by requiring the exchange of complete neighborhood information. To avoid this drawback, we present a fully beaconless protocol that

[1] Geographic routing, based on location information for route decisions, can be applied to the so-called Selection Diversity Forwarding [26], [27] — another way of achieving spatial diversity via forwarder selection — exploiting channel state information (CSI) and PHY-network cross-layer integration to select routes with favorable channel conditions. However, we do not examine this channel-adaptive scheme in this paper. The diversity gain we discuss is only from relay selection in cooperative networks.

does not require beacons in both the greedy forwarding and recovery modes.

Above, we have introduced the roles of interactions between the MAC and physical layers and between the network and MAC layers, in a cooperative scenario. In this paper[2], we aim at integrating the network, MAC, and physical layers as a network-MAC-physical cross-layer design to enhance overall system performance. Two issues, routing and relay selection, are the two chief considerations. We assume that the channel changes quickly as a symbol-wise varying channel. The proposed novel cross-layer framework, called CoopGeo, consists of two joint cross-layer designs, a joint network-MAC design for next hop selection and a joint MAC-physical design for relay selection. In particular, both the routing and relay selection solutions in CoopGeo are geographic protocols using contention-based selection processes, providing a strongly practical multi-layer integration for cooperative networks.

The contributions of this article are as follows:

- We propose a distributed MAC-PHY cross-layer design for relay selection based on the geographic approach [14], where the best relay is chosen as the one that provides the minimum average point-to-point SER.
- We present a fully beaconless approach to geographic routing with a MAC-NWK cross-layer design, where both the greedy forwarding and recovery modes are executed without periodic exchange of beacons and complete neighborhood information.
- Based on the use of geographic information and contention processes, the framework of CoopGeo that supports localized operation as well as high scalability is considerably practical for cooperative wireless ad hoc networks.

The rest of the paper is organized as follows. The network model of cooperative multi-hop networks and the problem statement are described in section II. Section III details CoopGeo, i.e., the proposed cross-layer design for cooperative wireless ad hoc networks, in which beaconless geographic routing and relay selection, along with a feasible protocol, are included. In section IV, we give the numerical simulation results for CoopGeo and evaluate its performance by comparing with an existing protocol. Finally, the conclusions are presented in section V.

[2] This paper is the extended version of our previous work [34].

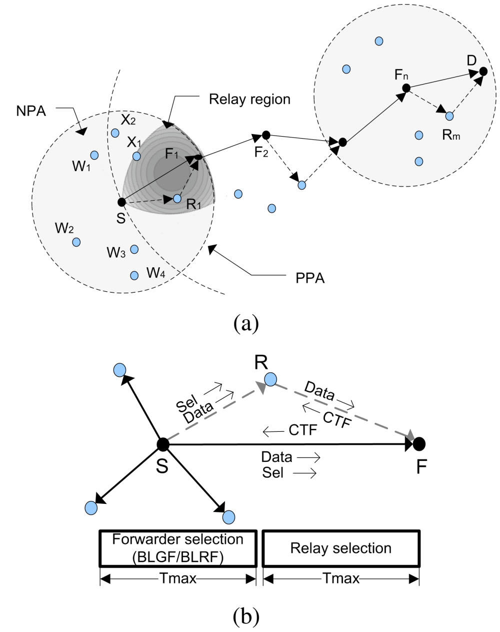


Fig. 1. (a) Cooperative multihop ad hoc network model (b) Direct and cooperative modes for each hop

II. Network Model and Problem Statement

A. Network Model

We consider a wireless ad hoc network of k nodes randomly deployed in an area, represented as a dynamic graph $G(V, E)$, where $V = \{v_1, v_2, \dots, v_k\}$ is a finite set of nodes and $E = \{e_1, e_2, \dots, e_l\}$ a finite set of links between the nodes. We denote a subset $N(v_i) \subset V$, $i = 1, \dots, k$, as the neighborhood of the node v_i, defined as those nodes within the radio range of v_i. Throughout this paper, we consider there is a single session in the network, where data delivery may cross over multiple hops.

Fig. 1(a) depicts the wireless ad hoc network model, in which the source S sends its data to the destination D in a multihop manner. In this figure the dashed circle centered at S illustrates the radio range of S, and so on. At the beginning of every data transmission, S broadcasts the data to its neighbors $N(S)$. One of these neighbors $N(S)$ is chosen as the next hop through a forwarder selection process, denoted as F_1. Two transmission modes, namely direct and cooperative modes, are considered to operate in each hop. In the direct mode, a point-to-point communication is performed by direct transmission; in the cooperative mode, it is done by cooperative relaying. The cooperative mode operates only when F_1 cannot correctly decode the data from S. After having a correct version of the data packet, F_1 acts as the source node and repeats the same procedure, and so on until the data packet reaches the destination D.

Since the multihop transmission is realized by concatenating multiple single-hop schemes, as shown in Fig. 1(b), for convenience of notations we denote S as the current source in a current hop and F the forwarder, also called the next hop or the intermediate node in this paper. In addition, we represent R_i, $i = 1, \ldots, |N(S)|$, as the candidate relays of S, one of which is going to cooperate with S whenever needed. In the following we introduce the signal models for the direct and cooperative transmission modes, respectively.

In the direct mode, S broadcasts its symbol x at the time index i with transmission power P, where the average power of x is normalized to unity. The received signals at F can be expressed as

$$y_{S,F}^{(i)} = \sqrt{P} h_{S,F}^{(i)} x + n_{S,F}^{(i)}, \quad (1)$$

where $h_{S,F}$ is the channel coefficient from S to F and $n_{S,F}$ is the additive noise term. Throughout this paper, we assume that each node has a single antenna operating over frequency-flat Rayleigh fading channels and can only either transmit or receive data at any time slot. Moreover, the fading channels are assumed to be sufficiently fast-varying such that any channel coefficient, say $h_{u,v}$, modeled as $h_{u,v} \sim CN(0, \sigma_{u,v}^2)$, is constant over a symbol duration and may change from a symbol to another as an *i.i.d.* random process. We also assume that all the channel coefficients among radio links are independent. Finally, we model all the noise terms as complex Gaussian random variables with zero mean and equal variance N_0, where, without loss of generality, we assume $N_0 = 1$.

For the cooperative mode, it applies a two-phase decode-and-forward (DF) strategy with single-relay selection, described as follows. In the first phase, S broadcasts its symbol x with transmission power P_x while the next hop F and a selected relay R (through a relay selection process) listen. The received signals at F and R can be respectively expressed as

$$y_{S,F}^{(i)} = \sqrt{P_x} h_{S,F}^{(i)} x + n_{S,F}^{(i)}, \quad (2)$$

$$y_{S,R}^{(i)} = \sqrt{P_x} h_{S,R}^{(i)} x + n_{S,R}^{(i)}, \quad (3)$$

where $h_{S,R}$ is the channel coefficient from S to R and $n_{S,R}$ is the additive noise term. In the second phase, with the simple adaptive DF strategy [35], the selected relay decides whether to forward the decoded symbol to the next hop. If the relay is able to decode the transmitted symbol correctly, it forwards the decoded symbol with identical transmission power P_x to the next hop, and if not, it remains idle. For practical use of this *adaptive* mechanism, we consider that each relay is able to evaluate its own condition based on an SNR threshold. If the received SNR at the relay is greater than a certain threshold, the relay forwards; otherwise, it remains idle.

$$I_R = \begin{cases} 1, & \text{if } R \text{ decodes the symbol correctly,} \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

Then, the received signals at the the next hop in the second phase can be written as

$$y_{R,F}^{(j)} = \sqrt{P_x I_R} h_{R,F}^{(j)} x + n_{R,F}^{(j)}, \ (j \neq i) \quad (5)$$

where $h_{R,F}$ denotes the channel coefficient from R to F and $n_{R,F}$ denotes the AWGN. Finally, the next hop coherently combines the received signals from the current source and the selected relay, i.e., $y_{S,F}^{(i)}$ and $y_{R,F}^{(j)}$, by using a maximum ratio combining (MRC)

$$y_F^{(j)} = \sqrt{P_x} h_{S,F}^{(i)*} y_{S,F}^{(i)} + \sqrt{P_x I_R} h_{R,F}^{(j)*} y_{R,F}^{(j)}. \quad (6)$$

Consequently, the decoded symbol $\hat{x}$ at the next hop is given by

$$\hat{x} = \arg \min_{x \in \mathcal{A}} |y_F - P_x(|h_{S,F}^{(i)}|^2 + I_R |h_{R,F}^{(j)}|^2) x|^2, \quad (7)$$

where $|\mathcal{A}| = \Theta$ denotes the cardinality of Θ-ary constellation.

By invoking the performance analysis in [36], the resulting symbol error rate (SER) at the next hop can be expressed as

$$P_s \approx \frac{4N_0^2}{b^2 P_x^2 \sigma_{S,F}^2} \left(\frac{A^2}{\sigma_{S,R}^2} + \frac{B}{\sigma_{R,F}^2} \right), \quad (8)$$

which is a tight approximation in a high SNR regime, where $b = \frac{3}{2(M-1)}$, $A = \frac{M-1}{2M} + \frac{(1-1/\sqrt{M})^2}{\pi}$, and $B = \frac{3(M-1)}{8M} + \frac{(1-1/\sqrt{M})^2}{\pi}$ in the case of M-QAM modulation.

Moreover, we make the following assumptions in the network model: 1) the network is dynamic and the network topology, including the cardinality of a node's neighborhood, the location of nodes, and the linkage between nodes, changes over time due to wireless environments, duty circles, and node failures, etc.; 2) each node is aware of its own location; 3) in addition to itself's location, the source knows the location of the destination, and so does any intermediate node; 4) all the network nodes are homogeneous, and each could become a source, relay, or forwarder.

B. Problem Statement

In considering how cross-layer design improves network throughput and reliability for wireless cooperative ad hoc networks, the first question that arises concerns the joint MAC-network cross-layer routing design. For a network $G(V, E)$, given a source-destination pair $v_S, v_D \in V$, the objective of a routing task is to find a subset of forwarders $P_F = \{v_{F_1}, v_{F_2}, \ldots, v_{F_n}\} \subset V$ that builds a routing path from v_S to v_D with successful packet delivery guaranteed. In particular, each forwarder in P_F is determined locally, within a forwarding area defined as the radio coverage of the current source, which is divided into a positive progress area (PPA) and a negative progress area (NPA). In both, the PPA and NPA areas, the beaconless greedy forwarding (BLGF) and beaconless recovery forwarding (BLRF) phases are applied, respectively (as shown in Fig. 2).

The second question that this study addresses concerns the joint MAC-PHY cross-layer relay selection design. The aim of CoopGeo relay selection is to find a subset of optimal relay nodes $P_R = \{v_{R_1}, v_{R_2}, \ldots, v_{R_m}\} \subset V \setminus P_F$ to enhance the network reliability, where each optimal relay v_{R_i} that minimizes the average point-to-point SER for each cooperative hop is locally selected within a predefined relaying area.

One design goal of CoopGeo is to develop a fully beaconless approach to geographic routing that does not rely on periodic exchange of beacons as well as complete neighborhood information. Therefore, forwarder and relay selection use a local contention process based on geographical information and area-based timers. A specified interval of time T_{max} is assigned to each selection process.

By tackling the above issues, we contemplate a feasible cross-layer protocol that comprehensively integrates the NWK, MAC, and PHY layers to achieve a highly-efficient communication. In the following section we detail the framework of the proposed cross-layer design.

III. CoopGeo: A geographic cross-layer protocol for cooperative wireless networks

CoopGeo, in general, performs two tasks in wireless cooperative ad hoc networks: routing and relay selection. As described above, the routing process works in two phases, i.e. BLGF and BLRF. Both phases share equally a T_{max} interval of time where the forwarder selection is executed. The first half of the T_{max} period is allocated to the BLGF phase and the second half to the BLRF phase.

In the BLGF phase, a next hop that provides maximal progress toward the destination is selected through a timer-based contention process. When failing to find a next hop in the BLGF phase, the routing process enters transparently to the BLRF phase and applies face routing by using graph planarization along with a select-and-protest principle. Cooperative relaying is required after the routing task, whenever the selected next hop decodes the data packet erroneously. In this case, CoopGeo starts out to execute the relay selection task within another interval of time T_{max}, selecting an optimal relay that offers the best cooperative link between the current source and the next hop.

Fig. 1(a) gives an example for both the routing and relay selection in CoopGeo. The nodes competing in the BLGF phase are those located in PPA, i.e., X_1, X_2, R_1, and F_1. Those located in NPA, i.e., $W_1, \ldots, W_4$, are considered to compete in the BLRF phase. The node F_1 is selected as the forwarder node, where the data transmission between the source S and the forwarder F_1 is carried out through a direct or cooperative transmission. In the case of cooperative transmission, the candidate relays with respect to the transmitter-receiver pair (S, F_1) that participate during the relay selection process are those within the relaying area (that will be defined later), including R_1 and X_1. In this figure R_1 is selected as the optimal relay node of the cooperative transmission.

A. Beaconless Greedy Forwarding (BLGF)

At the beginning of a data transmission, S triggers the BLGF phase of the routing process by broadcasting its data to the neighborhood and then waits for the best next hop's response during the first half of the T_{max} time. During this period, the neighborhood compete to forward the message by setting their contention-based timers (T_{CBF}), as explained in Section III-A1. When the best forwarder node is selected due to its timer expiration, it sends a clear-to-forward (CTF) message to S, then, the other candidates overhearing this message suppress their running timers and delete the data received from S. Since some candidates situated at the forwarding area may be unable to hear the CTF message, the hidden terminal problem could appear. To prevent it, S broadcast a warning message (SELECT) to indicate that a forwarder node has been found. The hidden candidates overhearing it, will suppress their timer and the data packet. Immediately, F send an acknowledgement (ACK) to S and thereafter, it acts as the source and repeat the process hop-by-hop until the data is delivered to the final destination D.

1) Geographic contention-based forwarder selection (T_{CBF}): To implement the BLGF phase, we base the timers settings on the metric proposed in [33], which applies an area-based assignment function. Fig. 2 depicts, as mentioned above, two areas, PPA and NPA, that divide the radio coverage of a current source, both of which are further divided into sub-areas called Common Sub-Areas (CSAs) in order to avoid collisions during the contention period. Moreover, those candidate nodes situated at the same CSA offer similar progress toward D, and thus, they have similar T_{CBF} values. Note that unlike [33], we

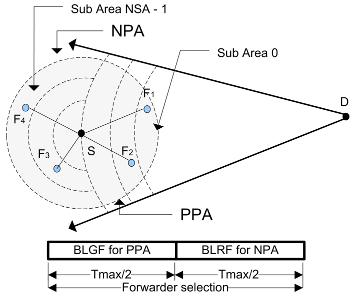


Fig. 2. Area division for CoopGeo routing. F_1 and F_2 are sub-area 0 and 1 of PPA respectively, whereas F_3 and F_4 are sub-area 4 and 5 of NPA respectively.

divide the NPA area by using concentric coronas instead of slides as used at the PPA area. We will discuss the reason at the BLRF section.

The timer setting for each candidate node is given as follows. First, each candidate node situated in PPA identifies which CSA group it belongs to by using the following equation:

$$CSA_{PPA} = \Big\lfloor NSA \times \frac{r - (d_{S,D} - d_{F_i,D})}{2r} \Big\rfloor, \qquad (9)$$

where NSA is a predefined even number of sub-areas to divide the coverage area, r is the transmission range which is equal to the largest progress, and $(d_{S,D} - d_{F_i,D})$ represents the candidate progress to the destination.

Next, given CSA_{PPA}, hereafter called CSA, each candidate calculates its T_{CBF} timer according to:

$$T_{CBF} = \Big(CSA \times \frac{T_{max}}{NSA}\Big) + rand\Big(\frac{T_{max}}{NSA}\Big), \qquad (10)$$

where T_{max} represents the maximum delay time that the current source S will wait for a next hop's response, and $rand(x)$ a function obtaining a random value between 0 and x to reduce the collision probability. The T_{CBF} function allocates the first half of T_{max} to PPA candidates for the BLGF phase and the second half to the NPA candidates for the BLRF phase.

B. Beaconless Recovery Forwarding (BLRF)

As introduced before, the BLGF mode may suffer from the local minimum problem: the packet may be stuck at a node that does not have a neighbor (at PPA) closer to the destination than itself. To solve this problem, the Beaconless Forwarder Planarization (BFP) algorithm of [37], which guarantees the packet delivery is applied at BLRF. BFP reduces the number of messages exchanged by using the select-and-protest principle. In the select stage, some NPA neighbors are selected to form a planar subgraph according to a contention function, then, in the protest stage, falsely planar edges are removed from the subgraph. Finally, the traditional face routing algorithm is applied to select the forwarder node.

BFP is implemented at the BLRF phase of CoopGeo as follows. First, the current source detects the local minimum when a $T_{max}/2$ time has passed without receiving any CTF message from any neighbor situated at PPA. Thus, CoopGeo switches automatically from the BLGF mode to the BLRF mode so that, BFP is applied during the second half of T_{max}. To accomplish this, the candidate nodes situated at the NPA area determine their CSAs and compute their contention timers (T_{CBF}) that will be used by the BFP algorithm. Once the planar subgraph is build, S send a SELECT message to the node that has been elected forwarder node, which confirms the reception with an acknowledgement.

In [33], the CSAs of NPA are created according to the progress toward the destination. CoopGeo, by contrast, adopts the distance with respect to the node that is suffering the local minimum problem, and accordingly the slides are modified to concentric coronas. Thus, The NPA area is divided into $n = NSA/2$ equally sized concentric coronas (see Fig. 2), where the width of the i-th corona is $(\sqrt{i} - \sqrt{i-1})r_1$, and r_1 is the radius of the first corona, being calculated with $r_1 = r/\sqrt{n}$. To use the same terminology as the one used at the BLGF phase, in the following a corona will be referred as a CSA. To set a contention timer, a candidate F in NPA first finds its CSA_{NPA} index by using the following equation:

$$CSA_{NPA} = \Big\lfloor \Big(\frac{\sqrt{n} \cdot d_{S,F}}{r}\Big)^2 \Big\rfloor + \frac{NSA}{2}. \qquad (11)$$

With knowledge of their CSA_{NPA} index, hereafter called CSA[3], each NPA forwarder candidate determines its contention timer according to (10), and BFP is applied.

In this paper, we do not explain the BFP algorithm of [37] in detail. Instead, we present an example to illustrate the process in Fig. 3. Let us consider a scenario where the source S is surrounded by six neighbors which respond in the order: F_1, F_4, and F_5 according to their timers defined by (10). F_2 receives the CTF message from F_1 and becomes a hidden node, F_3 receives the CTF from F_4, and F_6 receives the CTF from F_5. Thus, the hidden nodes are F_2, F_3 and F_6. F_2 is located in the proximity region (Gabriel Graph) of F_1 and F_3 in the proximity region of F_4. So, in the protest phase, F_2 protests against F_1 and F_3 protests F_4. Thus, S removes the links with violating nodes (node in the proximity

[3] A CSA value at the forwarding selection is a nonnegative integer that falls in $[0, NSA-1]$, where 0 corresponds to the area closest to D and $(NSA-1)$ to the farthest one.

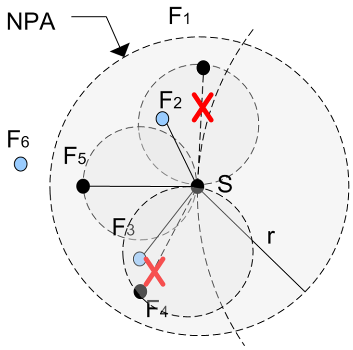


Fig. 3. Beaconless Recovery Forwarding happens at NPA area when the Beaconless Greedy Forwarding fails

region of a node) and obtains a planar subgraph that will be used by the face routing algorithm to find the next forwarding node.

C. MAC-PHY Cross-Layered Relay Selection

The relay selection process takes place after the forwarder selection whenever the demand for cooperation is announced by a forwarder. In such a case, a new contention period will be allocated for relay selection. The relay selection process, in this paper, is based on the selection criterion of [14], in which we had addressed a geographic relay selection problem. Specifically, the best relay is selected according to a distance-dependent metric m_i, as shown in (15), relying on a combination of the source-relay and relay-destination distances.

Rewriting (8)—with a relay index i introduced—in terms of coding gain and diversity order, we have

$$P_s = (\Delta \cdot \gamma)^{-d}, \tag{12}$$

where Δ denotes the coding gain of the scheme, given by

$$\Delta = \sqrt{\frac{b^2\sigma^2_{S,F}}{16}\left(\frac{A^2}{\sigma^2_{S,R_i}} + \frac{B}{\sigma^2_{R_i,F}}\right)^{-1}}, \tag{13}$$

$d = 2$ is the diversity order, and $\gamma = P/N_o$ represents the SNR, where $P = 2P_x$ is the total transmission power. The goal is to select the best relay that maximizes the coding gain Δ and, consequently, minimizes the SER. In (13), the only term affecting the coding gain is

$$m_i \equiv \frac{A^2}{\sigma^2_{S,R_i}} + \frac{B}{\sigma^2_{R_i,F}},\ i = 1, 2, ..., N\,. \tag{14}$$

Consider a $\sigma^2_{i,j} \propto d^{-p}_{i,j}$ path loss model, where p represents the path loss exponent. Then the channel variances $\sigma^2_{i,j}$ in (14) can be replaced with the distance-dependent parameters $d^{-p}_{i,j}$. Thus, (14) becomes

$$m_i = A^2 d^p_{S,R_i} + B d^p_{R_i,F},\ i = 1, 2, ..., N\,, \tag{15}$$

where m_i is treated as our relay selection metric, which indicates the SER performance at the forwarder—the smaller the metrics is, the better the resulting SER performance will be. Therefore, the best relay can be determined according to the following criteria[4],

$$i^* = \arg \min_{i\in\{1,..,N\}} m_i = \arg \min_{i\in\{1,..,N\}} A^2 d^p_{S,R_i} + B d^p_{R_i,F}\,. \tag{16}$$

We note that the best relay selected by the above criterion is the one that provides the best source-relay-forwarder cooperative link in terms of average SER at F. The relay selection process in [14], however, requires a central controller to make a best-relay decision according to the responses from all candidate relays. To reduce the required overhead while achieving a more efficient relay selection process, we propose a distributed relay selection protocol using MAC-PHY cross-layer design, as presented in the following part.

1) Geographic contention-based relay selection: The election process starts as soon as each candidate relay overhears the DATA/CTF packets. Each possible relay acquires two relative distances d_{S,R_i} and $d_{R_i,F}$ to calculate its own selection metric according to (15). Here the path loss exponent is assumed as a known parameter. For the purpose of decentralization, the relay selection metric m_i is encoded in time difference inside a timer-based election scheme. Once a candidate whose timer expiration happens first, it relays the data packet to F, and the others candidates cancel their timers after receiving the packet. This contention-based relay selection scheme provides a distributed and efficient way to determine the best relay for each cooperative hop, and it answers the major question about cooperative MAC design, i.e., whom to cooperate with and how to do selection? The metric defined in (15) indicates the cooperative link quality in terms of average point-to-point SER, depending on the modulation type and the locations of nodes. In order to translate our relay selection selection metric (15) into a timer we normalized it according to their relative distance from $\mathbf{x}^*$, which is be the best placement of a relay (minimized the average point-to-point SER). We denote $\mathbf{x}_S, \mathbf{x}_F$, and $\mathbf{x}_i$ as the locations of the current source, the forwarder, and the i-th candidate relay, respectively. In addition, we define f as a mapping function that maps a candidate relay's location into its relay selection metric ($\mathbf{x}_S$ and $\mathbf{x}_F$ are

[4] Eq. (8) is a bound and it is given as an asymptotically tight approximation at high SNR. As the SNR is sufficiently high, the average symbol error rate (SER) as in (8) is the same with the exact SER. For low SNRs, although (8) does not hold anymore, it does not affect the correctness of the selection for the best relay (or the second-best relay, the third-best relay, and so on).

fixed), as in (17). The optimal point $\mathbf{x}^*$ can be obtained by solving the optimization problem (18). Thus, the best relay is the one whose metric is closest to $f(\mathbf{x}^*)$.

$$f(\mathbf{x}_i) = A^2 \left\|\mathbf{x}_i - \mathbf{x}_S\right\|^p + B \left\|\mathbf{x}_i - \mathbf{x}_F\right\|^p \quad (17)$$

$$\text{minimize} \quad f(\mathbf{x}) = A^2 \left\|\mathbf{x} - \mathbf{x}_S\right\|^p + B \left\|\mathbf{x} - \mathbf{x}_F\right\|^p \quad (18)$$

$$\mathbf{x}^* = \frac{A^2 \mathbf{x}_S + B \mathbf{x}_F}{A^2 + B} \quad (\text{as } p = 2)\,. \quad (19)$$

We then derive a mapping function $\mathcal{M}$, which scales our metric function f into the interval $[0, 1]$:

$$\mathcal{M}(f(\mathbf{x})) = \frac{f(\mathbf{x}) - f(\mathbf{x}^*)}{f(\mathbf{x}_{\max}) - f(\mathbf{x}^*)}\,, \quad (20)$$

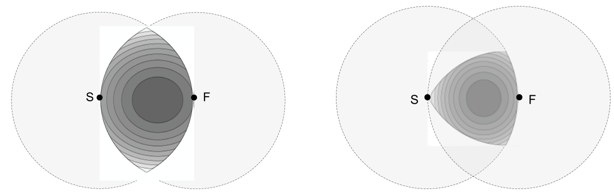
where $\mathbf{x}_{max}$ is an arbitrary point defined geometrically as far as possible of $\mathbf{x}^*$ inside the relay area [5]

Finally, a contention timer at each candidate relay is set by using the following function:

$$T_{CBR} = T_{max}\ \mathcal{M}(f(\mathbf{x})) + rand\Big(\frac{2T_{max}}{NSA}\Big)\,. \quad (21)$$

2) Relay selection area: The CoopGeo relay selection process do not use control messages as in the forwarding selection process so as to guarantee that only one node has been selected as relay, and thus avoiding message duplications or collisions. Besides overhearing the relayed message that triggers the contention timers suppression of the other candidate nodes, we have considered the relaying area size as a way to control these issues. Since the candidates should reside in a predefined area where relay selection is executed, the relaying area is determined by the source and forwarder nodes positions. In Fig. 4(a) and 4(b), two relaying areas are depicted. First, let the set $\mathcal{C}$ represent the potential relay nodes situated in the relaying area formed by the intersection of the source and forwarder node coverage areas. Second, let the set $\mathcal{D}$ represent a relaying area shaped by a Reuleaux triangle from the source node point of view. In the first case, for any relay candidate $\mathbf{x}_i \in \mathcal{C}$, its selection metric is mapped onto this set, where $\mathcal{M}(f(\mathbf{x}_i)) \in [0, 1]$. For the Reuleaux triangle, any relay $\mathbf{x}_i$ and any other possible relay $\mathbf{x}_j$ have the following relationship: $\left\|\mathbf{x}_i - \mathbf{x}_j\right\|^2 \le r, \forall \mathbf{x}_i, \mathbf{x}_j \in \mathcal{D}, i \neq j$, where r is the transmission range of a node. Hence, from the relaying areas depicted in the figure, the Reuleaux triangular area is the best suited to be used since all relay candidates can hear to each other, and accordingly, the hidden relay problem can be effectively avoided which is not the case of the intersection relaying area.

[5] $\mathbf{x}_{max}$ is an arbitrary point over the relay area used for normalization purpose, in (20) $f(\mathbf{x}_{\max})$ is theoritically the maximal distance that could be exist between $\mathbf{x}^*$ and any other point inside the relay set, for example in Fig. 4(a) the perfext value for $\mathbf{x}_{max}$ is the intersection between the transmission radius of S and F.



(a) (b)

Fig. 4. (a) Mapping of the metric onto the set $\mathcal{C}$ (b) Mapping of the metric onto the set $\mathcal{D}$ for a normalized distance between the current source $(0, 0)$ and its next hop $(1, 0)$

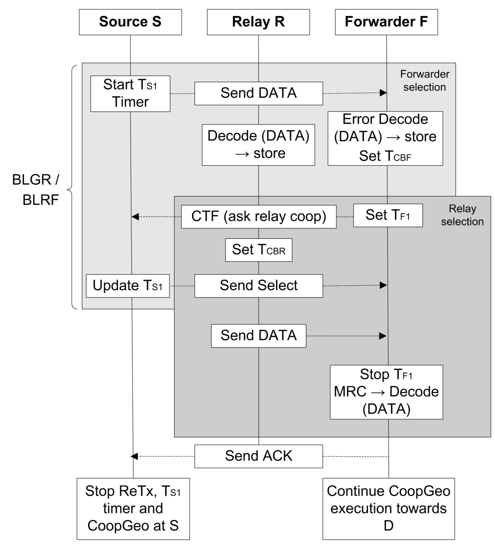


Fig. 5. CoopGeo in action

D. CoopGeo in Action

In this subsection, we depict the behavior of nodes running CoopGeo (cf. Fig. 5) when a data transmission between a source and a destination is performed.

When the source S intends to transmit its data to the destination D, it checks if the channel is free for a predefined time interval. In this case, S broadcasts its data packet DATA and starts a T_{S1} timer. The neighbors of the source then receive the packet, store it, and set up their T_{CBF} timers, as defined in (10), to participate in the forwarder selection process.[6]

The neighbor $F \in F_i$ whose timer expires first sends a CTF control message to claim the forwarding status, then, it initializes a T_{F1} timer. The other candidates hearing this control message quit the forwarding selection process.

The DATA/CTF handshake carried out by S and F is used to initiate the relay cooperation on demand if it

[6] In geographic protocols, the source generally has to indicate the location information of both itself and the destination in the packet header. The header added in the beginning of a packet is usually transmitted through low rate codes so that one could neglect its transmission error within the transmission range.

is needed, since within the CTF message, F indicates if relay cooperation is needed in case of error decoding. In this way, the neighbors situated in the relaying area formed by S and F and being able to correctly decode the DATA[7] start their T_{CBR} timers, as defined in (21), to participate in the relay selection process.

When S receives the CTF message, it replies with a SELECT message which confirms the forwarding status to F, and updates its T_{S1} timer to the maximum delay time allowed to receive an ACK from F. Meanwhile, the relay candidates decrement their T_{CBR} timers. Thus, when the candidate $R \in R_i$ expires its T_{CBR} timer the first, it becomes the relay node and immediately relay the stored data. The other candidates hearing the transmission notice that another node has relayed the data and quit the relay selection.

Consequently, the forwarder node combines the received signals from S and R, decodes the data, and stops its T_{F1} timer. Then, it sends an acknowledgment to S and continues the CoopGeo execution toward D.

In addition to T_{CBF} and T_{CBR} timers, two other timers were used: T_{S1} at the source and T_{F1} at forwarder node. At the beginning T_{S1} represents the maximum allowed time to find a forwarder node in the direction of D, given by

$$T_{S1} = T_{DATA} + T_{CTF} + T_{max}\,, \tag{22}$$

where T_{DATA} and T_{CTF} represent the data and CTF packet transmission times respectively, and, T_{max} represents the maximum time interval allowed to the forwarding selection process. For simplicity, in the equation, we do not express the propagation delay.

Since the DATA/CTF handshake represents that a forwarder node F was selected, T_{S1} is updated to a value that represents the maximum delay time allowed to receive an acknowledgement from F and it depends on whether relay cooperation is executed. The updated timer is given by

$$T_{S1} = \begin{cases} T_{SEL} + T_{ACK} & \text{if no cooperation is needed} \\ T_{SEL} + T_{max} + T_{DATA} + T_{ACK} & \text{otherwise}\,, \end{cases} \tag{23}$$

where the first statement includes the transmission time of the SELECT (from S to F) and ACK (from F to S) messages; the second statement includes the required time of the first statement as well as T_{max} and T_{DATA} which correspond to the maximum allowed time for the relay selection and the time needed to relay the packet.

For T_{F1}, the affected value depends on whether the forwarder F correctly decodes the received data from S, or relay cooperation is executed. For the former, F listens to the channel and waits for a SELECT message from S, which completes the direct communication mode; for the latter, F waits for the SELECT message and DATA relayed, from the source and the relay node, respectively.

$$T_{F1} = \begin{cases} T_{CTF} + T_{SEL} & \text{if no cooperation is needed} \\ T_{CTF} + T_{SEL} + T_{max} + T_{DATA} & \text{otherwise}\,, \end{cases} \tag{24}$$

where the first statement allocates to T_{F1} the time required to transmit the CTF message and the time required to receive a SELECT message from S respectively; the second statement adds to the first statement the maximum allowed time to select a relay node and the time the relay node needs to send the relayed data, respectively. Similar to T_{S1} timer, T_{F1} does not consider the propagation delay.

If the timer T_{S1} of S expires before receiving a CTF or an ACK from F, we have different possibilities: 1) S could not find a forwarder; 2) F could not receive the SELECT message from S 3) F could fail; 4) F could not receive the data packet from R in the cooperative mode. For all these situations, the CoopGeo protocol is restarted.

Thus, we can see that the two most significant timers are T_{CBF} and T_{CBR}, which are used to select a forwarder F and an optimal relay R in each hop through contention mechanisms. The timers T_{S1} and T_{F1} just help to detect a problem during the CoopGeo execution.

IV. Performance Evaluation

We first consider a single-hop cooperative relay network with $N = 5$ available relays, deployed in $\mathbf{R}^2$. Denote (x, y) as the coordinates of nodes. We locate the source and the destination at (0, 0) and (1, 0) respectively, and randomly place, with uniform distribution, the relays in a square field following $\{(x, y) \,|\, 0 \le x \le 1, |y| \le 0.5\}$. We assume that the channel variances between any two nodes follow $\sigma_{i,j}^2 \propto d_{i,j}^{-p}$, where the path loss exponent is taken to be $p = 2$ in our simulations. The channel variance is normalized to unity for unit distance. QPSK modulation is used in this simulation and the fading channels are assumed sufficiently fast-varying such that the channel coefficients keep constant only within every symbol interval. The number of network topologies is 200.

For each realization of nodes distribution, we can determine the distances from each relay to the source as well as destination, and then the corresponding selection metric for each relay can be determined by using (16). According to the selection criterion introduced in Sec.

[7] Neighbors can determine the correctness of the DATA based on the measurements of received SNRs, as described in Sec. II-A.

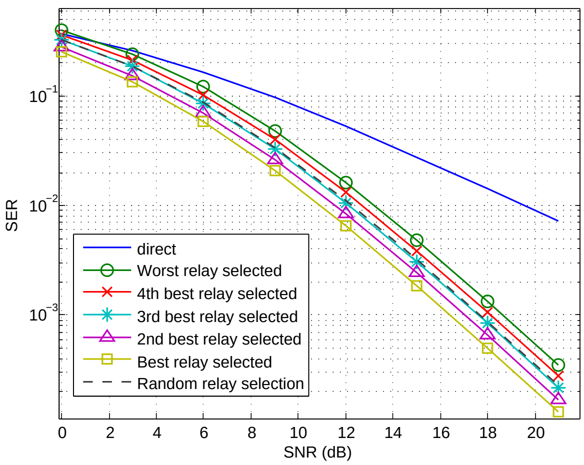


Fig. 6. Performance comparison for relay selection when using from the best to worst relays.

III-C, the best relay is the one with the minimum selection metric, while the second best relay has the second minimum selection metric and so on.

Fig. 6 depicts the SER versus SNR performance of the above scenario, where SNR is defined as P/N_0 and P is the total transmit power fixed. In Fig. 6, the performance of direct transmission from the source to the destination is provided as a benchmark for a non-cooperation scheme. Fig. 6 shows that the selected best relay contributes to the minimum SER at the destination as compared to other relays. In addition, it also reveals that worse relays corresponds to larger selection metrics, that is, the smaller the selection metrics, the better the resulting SER performances. Thus, we have demonstrated that by using the geographical information, nodes in cooperative networks can efficiently perform relay selection to improve the SER performance at the destination. In addition, we also compare the performance with a possible relay selection approach, named random relay selection, which means that the source randomly selects a cooperating relay without any information for each transmission. We see, in Fig. 6, that the performance curve of the random selection scheme lies in between the best and worst selections. This is because each relay has the same opportunities to be selected so that the performance will be averaged over all the distributed relays.

The next step in our simulation methodology is to evaluate the PHY/MAC layer performance of CoopGeo with Monte-Carlo simulations. We simulated the three lower layer processes, and our simulation settings are given in Table I. Our results are based on 20,000 random generated topologies, where all the nodes are competing to access the channel. We start by solving the two problems stated in Section II-B. Once the forwarder and relay node sets are obtained, we use them to evaluate the packet error rate, average transmission probability, saturated throughput, and some other results with varying the input parameters.

TABLE I
SIMULATION SETTINGS

Input	Value	Input	Value
No. of Neighbors	1-20	Tx. Power	25 dBm
Channel Model	Rayleigh	Average Noise	20 dB
Pass Loss Exp.	2	Noise Figure	15 dB
Carrier Freq.	2.412Ghz	Packet Size	1538 Bytes
Channel BW	22Mhz	Contention Period	500 μs
Modulation Type	QAM	# of Topologies	20000
Constellation Size	4-128	# of Trials	2000000

A. *Packet Error Rate and Transmission Error Prob.*

In Fig. 7(a), we show the average packet error rate of two different protocols, one is the proposed CoopGeo using a cooperative relaying technique and the other is BOSS [33]. The packet error rate presented in Fig. 7(a) includes both the probability of collision inside different contention periods and the probability of error over the wireless channel. Fig. 7(a) shows that our protocol experiences a lower packet error rate of 2.5 times less than the traditional geographic based routing protocol in the best circumstances. Also, we can see that the packet error rate of the two protocols gets closer to each other as a function of the increased number of nodes in the neighborhood. This error rate depends on the number of nodes and is induced by the collisions inside the different contention periods. Moreover, in Fig. 7(b), we show that CoopGeo improves significantly the average error transmission probability with increasing the number of nodes in the neighborhood. This is due to the accurate selection of the relay node when more nodes are present in the neighborhood. We note that the CoopGeo experiment provides a very low transmission error rate, which allows increasing the constellation size of the modulation scheme to improve the bandwidth efficiency without loosing end-to-end throughput.

B. *Results with Varying Input Parameters*

1) Varying the contention window T_{max}: In this simulation, we investigate the impact of the contention window size T_{max} (that controls the delay affected to a contending node when it tries to forward/relay a packet) on the CoopGeo performance. Initially, we simulate our protocol with T_{max} values from $100\mu s$ to

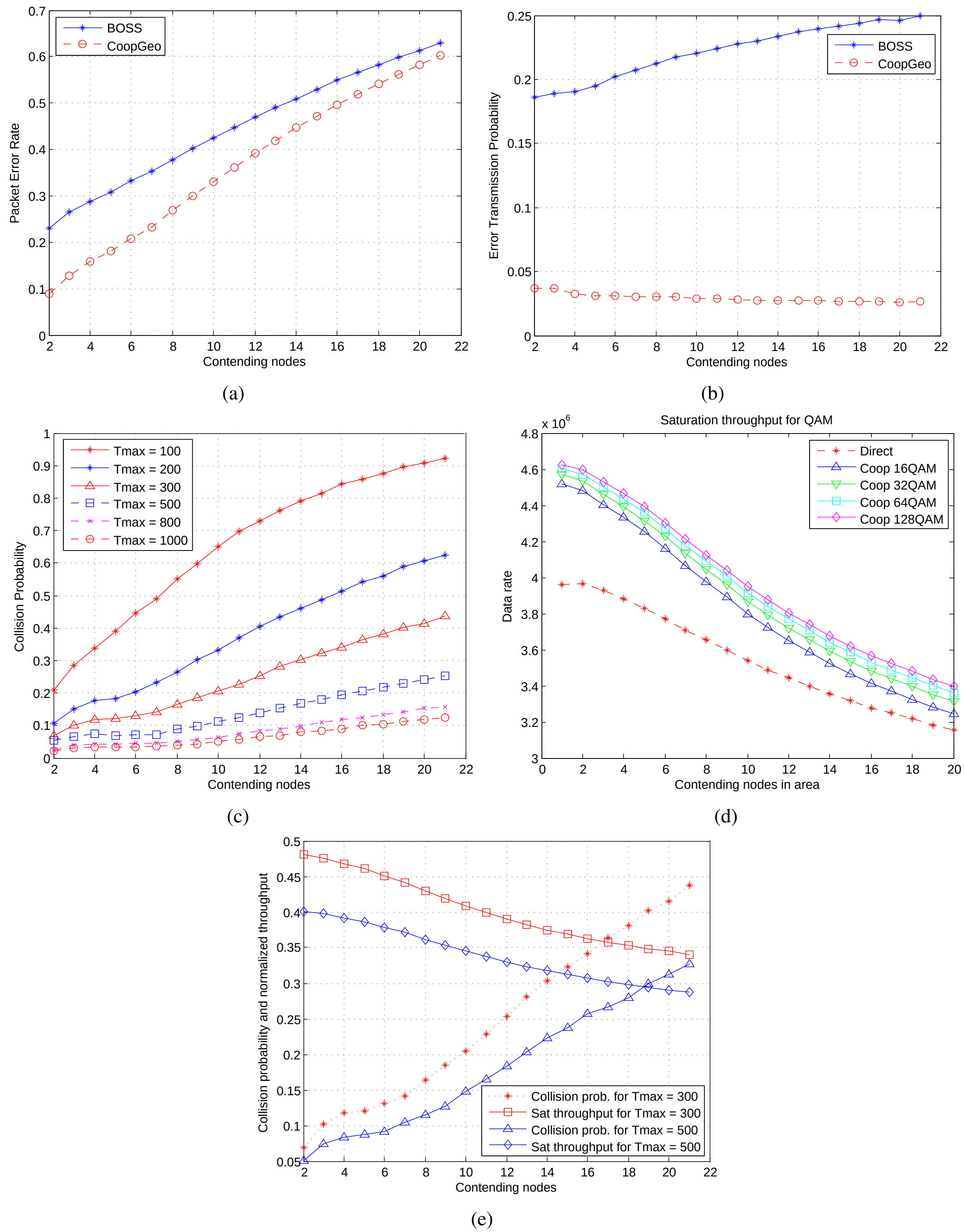


Fig. 7. (a) Packet error rate for T_{max} = 500μs; (b) End-to-end transmission error probability for T_{max} = 500μs; (c) CTF-Relayed message collision probability with changing T_{max} from 100μs to 1000μs; (d) CoopGeo saturated throughput for QAM fom 16-128; (e) Normalized saturated throughput and collision probability for T_{max} = 300μs and T_{max} = 500μs

1000μs. In Fig. 7(c), we see that the collisions caused by the contending nodes when they send their CTF and relayed messages decrease while increasing the T_{max} size. The sizes from 500μs to 1000μs are the best suited for CoopGeo, as they achieve much lower collision probability as compared with the other cases. We analyze the relationship between the normalized throughput with cooperative communications vs. the CTF-relayed messages collision probability, we observe that we may use a smaller T_{max} size without affecting the performance of the protocol when fewer contending nodes are used for the case T_{max} = 300μs, as shown in Fig. 7(e).

Taking $T_{max} = 500\mu s$ from the previous result as a reference show us that for a smaller saturated throughput rate with respect to $T_{max} = 300\mu s$ value, we may handle scenarios with higher densities.

2) Varying the constellation size: Finally, in Fig. 7(d), we provide the saturated throughput of the (MAC-PHY cross-layer) CoopGeo and compare it with a traditional geographic MAC-routing approach BOSS. Fig. 7(d) shows that the CoopGeo outperforms the traditional scheme in terms of saturated throughput, with different constellation sizes used. Due to very low transmission error rate in the cooperation-based CoopGeo scheme, we are able to increase the constellation size according to different transmission environments without deteriorating the end-to-end throughput.

V. Conclusions

In this paper, we have proposed a cross-layer protocol CoopGeo based on geographic information to effectively integrate the NWK, MAC, and PHY layers for cooperative wireless ad hoc networks. The CoopGeo provides a MAC-NWK cross-layer protocol for forwarder selection as well as a MAC-PHY cross-layer protocol for relay selection. Both the selection schemes are based on geographical information of the nodes without periodic exchange of beacons and complete neighborhood information. Simulation results demonstrate that the proposed CoopGeo can work with different densities and achieve better system performances than the existing protocol like BOSS, in terms of packet error rate, transmission error probability, and saturated throughput. Due to the beaconless local operation property, the CoopGeo is very efficient and scalable to any change in the network topology.

References

[1] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Info. Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.

[2] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

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

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

[5] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity part I and part II," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1948, Nov. 2003.

[6] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Trans. Info. Theory*, vol. 51, no. 9, pp. 3037–3063, Sept. 2005.

[7] A. K. Sadek, W. Su, and K. J. R. Liu, "Multinode cooperative communications in wireless networks," *IEEE Trans. Signal Processing*, vol. 55, no. 1, pp. 341–355, Jan. 2007.

[8] H. Shan, W. Zhuang, and Z. Wang, "Distributed cooperative mac for multihop wireless networks," *IEEE Commun. Mag.*, vol. 47, no. 2, pp. 126–133, Feb. 2009.

[9] A. S. Ibrahim, A. K. Sadek, W. Su, and K. J. R. Liu, "Cooperative communications with relay selection: when to cooperate and whom to cooperate with?" *IEEE Trans. Wirel. Commun.*, vol. 7, no. 7, pp. 2814–2827, July 2008.

[10] 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.

[11] M. Dianati, X. Ling, K. Naik, and X. Shen, "A node-cooperative ARQ scheme for wireless ad hoc networks," *IEEE Trans. Vehic. Tech.*, vol. 55, no. 3, pp. 1032–1044, May 2006.

[12] T. C.-Y. Ng and W. Yu, "Joint optimization of relay strategies and resource allocations in cooperative cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 328–339, Feb. 2007.

[13] Z. Yi and I.-M. Kim, "Diversity order analysis of the decode-and-forward cooperative networks with relay selection," *IEEE Trans. Wirel. Commun.*, vol. 7, no. 5, pp. 1792–1799, May 2008.

[14] C.-L. Wang and S.-J. Syue, "A geographic-based approach to relay selection for wireless ad hoc relay networks," in *Proc. 2009 IEEE Vehic. Tech. Conf. (VTC 2009-Spring)*, Barcelona, Spain, April 2009, pp. 1–5.

[15] P. Liu, Z. Tao, Z. Lin, E. Erkip, and S. Panwar, "Cooperative wireless communications: A cross-layer approach," *IEEE Trans. Wirel. Commun.*, vol. 13, no. 4, pp. 84–92, Aug. 2006.

[16] E. Beres and R. Adve, "Selection cooperation in multi-source cooperative networks," *IEEE Trans. Wirel. Commun.*, vol. 7, no. 1, pp. 118–127, Jan. 2008.

[17] A. Bletsas, A. Lippman, and D. P. Reed, "A simple distributed method for relay selection in cooperative diversity wireless networks, based on reciprocity and channel measurements," in *Proc. 2005 IEEE Vehic. Tech. Conf. (VTC 2005-Spring)*, May 2005, pp. 1484–1488.

[18] A. Gletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[19] T. Guo, R. Carrasco, and W. L. Woo, "Performance of a cooperative relay-based auto-rate mac protocol for wireless ad hoc networks," in *Proc. 2008 IEEE Vehic. Tech. Conf. (VTC 2008-Spring)*, May 2008, pp. 11–15.

[20] P. Liu, Z. Tao, and S. Panwar, "A cooperative mac protocol for wireless local area networks," in *Proc. 2005 IEEE Int. Conf. Commun. (ICC 2005)*, Seoul, Korea, May 2005, pp. 2962–2968.

[21] H. Zhu and G. Cao, "rDCF: A relay-enabled medium access control protocol for wireless ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 5, no. 9, pp. 1201–1214, Sept. 2006.

[22] H.-S. Shan, W. Wang, W. Zhuang, and Z. Wang, "Cross-layer cooperative triple busy tone multiple access for wireless networks," in *Proc. 2008 IEEE Global Commun. Conf. (GLOBECOM 2008)*, New Orleans, LA, USA, Dec. 2008, pp. 1–5.

[23] M. S. Gokturk and O. Gurbuz, "Cooperative mac protocol with distributed relay actuation," in *Proc. 2009 IEEE Wireless Commun. and Networking Conf. (WCNC 2009)*, Budapest, Hungary, Apr. 2009, pp. 1–6.

[24] C.-H. Yu, O. Tirkkonen, and J. Hamalainen, "Opportunistic relay selection with cooperative macro diversity," *EURASIP J. Wirel. Commun. Networking*, vol. 2010, pp. 1–14, 2010.

[25] Y. Wei, F. R. Yu, and M. Song, "Distributed optimal relay selection in wireless cooperative networks with finite-state

markov channels," *IEEE Trans. Vehic. Tech.*, vol. 59, no. 5, pp. 2149–2158, June 2010.

[26] P. Larsson, "Selection diversity forwarding in a multihop packet radio network with fading channel and capture," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 5, no. 4, pp. 47–54, 2001.

[27] M. R. Souryal, B. R. Vojcic, and R. L. Pickholtz, "Information efficiency of multihop packet radio networks with channel-adaptive routing," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 40–50, Jan. 2005.

[28] J. A. Sanchez, P. M. Ruiz, and R. Marin-Perez, "Beacon-less geographic routing made practical: challenges, design guidelines, and protocols," *IEEE Commun. Magazine*, vol. 47, no. 8, pp. 85–91, Aug. 2009.

[29] M. Heissenbüttel, T. Braun, T. Bernoulli, and M. Wälchli, "BLR: Beacon-less routing algorithm for mobile ad-hoc networks," *Computer Commun.*, vol. 27, no. 11, pp. 1076–1086.

[30] H. Fubler, J. Widmer, M. Kasemann, M. Mauve, and H. Hartenstein, "Contention-based forwarding for mobile ad hoc networks," *Ad Hoc Networks*, pp. 351–369.

[31] M. Zorzi and R. R. Rao, "Geographic random forwarding (GeRaF) for ad hoc and sensor networks: multihop performance," *IEEE Trans. Mobile Comput.*, vol. 2, no. 4, pp. 337–348, Oct.-Dec. 2003.

[32] B. Blum, T. He, S. Son, and J. Stankovic, "IGF: A state-free robust communication protocol for wireless sensor networks," in *Tech. Rep. CS-2003-11*, Univ. of Virginia, Charlottesville, VA, 2003.

[33] J. A. Sanchez, R. Marin-Perez, and P. M. Ruiz, "BOSS: Beacon-less on demand strategy for geographic routing in wireless sensor networks," in *Proc. 4th IEEE Int. Conf. on Mobile Ad-hoc and Sensor Systems (MASS 2007)*, Pisa, Italy, Oct. 2007, pp. 1–10.

[34] T. Aguilar, M. C. Ghedira, S.-J. Syue, V. Gauthier, H. Afifi, and C.-L. Wang, "A cross-layer design based on geographic information for cooperative wireless networks," in *Proc. 2010 IEEE Vehic. Tech. Conf. (VTC 2010-Spring)*, Taipei, Taiwan, May 2010.

[35] P. Herhold, E. Zimmermann, and G. Fettweis, "A simple cooperative extension to wireless relaying," in *Proc. Int. Zurich Seminar Commun.*, Feb. 2004, pp. 36–39.

[36] W. Su, A. K. Sadek, and K. J. Ray Liu, "Cooperative communication protocols in wireless networks: Performance analysis and optimum power allocation," *Wirel. Pers. Commun.*, vol. 44, no. 2, pp. 181–217, 2008.

[37] H. Kalosha, A. Nayak, S. Ruhrup, and I. Stojmenovic, "Select-and-protest-based beaconless georouting with guaranteed delivery in wireless sensor networks," in *Proc. INFOCOM 2008*, Phoenix, AZ, USA, Apr. 2008, pp. 346–350.