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Cooperative MAC and Routing Protocols for Wireless Ad Hoc Networks

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***Abstract*— Cooperative diversity techniques exploit the spatial characteristics of the network to create transmit-diversity, in which the same information can be forwarded through multiple paths towards a single destination or a set of destination nodes. In this paper, we study the integration of cooperative diversity into wireless routing protocols by developing distributed cooperative MAC (C-MAC) and routing protocols. The proposed protocols employ efficient relay selection-coordination and power allocation techniques to maximize the cooperation benefits in the network. Simulation results show that the energy-saving performance of the minimum-energy routing protocols can be significantly improved when they are implemented together with the proposed C-MAC protocol ($\%50$). We also show that the performance of the C-MAC protocol can be further enhanced when the initial path is selected using the cooperation characteristics of the network ($\%11$ more energy-savings compared to the previous case, i.e., C-MAC with minimum-energy routing).**

I. Introduction

Recently, widely emerging wireless ad hoc and sensor networking technologies have created a significant demand in energy-efficient communications [1]. This is because the nodes that are deployed in such networks typically operate on limited energy resources. Furthermore, typical applications for such networks do not permit the installation of base stations to organize and manage the communications inside the network. For this reason, these networks need to have self-organizing and self-managing characteristics, which further increases the communication-based energy burden on the membering nodes.

In order to minimize the energy consumption inside the network, many works have been proposed in the literature to design energy-efficient communication schemes. For instance, we can employ power-aware routing protocols to select minimum-energy paths (e.g., [2]) or energy-efficient MAC protocols to coordinate the transmission of nodes in a two-hop neighborhood with the goal of minimizing the total transmission energy (e.g., [3]).

Another difficulty that typically arises in wireless networks is related to the wireless channel characteristics. Wireless channels are known to be susceptible to occasional transmission errors and failures caused by fading related problems, i.e., multi-path fading [4]. In order to overcome these fading problems, diversity techniques have been proposed which can significantly improve the communication reliability and, as a result, improve the channel capacity and/or energy savings. Diversity techniques mainly operate by transmitting the signals over uncorrelated channels. These techniques can be classified as time-diversity, frequency-diversity, or space-diversity techniques.

In this paper, we are mainly interested in space diversity, which is typically achieved by using multiple antennas at both the transmitter and receiver sides (multi-input multi-output (MIMO) systems [5]). However, because of the antenna separation requirements of such systems and the nodes being designed to be as small as possible (i.e., sensor nodes), it is difficult to implement MIMO systems in wireless networks. In order to overcome this practicality problem of MIMO systems while also taking advantage of its basics, a distributed version of space-diversity has been proposed, which is referred to as cooperative-diversity [6, 7]. Cooperative diversity has been shown to provide the benefits of spatial diversity by increasing the achievable rate and improving the reliability of transmissions. In cooperative diversity, each node in the network acts as a part of a virtual antenna transmission system. Specifically, after successfully decoding the transmitted information, a group of nodes can cooperatively transmit to the destination node (or a group of destination nodes) using the original information, as in a multiple-antenna system. However, to take full advantage of cooperative diversity, there should be at least one node besides the main transmitting node that can reliably decode the transmitted signals and consequently cooperate with the main transmitter. Wireless networks inherently carry that feature through its broadcasting nature.

In wireless broadcasting, any node in the neighborhood of a transmitter can reliably decode the overheard packets as long as the signal-to-noise-ratio of the received signals is higher than the decoding threshold. In the case that a node is out-of-range of the maximum transmission range of the transmitter (resulting in a decoding-failure), the transmitted signals can still be detected, hence, received by those nodes (as long as the power of such signals is higher than the noise-floor value). Because of the multihop nature of such networks, without requiring any considerable extra overhead, cooperative diversity schemes can be employed to take advantage of the reliably and/or unreliably received signals.

Previous works on energy-efficient communication protocol design do not typically take advantage of the broadcast nature of wireless networks to reduce energy consumption. In this paper, we propose practical MAC and routing protocols to realize energy-efficient cooperative transmissions in wireless ad hoc networks. Through simulations, we show that by taking advantage of the broadcast nature of the wireless channel to coordinate the cooperative-based transmissions, the energy efficiency in the network can be significantly improved.

The rest of the paper is organized as follows. In Section II, we present the details of the proposed MAC and routing algorithms. The simulation results for the proposed protocols are given in Section III. We conclude the paper in Section IV.

II. Protocol Design

In this section, we propose two cooperative diversity-driven routing protocols for multihop wireless networks, which we ex-

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plain shortly. For the proposed schemes, we assume an end-to-end path to be selected based on the initial network-imposed constraints and define each node on this default path as one of the main transmitter/receiver nodes for the given flow. Cooperation is assumed to take place only among the main transmitter node and its neighboring nodes that can cooperate. These neighbor nodes form the *relay set* for the main transmitter node, and they all together form the *cooperative transmission set* or the *cooperative hop*.

We propose the following routing schemes: (i) two-step path acquisition and (ii) cooperative routing. The former protocol assumes the availability of a default *non-cooperative* [1] end-to-end path and integrates cooperative diversity onto that route by coordinating the cooperative transmissions. On the other hand, in cooperative-routing, we first establish a *cooperative* end-to-end path, then apply cooperation based coordination onto that route. In this paper, we also propose a cooperative medium access control (C-MAC) scheme, that will be integrated into the proposed routing protocols, to increase the cooperation gain. In C-MAC, both the set of relay nodes and the corresponding cooperation parameters are determined at the beginning of the data transmission period at each hop.

The necessity of C-MAC can be explained as follows for both cases. For the two-step path acquisition protocol, since the initial path selection does not take into account future cooperation-based advantages, in order to make use of such gains, we require the basic routing protocol to be complemented with the proposed cooperative MAC scheme. In the case of cooperative routing, our goal is to further increase the cooperation-based performance gains. For this reason, the route setup phase takes into account the cooperative advantage (i.e., performance improvements caused by cooperatively transmitting) at the neighborhood of each hop. Employing a cooperative MAC protocol to coordinate the transmissions over the resulting cooperative route allows us to obtain such gains.

For both schemes, we use the following assumptions:

1) We assume the channel to be slowly-varying.

2) We assume full synchronization among the transmissions of the cooperating nodes to achieve coherent reception at the receivers and the availability of multiple chip sequences to enable simultaneous CDMA-based transmissions. We first assume that each cooperating node can achieve synchronization in time at the receiver with the help of the employed TDMA-based access scheme and the exchanged control messages among the cooperating nodes. After synchronizing the transmissions in time, we can use training sequences to achieve phase synchronization, since each cooperating node employs a different pseudo-noise (PN) code sequence.

3) We assume that the base transmissions (i.e., transmissions from the original transmitters) utilize the same pre-determined chip sequence (which is the same for all nodes in the network), whereas relay transmissions use the additionally available chip sequences.

4) We assume the total number of available chip sequences to be a system dependent parameter, which we refer to as v. Therefore, the system can allow the utilization of at most $(v-1)$ relay nodes for each base transmission.

5) We assume the control and data packets to be transmitted over separate channels with different transmit power levels (i.e., control packets are transmitted at maximum power, whereas data packets are transmitted at variable power levels). This assumption is necessary to efficiently coordinate the spatially correlated transmissions and further improve the spatial reuse and network utilization. By doing so, we can provide the nodes with maximum coverage, while minimizing the interference caused by or indicted upon the data transmissions of out-of-range nodes [2].

6) We assume that the sender node can determine the angle of arrival for the signals transmitted by the relay nodes allowing us to achieve sufficient level of accuracy in the selection of relay node power levels.

Under the synchronization assumption, if the received signals for a given chip sequence have sufficient power, each receiver can recover the signals of each relay node's transmissions and be able to combine them additively [8]. Let us assume that the transmitted signal by node i is given by $s(t)\rho_i c_i$, where $s(t)$ is the source signal at unit power, ρ_i is the signal magnitude amplification factor, and c_i is the assigned chip sequence. After synchronizing the received signals, at the output of the CDMA correlator of the jth receiver, the received signal $r_j(t)$ can be given as:

$$r_j(t) = \sum_{\forall i \epsilon \mathcal{C}} r_{ij}(t) + n_j(t) \quad (1)$$

where $\mathcal{C}$ is the set of cooperating nodes, $n_j(t)$ is the noise process, which is assumed to be AWGN with unit power (i.e., $P_n = 1$), and $r_{ij}(t)$ is given as

$$r_{ij}(t) = s(t)\rho_i \upsilon_{ij} \quad (2)$$

where υ_{ij} represents the magnitude of the channel attenuation between the ith and jth nodes. Considering only the impact of path-loss on the calculation of the channel attenuation, the power of channel attenuation, υ_{ij}^2, can be assumed to be equal to $d_{ij}^{-\alpha}$ with α representing the path-loss exponent, which typically takes values between $2-5$ depending on the assumed propagation model. Because of the synchronization of the transmitted signals at the receiver, the signal-to-noise ratio (SNR) at the receiver node j can be assumed as

$$SNR_j = \frac{[\sum_{\forall i \epsilon \mathcal{C}} \rho_i \upsilon_{ij}]^2}{P_n}. \quad (3)$$

From (3) we observe that, with the help of the synchronously combined cooperative transmissions at an arbitrary receiver, we can reduce the total energy required to forward a single packet at each hop at a rate that depends on the number and the topology of the cooperating nodes. However, the SNR value of the received signals has to be greater than a pre-determined threshold, SNR_{thr}, to reliably decode the transmitted packets at the given receiver, thereby putting a lower bound on the transmit powers. Nevertheless, the energy consumption at each hop can be minimized by appropriately choosing the transmit power level of each cooperating node.

Selecting the optimum power distribution [3] requires, at the least, the knowledge of the relative locations of the cooperating nodes at the decision making nodes (the main transmitter and/or receiver). We can explain how we can obtain this information with a simple

[1] "Non-cooperative" refers to the case of not taking advantage of cooperative diversity during the route setup process.

[2] Note that the average size of data transmission is assumed to be much larger than the average control message overhead reducing the possibility of collisions between two different control message transmission period.

[3] Here, optimum power distribution is specified in the sense of minimum total transmit power consumption that achieves the SNR_{thr} at the receiver.

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example. Let us consider the network topology depicted in Figure 1. In that figure, we want each node to obtain the location information up to its two hop neighbors without the need of a GPS device. Let us assume that nodes (n_2,n_3,n_5) are in-range of node n_1, nodes (n_2,n_3,n_4) are all in-range of each other, node n_4 (n_5) is out-of-range of node(s) n_1 (n_2, n_3, n_4).

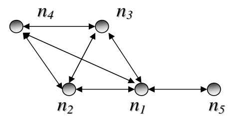

Fig. 1. Location estimation example.

Typically, using the channel gain information, each node can determine the distance between itself and its one-hop neighbors. By allowing this information to be exchanged among the neighboring nodes, we want each node to approximate the relative location of its neighbors. For instance, let us consider the information exchange among the nodes (n_1, n_2, n_3). Node n_1 knows the distance of itself to each of its neighbors, hence, d_{n_1,n_2} and d_{n_1,n_3} are known at n_1. Using the approximate distance information broadcasted by either n_2 or n_3, n_1 can learn d_{n_2,n_3}. Using geometrical concepts, the above information allows n_1 to recover the angular distance between each node couple [4].

Let us now consider the following node set, (n_1, n_2, n_4). Since n_4 is out-of-range of n_1, we cannot apply the above methodology to obtain neither the distance nor the angular position information at node n_1. In this case, we need at least one more node to obtain the above information, and this node should be the common neighbor of all the above nodes (i.e., n_3). Note that we can also employ two nodes, one of which is a common neighbor of n_1 and n_2 (say n_{c1}), and the other is a common neighbor of n_2, n_4, and n_{c1}. Therefore, using the above procedures, relative locations among neighboring nodes can be obtained, which can be used in finding the optimum transmit power levels.

In the proposed protocols, the main system constraint is assumed to be the total transmission energy. Therefore, we will give the main attention to minimize the energy consumption. Note that, in cooperative diversity based communications, energy improvement may come at a price of reduced network utilization, because of employing multiple nodes at each hop. However, due to space limitations, we will limit the current discussion to energy-efficiency and evaluate the utilization-energy tradeoffs in our future work.

A. Two-step Path Acquisition

Assume that the default route is formed based on the energy constraints [5]. We want to coordinate the transmissions of the cooperating nodes so that we can successfully combine multiple copies of the same packet at the intended receivers (i.e., next hop on the default path) and reduce energy consumption with limited interference. The coordination is achieved by using the proposed cooperative MAC (C-MAC) protocol, which is based on CSMA/CA protocol.

In CSMA/CA, before data transmission, request-to-send (RTS) and clear-to-send (CTS) packets are transmitted by the transmitter/receiver pair to reserve the transmission floor for the upcoming data transmission. In C-MAC protocol, RTS/CTS exchange initially reserves the floor and provides collision free handshaking for the upcoming control packet transmissions that are used to enable the integration of cooperative diversity into the routing protocol. Note that, in C-MAC, control packets are transmitted at maximum power, P_{max}. The operation of the C-MAC protocol, which is illustrated in Figure 2, is explained next.

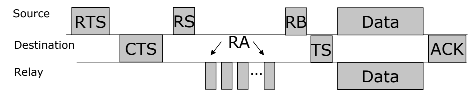

Fig. 2. Packet transmission order in cooperative MAC.

In the following analysis, we assume that nodes (s,d) represent the main transmitter and receiver nodes (i.e., current and next hops based on the initial non-cooperative path).

Step 1: First, after sensing the control channel to be idle, if there is no reserve for the data channel, s initiates the handshaking procedure by transmitting the RTS packet. This packet is used to (i) reserve the transmission floor during the control phase and (ii) broadcast the information on the upcoming transmission to the neighboring nodes so that these nodes can determine whether they are eligible for relaying or not.

Step 2: After d successfully receives the RTS packet, it responds with a CTS packet if the data channel is not reserved by any other neighboring node at the estimated start time of data packet transmission. CTS packets include information regarding the unavailable chip sequences (due to in-range relay node transmissions), which can be indicated using a (v-1)-bit length chip sequence field in the CTS packet, in which each bit location corresponds to a known chip sequence. The bits corresponding to the locations of the unavailable chip sequences can be set to inform the sender regarding the allowable chip sequences. Any node i other than d that receives the RTS packet determines the signal strength of the received RTS packet ($P^{(i)}_{rcv,s}$). Since control packets are transmitted at P_{max}, using the values of P_{max} and $P^{(i)}_{rcv,s}$, i can determine the channel gain between itself and s, i.e., $G_{s,i} = P^{(i)}_{rcv,s}/P_{max}$ (assuming channel reciprocity, $G_{i,s} = G_{s,i}$). Note that, any node i that is in the maximum transmit-power range of both s and d also determines the channel gain between itself and node d,i.e., $G_{d,i}$.

Step 3: Next, s broadcasts the relaying-start (RS) packet to initiate the relay acknowledgement procedure which is used to probe the *potential relay* nodes. Notice that, each potential relay node needs to observe the control and data channels to determine the unavailable PN sequences in order to prevent a local destination node receiving uncorrelated signals spread with the same PN sequence. The order of relay transmissions is also indicated in the RS packet using node IDs. This information is obtained with the help of "*Hello*" packet broadcasts that are used to achieve network connectivity and update neighborhood information. Note that, s can limit the number of responses by using a separate field in the RS packet.

Step 4: After receiving the RS packet, based on the transmission order indicated in the RS packet by node s, each potential relay node transmits a relay-acknowledgement (RA) packet to node s after determining its order of acknowledgement. RA packets carry information on the unavailable chip sequences (due to in-range receivers) and maximum allowable transmit-power level in addition to the ID of the potential relay node. Information on the unavailable chip sequences is carried in the same way as in the case of CTS

[4]Without extra information, n_1 cannot determine the actual location, i.e., the rotation pattern in the angular information.

[5]Note that the performance measure applied in the default path selection process does not affect the operation of our protocol.

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packets. Using the chip sequence field in the RA packet, potential relay nodes can inform the sender on the possible chip sequences that can be assigned to them. RA packets reserve the available chip-sequences for that potential relay node for a specific time period (which depends on the duration of the relay acknowledgment period). Note that, during data transmission, by monitoring the data channel, each node can determine the approximate interference level for a given PN code sequence.

Step 5: After receiving the RA packets, s determines the relay node set, $\mathcal{R}_s$, and the transmit power levels that will be used by each relay node i, $P_{ct}^{(i)}$, $\forall i \epsilon \mathcal{R}_s$. The methodology for relay selection and power distribution will be explained shortly. Having determined the cooperation parameters, s broadcasts the relay-broadcasting (RB) packet with the information stated above.

Step 6: Upon receiving the RB packet, d broadcasts the transmission-start (TS) packet to its neighborhood. The main goal of this step is to inform the neighbors of the destination regarding the chip sequences that are reserved for d's transmission, for the duration of its data transmission period.

Step 7: After the transmission of the TS packet, data transmission commences, with each selected relay node cooperatively transmitting with the sender node to the next hop using the assigned chip sequences and transmit power levels.

Next, we explain the selection process for the transmit powers in detail. The optimum power allocation for the multiple-source-single-destination case when the transmit powers are not constrained is determined in [9] using Lagrangian multiplier techniques on the optimization problem of minimizing the total cooperative-transmit energy consumption under the constraint of $SNR_{rcv} \geq SNR_{thr}$. Then, the resulting transmit power values for each cooperating node can be given as follows:

$$\rho_i = \frac{\upsilon_{id}}{\sum_{\forall j \epsilon \mathcal{C}} \upsilon_{jd}^2} \sqrt{SNR_{thr} P_n}. \tag{4}$$

Using (4) the total power consumption for the given cooperative transmission scenario can be found to be [9]:

$$P_t = \frac{SNR_{thr} P_n}{\sum_{\forall j \epsilon \mathcal{C}} \upsilon_{jd}^2}. \tag{5}$$

Instead of directly including all the potential relay nodes in the cooperation set, s one-by-one calculates the additional cooperative gain (i.e., additional gain in energy savings) that can be achieved with each addition of possible relay node in the cooperation set. In this process, we use the information regarding the possible relay node locations relative to d.

After each addition of relay node to the relay node set $\mathcal{R}_s$, s updates the value for P_t. Relay selection process stops when the amount of increase in the energy-efficiency caused by the inclusion of the next node is lower than a threshold, α. The order of inclusion in $\mathcal{R}_s$ is proportional to the distance of the given potential relay node to d. We employ the constraint on the transmit powers regarding the relay nodes' transmissions suboptimally using the following approach. After determining the relay node set and the transmit power values, if any of the selected values conflicts with the corresponding allowable transmit power constraint, the transmit power of the given node is reduced to the constrained level. This is done for each such node. After deducting the impact of these nodes' transmissions at the receiver, initially selected transmit powers of the remaining nodes in the cooperation set are re-adjusted using the above equations. If the process finalizes with at least one relay node not satisfying the power constraint requirement, we increment the transmit powers of nodes that still satisfy the power constraint and can have the biggest impact on the received power level at the receiver with minimum transmit power increment.

We observe an energy-utilization tradeoff in forming the relay node set. The inclusion of an additional node in the cooperation set typically increases the area reserved for transmission, which may result in decreasing the network utilization. Furthermore, including more nodes in the cooperation set refers to a decrease in the effective spatial reuse since total number of different bits transmitted per node in the network reduces with an increase in the number of relays. However, due to transmitting relay transmissions over orthogonal channels and using the minimum possible amount of energy for each relay transmission, we limit the level of interference caused by cooperative transmissions. We can also change the order of including the relay nodes in the cooperation set based on the proximity to the sender node rather than proximity to the destination node. This way, compared to the previous case, each additional relay node introduces less amount of increase in the reserved transmission floor.

In (4) and (5), the relay selection process only depends on the destination node. Therefore, the resulting power levels are optimized only for a single node (i.e., main receiver at the next hop) and the transmitted signals are not guaranteed to be reliably combined at the other receiver nodes (i.e., neighbors of the main receiver). For this reason, in order to improve the reception quality at those nodes while relinquishing little from the total transmission energy, instead of selecting transmit powers solely based on the next hop, we can also select the transmit power levels by taking into account the neighbors of the next hop.

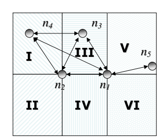

Fig. 3. Example of regional placement of nodes in a topology.

We observe in Figure 3 that the nodes, which can be made reliable without increasing the transmit power level excessively, are the common neighbors of the main sender and receiver nodes (i.e., nodes in regions III and IV). For this reason, the optimization procedure can include a subset[6] of these nodes in addition to the destination. Let us assume that m nodes are cooperating for transmission and n nodes are selected to form the destination node set, $\mathcal{D}$. For the given case, the optimization problem can be stated as follows:

$$\text{Minimize} \sum_{i=1}^{m} \rho_i^2 \ \text{subject to} \ \frac{(\sum_{i=1}^{m} \rho_i \upsilon_{ij})^2}{P_n} \geq SNR_{thr}, \forall j \epsilon \mathcal{D}. \tag{6}$$

In order to solve the above multiple constrained optimization problem, Lagrangian multiplier technique can be used again. However, because of the nature of the problem, the result is not as straightforward as in (4). The power allocation for this case can be found as follows:

[6]The farther the node away from the cooperating nodes, the less possible it is to include the node in the optimization procedure.

$$\rho_i = 1_{[1xn]} \mathbf{\Psi}_{[\mathbf{nxn}]} \mathbf{\Upsilon}^{[\mathbf{i}]}_{[\mathbf{nx1}]} \sqrt{SNR_{thr} P_n} \quad (7)$$

where $\mathbf{\Upsilon}^{[i]}$ represents the ith column of the channel amplitude gain matrix, $\mathbf{\Upsilon}_{[nxm]}$, in which $[\Upsilon]_{(ij)}$ represents υ_{ij}, and $\mathbf{\Psi}$ refers to the inverse of $\mathbf{\Upsilon}\mathbf{\Upsilon}^T$ (assuming the inverse of the given matrix can be found).

Using the above equations, we allow s to include the nodes in $\mathcal{D}$ that can increase the total energy consumption (compared to the minimum energy determined based on only the main destination node) with a ratio of less than β. In addition to the common neighbors, we can also include nodes that are only neighbors of the destination node or nodes that are neighbors with the relay nodes [7] in $\mathcal{D}$. Any node that reliably receives a given packet keeps this packet in its buffer for a limited time to allow for future cooperation, when it is possible.

B. Cooperative Routing

In this section, we present the proposed cooperative routing protocol that establishes a default cooperative diversity driven path, in which each hop consists of a single node. The path is selected in such a way that, in the case of optimum path selection and under ideal conditions [8], the chosen path is expected to provide maximum support for cooperation. Thus, by transmitting over the cooperative path, we can achieve maximum energy savings between the end nodes of a given flow. The optimum cooperative path is supported with the cooperative MAC proposed in the previous section.

The main problem in forming a cooperative path is to determine the expected gain of employing cooperation (i.e., cooperative advantage) using the neighborhood information and the received broadcast packets. As opposed to the case in C-MAC, in which the information processing occurs at the sender node which can determine the relative neighbor locations, here, the information processing occurs at the prospective destination node. Therefore, in order to estimate the value for cooperative advantage, in addition to the previous assumptions, we include one more assumption and assume that the directional knowledge on the two-hop neighbors from the view of the one-hop neighbors can be obtained using the information exchange during connectivity updates. The example of a direction-based regional partitioning approach is illustrated in Figure 4.

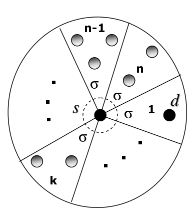

Fig. 4. Regional partitioning approach.

In the given figure, the transmission coverage area of node s is partitioned into n areas. We have previously showed that node s can determine the angular distance between its neighbors. Therefore, node s can be able to place its neighbors into each of these regions. During the neighborhood information exchange, node s can publish this regional information by ordering the node ID's in the broadcasted packet according to their relative region. Since the regional formation follows a pattern, each neighbor of s, receiving the broadcast packet, can not only learn its region but also determine the approximate regional location of node s's neighbors that are not common to the receiving node. The advantage of employing regional information will become clear next, when we explain the proposed routing scheme.

In the proposed protocol, route formation is achieved by broadcasting route request (RREQ) packets. We employ a cost parameter, which is carried within the RREQ packets and updated at each hop, to decide on the minimum cost path. Here, the cost parameter represents the expected value of the required cooperative-transmission energy under ideal conditions. The RREQ packets carry two types of information necessary for cost estimation. The first one is the estimated transmission cost up until the main transmitter node s. The second information indicates the nodes that can both receive the previous RREQ packet simultaneously with s and cooperate with s during the upcoming transmission period. Typically, the nodes that receive simultaneously with s are the common neighbors (at maximum power) of s and the transmitter according to s (node o). However, because of using a minimum-energy based transmission policy, only a subset of these nodes can actually receive during a cooperative data transmission. Therefore, the actual subset of possible cooperative nodes is formed by nodes that can be reached at ϕP_{min} power, where P_{min} is the minimum required energy for reliable communication between nodes o and s and ϕ is a weighting factor that depends on the topology between o and s. In a slowly varying topology, the neighborhood information does not change significantly for the duration of a connection. Therefore, by using an l bit field in the RREQ packet (in which the kth location refers to the neighbor with the kth highest node ID), the source node can set the bits at the locations corresponding to the subset of the neighbors that have received the broadcast packets. This way, each neighbor of s, that received the RREQ packet broadcasted by s, can determine the cooperative advantage.

The cooperative link costs are obtained as follows. Let us again consider the topology shown in Figure 4. The RREQ packet transmitted by s is received by node d. Using the RREQ packet, d determines the neighbors of s that can cooperatively transmit with s. Furthermore, d has the latest information on the distances between s and its neighbors. Node d also knows the region that it is in, and that of the given neighbors. If the exact distances between d and those neighbors of s were to know, the optimum transmit energy can be determined using (5). Here, we can use two approaches to approximate the optimum value. In the first approach, we assume the location of the neighbors to be uniformly distributed. Therefore, by using the relative distance information with respect to d, we can place each of these neighbors into the center of the regions they are in according to d. Then d can use the approximate location information and put it in (5) to determine the approximate value for the total transmission energy. The second approach determines the upper bound on the transmission cost by placing the neighbor to the farthest point possible in the allowable region of placement. Note that if we increase the number of regions that are indicated in the neighborhood information exchange packets, then we can closely approximate the optimum cost using the first approach. After the initial cost calculation, d uses the common

[7] If the neighbor of the relay node is a neighbor of a future hop, then we can take advantage of this neighbor's reliable reception in reducing the total end-to-end energy consumption.

[8] The ideal conditions refer to the case where each node taken into account during route setup phase can transmit on unlimited number of orthogonal channels.

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neighbor information to update the initial cooperative link cost to include the common neighbors in the future cooperation scenario. Eventually, d updates the RREQ packet that is to be broadcasted next with the new path, transmission cost, and neighborhood information. In order to allow the route to converge to the optimum route, we allow each node, that already broadcasted a given RREQ packet, to observe the channel for future RREQ broadcasts of the same connection. If the resulting transmission cost for a future broadcast is lower than the one in the already broadcasted RREQ packet, then this information is placed into the cache and updated if necessary.

After the destination node receives the RREQ packets, it replies with a route reply (RREP) packet that includes the path information using the reverse route. After the RREP packet is received by an intermediate hop, it checks its cache whether there is a reverse route that incurs less cost or not. If there is one, then the RREP packet is updated with the given route information and forwarded over that path. Otherwise, no change is made in the RREP packet.

III. Performance Evaluation

We evaluated the performance of the proposed protocols assuming static network topologies. Since our main goal is to observe the impact of cooperation decisions in routing, we only considered the case of a single flow to determine the achievable cooperation gains. The network area is assumed to be a $1000m$x$1000m$ region, in which the nodes are uniformly distributed. The maximum transmission range is assumed to be $250m$. For each case, the simulations are run for 100 times, and for each run, we randomly select a different source and destination pair. In the following results, the average of these runs are reported. We compare the proposed protocols (at $\alpha = 0.01$) with the basic minimum energy routing protocol. For the basic minimum energy routing protocol, we assume the path selection to be based on total transmit power, and control and data packets to be transmitted over separate channels. Assuming the impact of control packet transmissions to be negligible on the final results, the reported results only represent the energy savings based on the total required power for the data packet transmissions.

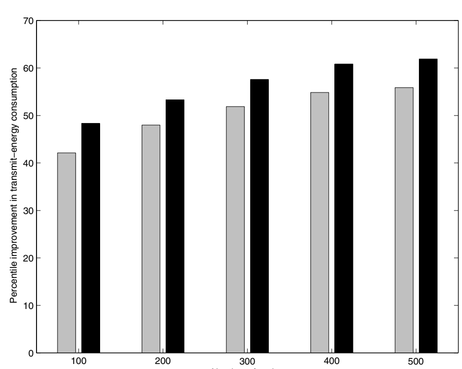

Fig. 5. Energy-efficiency of cooperative protocols with respect to minimum energy routing.

The simulation results are shown in Figure 5 under various node densities. We observe that significant energy savings can be achieved in data transmission by employing C-MAC with minimum energy routing ($\%50$). We also observe that the improvements caused by C-MAC can be further increased (up to $\%56$) if the default route is set up by taking into account the cooperative advantage. The main reason for the difference between the two-step path acquisition and cooperative-routing is because when C-MAC is employed over a non-cooperative path, if the selected path goes through the low-density part of the network, the energy-based improvements will not be as high as expected due to lack of cooperation. On the other hand, by increasing the chance of cooperation along the route with the initial path selection, cooperative routing can both compensate the energy-loss over the default path and improve upon it using cooperative transmissions. We also observe that, as the node density increases, total energy consumption decreases, which is an expected result because of the increased number of neighbors that can join cooperation.

IV. Conclusion

In this paper, we focused on the problem of practical implementation of cooperative diversity techniques in wireless ad hoc networks. We proposed cooperative MAC and routing protocols that enable and support the cooperation among the neighboring nodes to reduce the transmit-energy consumption in the network. By taking advantage of the control message exchanges in the local neighborhood, we first proposed a MAC-framework to determine the optimum set of relay nodes and the optimum power allocation among the cooperating set. Then, by allowing the nodes to combine their local information with the neighbor nodes' local information, we proposed a cooperative routing protocol that establishes end-to-end paths to maximize the cooperative advantage in the network. Through simulations, we demonstrated the benefits of employing the proposed cooperative MAC and routing protocols, which showed significant energy savings ($\%50 - \%56$) compared to the specified non-cooperative minimum energy routing protocol.

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