Multi-criteria Cooperative Energy-aware Routing in Wireless Ad-Hoc Networks

I. Gravalos, P. Kokkinos, E. A. Varvarigos
Computer Engineering and Informatics Department, University of Patras, Greece, and
Research Academic Computer Technology Institute,
Patra, Greece

Abstract **- The cooperation among mobile hosts in wireless ad-hoc networks is usually in the form of nodes acting as intermediate relays that forward data from a source to an otherwise distant destination using point-to-point or point-to-multipoint links. A technique that has gained considerable recent attention is cooperative diversity, where nodes are organized for transmitting the same signal to a given, often otherwise unreachable, node. The receiver combines the multiple receptions to reconstruct the original signal. In this work, we examine the routing and power allocation problem under such a cooperative communications model, so as to obtain a cross-layer design of the network and the physical layer. We present and evaluate a multi-criteria cooperative routing algorithm that uses as parameters the nodes' residual energy and their transmission power. This algorithm selects for each source-destination pair a path, in the form of a sequence of groups of cooperative nodes, and the nodes' transmission powers. We perform a number of simulation experiments, assuming nodes with variable or fixed transmission power, evaluating the benefits of the proposed multi-criteria cooperative routing algorithm. The results show that our algorithm achieves significant energy savings and a larger number of successfully delivered packets than in the case where cooperation is not applied.**

Keywords – wireless networks, cooperative, multi-criteria, energy-aware.

I. INTRODUCTION

In ad-hoc networks a number of wireless nodes, with limited computational, storage and energy capabilities, are self-organized and self-managed so as to create a connected network infrastructure. This network infrastructure can be set up on emergency or other situations when rapid and efficient data connectivity is required.

As wireless transmission rates increase to meet the increasing demands of applications, device power consumption is also increasing by an estimated 150% every two years, while battery technology is improving at a modest 10% every two years, leading to an exponentially increasing gap between the energy demand and the battery capacity offered. The main limitation on the transmission rates of future wireless networks is going to come from the battery limitations, at least for the mobile hosts.

Routing in wireless ad-hoc networks is an important issue that affects not only their efficiency and utility, but also their power consumption. In particular, in these networks, direct communication between wireless nodes is not always possible or desirable and as a result multi-hop paths have to be discovered to connect them. Even if a receiver node can be reached in a single hop, energy and capacity-interference considerations make a multi-hop path often more desirable.

We can distinguish between two routing approaches in ad-hoc networks: the single-cost and the multi-cost approach. Most routing protocols proposed to date are based on the single-cost idea, where a single metric is used to represent the cost of using a link. This link metric can be a function of several parameters (such as link traffic load, energy consumption, and interference), but it is still a scalar. Routing algorithms of this kind calculate the minimum cost path for each source-destination pair. In contrast, in the multi-cost (or multi-criteria) approach each link is assigned a cost vector consisting of several cost parameters. A cost vector can then be defined for a path by combining component-wise the cost vectors of its links according to some associative operator. Furthermore, traditional networking approaches optimize separately each of the three layers: physical layer, medium access and routing. This may lead to largely suboptimal network designs. In the multi-cost approach, the parameters included in the cost vector may refer to different network layers, enabling joint and cross-layer optimization.

Recently, the use of “cooperative communication” techniques [3] (also called, cooperative Multiple-Input Multiple-Output – MIMO, virtual MIMO) has been proposed, for wireless networks.

According to these techniques, a receiver can benefit from multiple transmissions combining signals coming from multiple sources either simultaneously or at different times. To the best of our knowledge, there are three different approaches so far discussed in literature. One technique refers to energy accumulation from multiple transmissions [18]. In energy accumulation a receiver collects the required energy for reliable communication from repeated transmissions. Another approach is the mutual information accumulation [19][20][22]. In this approach a receiver accumulates mutual information for a packet from multiple transmissions until it can be decoded successfully. The last one, which is our approach in this study, is coherent cooperative transmission [1][2][21]. Using this method, a receiving node can combine multiple (often low power) signals received from neighboring nodes, to recompose an initial signal (and therefore the corresponding data packet) that has been sent from a main transmitting node. Without the use of this technique the receiving node might not be able to decode the single signal received by the main transmitting node. Figure 1 presents a simple wireless topology, where *s* and *d* are the source and destination nodes respectively. We observe that, for example, cooperation is applied in the case of nodes *A*, *B*, *C* (in the circle). In particular, node *A* cannot directly communicate with node *C* and as a result node *B* is also used as a cooperative node for transmitting the same packet to *C*. We assume that node *B* overhears node's *D* transmission to *A*, acquiring the transmitted packet without any additional cost (the “broadcast advantage” of wireless communications) and then sends the overheard packet to node *C*. In this way node *C* successfully receives this packet; a reception that would be impossible otherwise, at least without

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increasing the transmission power of node *A*. Even when it is possible for *A* to raise its transmission power so that it is heard at *C*, the cooperation of *A* and *B* may still be advantageous since it can lead to smaller energy consumption and interference, and larger battery life time, by exploiting the broadcast advantage.

In this work, we assume multipoint-to-point cooperative links, where multiple nodes cooperate to transmit the same signal to a given node. Each node has a single antenna. We assume coherent reception, where the transmitters adjust their delays so that all signals arrive in phase and add up at the receiver. A packet is correctly received if the total SNR at the receiver is above a certain threshold. A path of cooperative links in the network corresponds to a sequence of transmitting groups, where each node in a transmitting group must have correctly decoded the packet in a previous transmission. Thus, end-to-end delivery of a packet in an ad hoc network under the cooperative communication problem involves finding the sequence of transmitting groups to be used (i.e., routing and relay selection) and the transmission power each node in a group should use (i.e., power allocation).

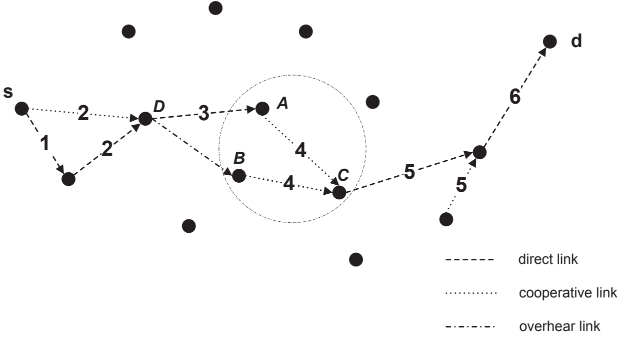


Figure 1: An example of cooperative multi-hop routing. The link labels denote the cooperative or not links of the (*s*, *d*) path.

We present and evaluate a CooperAtive Multi-criteria Energy-aware Routing Algorithm (abbreviated *CAMERA*) for wireless ad-hoc networks that aims at jointly optimizing the routing, transmission power, and cooperating group selection decisions. Our algorithm consists of two phases: it first computes a set of candidate non-dominated paths for a given source-destination pair, and then it selects the path that minimizes a desired optimization function. Our algorithm uses as criteria the nodes' residual energy and their transmission power, attempting to minimize the total energy consumption in the network and maximize the minimum of the residual energies of the nodes in the network. Minimizing total energy consumption alone is not enough for efficient network operation, since it is also desirable for this energy consumption to be, to the degree possible, uniformly distributed among the network nodes. This is because if the battery of some mobile nodes is depleted, the network will soon become disconnected even if there exist nodes that have a lot of remaining energy.

We evaluated the performance of the proposed multi-criteria cooperative routing algorithm in a network consisting of randomly placed nodes with either variable or constant transmission power. Since analytic performance results are difficult to obtain (except for regular linear array or 2-dimensional mesh topologies [1]), we performed a number of simulation experiments, evaluating the benefits of applying the cooperative diversity technique. We also draw conclusions regarding the way network connectivity affects the performance of the cooperative transmission technique. Our algorithm achieves significant energy savings, increased network lifetime and larger number of packets successfully delivered to their destinations than the case when cooperation is not applied. Also, the use of the multi-cost routing approach results in the discovery of more candidate paths (sequences of transmitting sets), while the energy-related optimization function used for choosing the paths to be followed, yields not only smaller energy consumption but also a more uniform utilization of the network's energy reserves.

The rest of the paper is organized as follows. In Section II we report on previous work. In Section III we present the signal transmission and attenuation models considered in our work. In Section IV we describe the proposed algorithm for cooperative multi-cost routing, while in Section V we discuss issues related to the complexity imposed due to the cooperation of the nodes. The simulation results are presented in Section VI. Finally, Section VII concludes the paper.

II. RELATED WORK

The performance of the routing procedure is highly related to physical layer parameters, the most important of which is the transmission power. This is because the transmission power is the parameter that is easier to control, it determines the transmission range and the interference caused, it affects the residual energies of the nodes, and together with these, defines the topology of the network. (Another important parameter is the modulation format used, which is outside the scope of the current paper). A technology that has been developed to provide more flexibility and control at the physical layer is Multi-Input-Multi-Output (MIMO) [3]. MIMO technology relates to the use of multiple antennas at both the transmitter and the receiver to improve communication performance. MIMO has attracted attention in wireless communications, since it offers significant increases in data throughput and link range. Another relevant technology, which is the one assumed in the current work, is virtual MIMO (or cooperative transmission) [4], where each node has a single antenna and nodes cooperate so as to form arrays of transmitting antennas, achieving diversity gains.

Cooperative transmission schemes have been studied mainly at the PHY and MAC layers, with the network layer receiving somewhat less attention. Also, only a few works handle jointly cross-layers issues in networks using cooperative techniques. In particular, in [7] the authors propose two MAC protocols that extend the CSMA/CA protocol so as to perform cooperative transmissions, using two different cooperative diversity techniques at the physical layer. They also propose a cooperative routing protocol based on AODV. Also, in [6] a cooperative MAC protocol is proposed that uses information from the routing layer to identify the existence of nodes that form a diamond topology. These nodes coordinate their transmissions, so as to improve MAC layer's performance and exploit network capacity more efficiently. In [8], an efficient shortest path routing implementation is proposed for multi-hop wireless sensor networks. In particular, a new link metric is defined that balances performance and energy consumption, while a method of cooperative data aggregation is also proposed. Another cooperative routing approach is presented in [5] for clustered sensor networks, where sensors within each cluster relay data packets to nearby clusters using cooperative communications. Two cooperative routing algorithms are proposed in [1] and [2]. These algorithms use a single link cost approach to estimate the optimal path from source to destination node, where the link cost metric is related to the propagation attenuation and hence the distance between transmitting and receiving node. In [10], a distributed cooperative routing algorithm is described, which selects the best relays with minimum power consumption in a distributed manner, and then forms cooperative links for establishing a route from a source to a destination node. Analytical results are also developed that show the energy efficiency of the proposed algorithm. In [11], a distributed cross-layer optimization framework is presented that uses cooperative diversity. The authors actually decompose the original joint routing, relay selection, and power allocation problem into two sub-problems: a routing sub-problem in the network layer, and relay selection and power allocation in the physical layer.

Most routing protocols follow the single-cost approach, in the sense that they base their decisions on a single scalar metric (which maybe a function of several metrics). Multi-constrained routing algorithms have also been investigated, especially for wired networks. Finding paths subject to two or more cost parameters/constraints is in most cases an NP-complete problem [12][13]. The multi-constrained problem has been less studied in the context of wireless ad-hoc networks [14][15][16], even though these networks have important reliability, energy, and capacity constraints that are not present in wired networks. In [15], a multi-constrained routing algorithm for mobile ad-hoc networks is proposed that uses simulated annealing. In [16], the authors present an algorithm based on depth-first-search that solves the general *k*-constrained problem with pseudo-polynomial time complexity.

In our work we combine the notion of multi-criteria routing with the cooperative diversity technique to perform joint optimization of the routing, power allocation and cooperative group selection decisions. In this way all the non-dominated candidate paths and the corresponding groups of cooperative nodes are discovered for each source-destination pair, while in the end an optimization function is applied so as to select the one that is optimal in terms of an appropriate function of the energy consumed and the maximum of the residual energies of the nodes. Regarding the performance analysis, some related works assume regular linear array or two-dimensional grid topologies and are sometimes able to produce interesting analytical results. In our work we consider general network topologies and for this reason we have to rely on simulations.

III. SIGNAL TRANSMISSION AND ATTENUATION

We consider both the case where the nodes' transmission power is fixed and the case where the nodes are able to adjust their transmission power. In both cases, each node is equipped with a single omni-directional antenna. Also, we assume the standard propagation model for wireless communications, where the signal power at distance R from the source is proportional to R^{-m}. Parameter m takes values between 2 and 6, depending on the transmission environment (urban or rural), obstacles existing in the area, etc). In particular, the signal power P_r at a receiving node r is related to the transmission power T_n of the sending node n as:

$$\frac{P_r}{T_n} = G_1 G_2 \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{R}\right)^m = a_{nr}$$

where G_1, and G_2 are the gains of the transmitting and receiving antennas, respectively, λ is the wavelength and R is the distance between the transmitting and the receiving nodes. Parameter a_{nr} is called the attenuation factor of the channel between nodes n and r; when the receiver is given we will use a simpler notation, suppressing the dependence on r.

We assume that a node receives successfully data from another node when the received signal's power P_r is larger than P_{min}, where P_{min} is a threshold that gives an acceptable signal to noise ratio (SNR) value. The SNR at the receiver must be greater or equal than the $SNR_{\min}$, which constitutes the threshold for successful transmission.

In the case when cooperative transmission is applied and several nodes $n_1, n_2, \ldots, n_w$ coordinate their transmissions to another node r, the received signal's power at node r is given by

$$P_r = \sum_{i=1}^{w} P_{n_i,r} + 2\sum_{i<j}^{w} \sqrt{a_i T_{n_i,r}}\sqrt{a_j T_{n_j,r}}$$

where $T_{n_i,r}$ is the transmission power of node n_i when sending to node r, $P_{n_i,r}$ is the power of the signal node r receives from node n_i, and a_l is the attenuation factor for the channel between node n_l, and r.

We distinguish two cases: the case where all nodes have fixed and equal transmission power, and the case where the nodes can adjust, at will, their transmission power.

When all nodes have fixed transmission power $T_{n_i,r} = T$, the received signal at node r is

$$P_r = \sum_{i=1}^{w} P_{n_i,r} + 2T\sum_{i<j}^{w} \sqrt{a_i}\sqrt{a_j}$$

The transmission is successful if the received signal power P_r is larger than the minimum power $P_{\min}$ required to decode successfully the signal.

When nodes are able to adjust their transmission power, the optimal transmission power that should be used by node n_l in order to transmit to node r can be calculated, as shown in the works of Modiano et al. [1] and Lippman et al. [2], to be

$$T_{n_l,r} = \frac{a_l}{\left|\sum_{t=1}^{w} a_t\right|^2} \cdot P_{\min},$$

where $P_{\min}$, is the minimum signal power that can be decoded successfully by a receiving node. When the nodes n_l, $l=1,2,\ldots,w$, adjust their transmission powers according to the preceding equation the received power at r is equal to the minimum required, that is,

$$P_r = P_{\min}.$$

Here we have assumed that the signals received at node r by the cooperative nodes ($n_1, n_2, \ldots, n_w$) can be combined additively, producing the originally transmitted signal. For this to happen, the cooperative nodes should be able to adjust their transmission delays so that the received signals at node r are perfectly phase synchronized. Mechanisms for achieving synchronization are described in [17].

IV. COOPERATIVE MULTI-CRITERIA ROUTING ALGORITHM

In this section we describe the proposed CooperAtive Multi-criteria Energy-aware Routing Algorithm (abbreviated *CAMERA*) for wireless ad-hoc networks. For a given source-destination pair, *CAMERA* finds a multi-hop path consisting of direct and cooperative links. A direct link involves only the two end nodes that communicate directly without the use of relay nodes, while a cooperative (or virtual) link is formed by a group of nodes that cooperate for the transmission of a signal to the end node. Figure 1 shows such a virtual link, where nodes A and B cooperate for transmitting to node C.

The *CAMERA* algorithm consists of two phases. In the first phase, *CAMERA* finds all the candidate paths, with or without cooperative links and with different number of nodes forming the cooperative group of nodes at each corresponding link. In addition, in the case when nodes are able to adjust their transmission power, the proposed algorithm also selects the nodes' transmission power. In this phase domination relations, to be discussed later, are applied so as to reduce the number of paths finally discovered. In the second phase, the optimal path for routing the data is selected based on the desired optimization function. *CAMERA* uses two criteria for its decisions, the nodes' residual energy and their transmission power. In what follows we describe in more detail the *CAMERA* algorithm. We should note that *CAMERA* is a network/physical layer algorithm that does not consider MAC issues. We assume that a MAC protocol exists to achieve node coordination and deal with packet losses and retransmissions.

Phase 1st

In the first phase, *CAMERA* finds all the possible paths between the source and the destination node. For each candidate path the algorithm maintains a group S of parameters:

$$S = ((u_1, u_2, \dots, u_h), V, G, C),$$

where $(u_1, u_2, \dots, u_h)$ is the ordered sequence of the paths' nodes and $V_S = (R_S, T_S)$ is the cost vector of the group, consisting of: (i) the minimum residual energy R_S of the sequence of the nodes $u_1, u_2, \dots, u_h$, (ii) the total power T_S consumed when these nodes are used for transmission. G is the set of nodes, which receive (as members of the path) or overhear (as non-members of the path) any packet transmitted over this path. Also, C contains the groups of nodes (if any) that cooperate for a transmission over a cooperative link.

The algorithm applied in this first phase is a generalization of Dijkstra's algorithm. The basic difference of this algorithm with Dijkstra is that a set of non-dominated paths between a source node and a destination node is obtained, instead of a single path. Initially, there is only one candidate path consisting of the source node. Next, at each step, every candidate path is extended to the next node, to which the last node of the path can communicate either directly or by cooperating with other nodes. The nodes that can be used for cooperation are those contained in the set G. This procedure is repeated until every path reaches the destination node or it cannot be extended, in which case it is discarded from further consideration. Hence, any path is extended to all the different nodes that are candidates as next hops, creating a set of new paths. At the time when there are no other paths to be discovered or that can be extended further, we discard those that have not reached the destination node.

For each new candidate path, the algorithm updates properly the corresponding group S containing the path's characteristics. In particular, the cost vector V is extended as follows:

- $V' = V \cup \{n_i\}$, where n_i is the next node in the path.
- $R' = \min(R, R_i)$, where R_i is the residual energy of the node or nodes (in the case of cooperative transmission) that participate in the path's last hop transmission.
- $T' = T + T_i$, where T_i is the transmission power of the node or nodes that participate in the path's last hop transmission.
- $G' = G \cup On_i$, where On_i is the set of nodes consisting of n_i and any other node that overhears the transmission of the last hop, without any additional cost, since they are inside the transmission range of the node or nodes that participate in this transmission.
- $C' = \{C, S_i\}$, where S_i is the set of nodes that cooperate for the transmission in step i.

After, a new path or a set of paths have been discovered, domination relations are applied in order to reduce the solution space, by discarding dominated candidate paths. This is important so as to also reduce the algorithm's execution time and complexity. In particular, we will say that path P_1 dominates path P_2, when:

- $V_1 \subset V_2$, meaning path P_1 is a sub-path of P_2 path
- $T_1 < T_2$
- $R_1 > R_2$
- $G_1 \supset G_2$, meaning path P_1 "covers" more nodes than P_2

In other words, path P_1 dominates path P_2, if P_1 is a sub-path of P_2, covers a larger set of nodes, consumes less total transmission power, including the transmission power of the cooperative nodes being used, and the minimum residual energy of P_1 path's constituent nodes is larger than that of P_2.

Phase 2nd

In the second phase, among the candidate paths that have been discovered during Phase 1, *CAMERA* selects the one that optimizes the following cost function:

$$F(S) = \frac{R_S}{T_S}$$

Thus, we select the path that tends to consume less energy for transmissions and whose constituent nodes have large residual energy. Small values of the numerator correspond to less total energy expended, while large values of the denominator correspond to more uniform distribution of the energy consumption among the nodes. Of course, other optimization functions can also be used.

In addition, *CAMERA* can be extended to the case where nodes are able to adjust their transmission power. In this case, at each step of Phase 1 where a candidate path is extended, the transmission power of the node or nodes (in case of cooperation) that participate in the last hop, is adjusted to the minimum power required to achieve communication.

V. COMPLEXITY CONSIDERATIONS

The complexity of *CAMERA* algorithm depends on the number of candidate paths produced. In each step, *CAMERA* extends each candidate path $P=(u_1,u_2,\ldots,u_h)$, considering the neighboring nodes of u_h (the last node of path P) and all the possible cooperative combinations of u_h with all the other nodes in the set G, which have already received or overheard a transmission.

The maximum number of these cooperative sets is equal to the number of combining node u_h with the nodes in set G, except of course for u_h. In the worst case, only the path's nodes are included in the set G. As a result the number of different cooperation sets formed at a step of the algorithm is

$$\sum_{r=1}^{h}\binom{h-1}{r}$$

We observe that the number of different candidate paths produced by the execution of *CAMERA* can increase exponentially, making its execution computationally intractable, even for small sized networks. To control the number of candidate paths, our algorithm applies domination relations that reduce considerably the number of candidate paths. In addition, in our simulation experiments that follow, we also restrict the number of nodes that participate in a cooperative transmission, reducing in this way our algorithm's computationally complexity and execution time. For example assuming that a maximum of three nodes can participate in a cooperative transmission, the total number of different paths produced, at each step, by extending a path P become equal to:

$$\sum_{r=1}^{3}\binom{h-1}{r}$$

This reduction of course comes at the cost of making the algorithm sub-optimal.

VI. PERFORMANCE RESULTS

In our work, we performed a number of simulation experiments evaluating the proposed *CAMERA* algorithm.

A. Simulation Settings

Initially, we evaluated the proposed algorithm over a network of 20 wireless nodes placed in a 2-dimensional area of dimensions 1000 by 1000 meters according to a 2-dimensional uniform distribution. Each node was able to transmit to a distance of 250 meters; this was the fixed or the maximum transmission distance depending on whether nodes used a fixed transmission power or they were able to adjust their transmission power. The random topologies created in our experiments were not always connected, resulting in packet losses when no path existed between two nodes. We also tested the performance of our algorithms over a 4x4 grid network topology of 16 stationary nodes. The distance between neighboring grid points was set at 200m, ensuring in this way the networks' connectivity.

CAMERA was evaluated under the "packet evacuation" model, where each node starts with an initial amount of energy and a given number of packets to send and the objective is to serve as many packets as possible with the available energy. In particular, the initial energy of the nodes was taken to be 2 Joules, meaning that several nodes may run out of energy during the experiments, depending on the amount of traffic they end up serving. We assume that the energy a node consumes when transmits depends on the node's transmission power and the packet's size. The number of packets per node that have to be delivered to their destinations ("evacuated" from the network) in our experiments varied from 10 to 100 (at steps of 10) packets per source node. All packets have equal length that is taken to be 500 bytes. Packet destinations were assumed uniformly distributed over all remaining network nodes and the packet generation rate at each node was equal to 0.1 packets/sec.

For the evaluation of our algorithm, we measure the average node's residual energy, its variance, the average number of hops and the packet loss ratio. Also, because of the large complexity that can occur by generating all possible cooperative combinations, in each step, we constrain the number of cooperative nodes to be at most 2 for each virtual link.

B. Results

1) Cooperative versus non Cooperative routing.

Initially, we evaluated the benefits of cooperative versus non cooperative routing. *CAMERA* was used in both cases enabling and disabling respectively the capability of the nodes to cooperate for a packet transmission. This evaluation was based on the 20-node randomly generated topology under the packet evacuation model.

Figure 2 illustrates the average number of hops of the paths constructed by the cooperative and non cooperative versions of the *CAMERA* algorithm. We observe that the Cooperative *CAMERA* results in a significantly smaller number of hops per path, while this hop count is not affected by the network load. On the other hand, the Non-cooperative *CAMERA* selects initially longer paths, while when the network load increases shorter paths are selected. This is due to the decline of the nodes' energy reserves, leading to the selection of shorter paths.

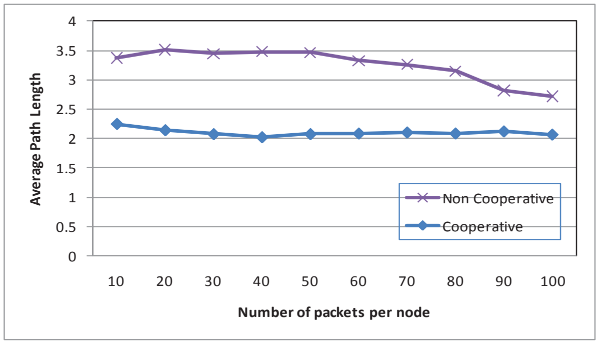
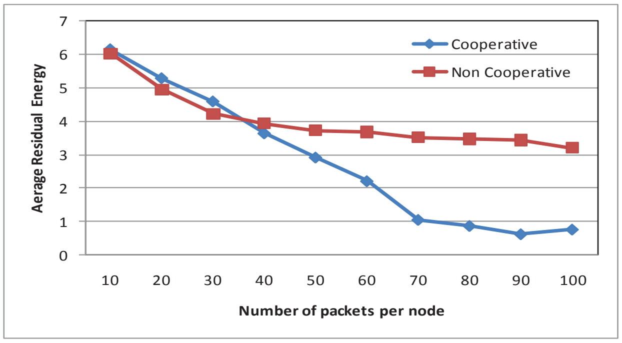


Figure 2: The average number of hops of the paths constructed by the Cooperative and Non-cooperative versions of the *CAMERA* algorithm. The results were obtained for the case of the 20 nodes randomly generated topology as a function of the number of packets generated per node.

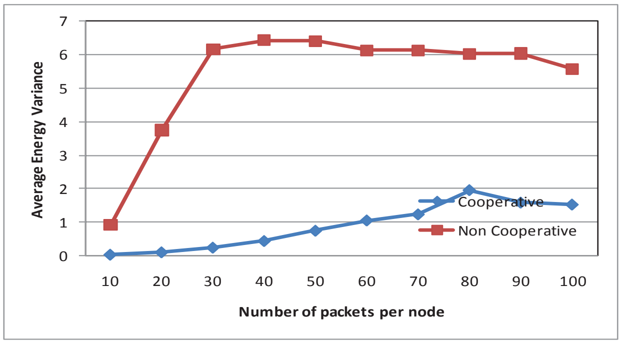
Figure 3.a shows the nodes' average residual energy after all packets have been evacuated from the network. We observe that the Non-cooperative version of *CAMERA* results in larger energy reserves at the nodes at the end of the experiments, since only one node participates in each transmission, in contrast to the Cooperative version of *CAMERA*, where more than one node may participate. However, this benefit comes at

the cost of larger variance of the residual energy (Figure 3.b) in the network nodes (less uniform consumption of the energy amondg the network nodes) and faster energy depletion at some of them. This leads to early network disconnection, since some nodes' energy is exhausted (even though some other nodes may have significant residual energy). On the other hand, when the Cooperative version of *CAMERA* is used, even though nodes consume on average more energy (Figure 3.a), the energy is more uniformly consumed in the network nodes (Figure 3.b), which all participate in cooperative transmissions and the network remains connected for longer time.

This is also confirmed in the results depicted in Figure 4, where we observe that the Cooperative version of *CAMERA* is able to deliver more packets to their destination than the Non-Cooperation version. This is due both to the more uniform energy consumption achieved by Cooperative *CAMERA* (Figure 3.b) and to the fact that cooperation makes possible the establishment of additional links (virtual links) and corresponding paths. These paths would have been infeasible otherwise, considering also that our random topology may be a disconnected one. Actually, the initial packet losses of Cooperative *CAMERA*, for packet loads from 10 to 70, are due to this reason, that is the network being disconnected from its creation, while for larger loads, packets are dropped due to nodes running out of energy. On the other hand, the Non-cooperative version of *CAMERA* results in a large number of packet losses even for relatively small loads, both due to its poor energy management and also due to its inability to find feasible paths in cases where the Cooperative *CAMERA* was able to find.



(a)



(b)

Figure 3: (a) The nodes' average residual energy and (b) the variance of the average residual energy for the Cooperative and Non-cooperative versions of *CAMERA*. The results were obtained for the 20-node randomly generated topology, by varying the number of packets generated from each node.

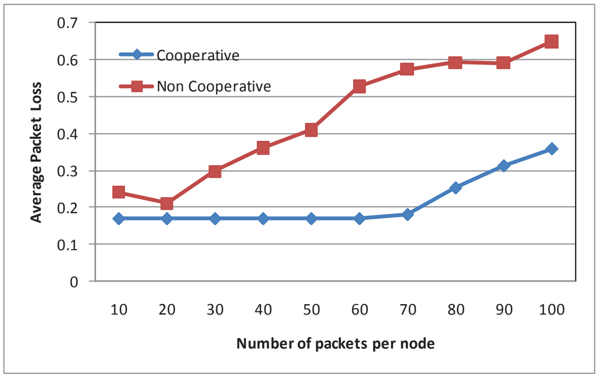
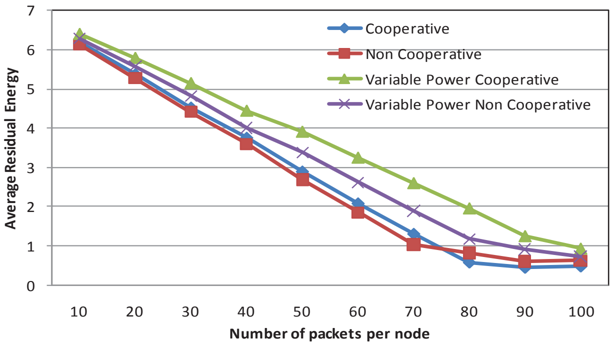


Figure 4: The average packet loss for the Cooperative and Non-cooperative versions of the *CAMERA* algorithm. The results were obtained for the 20-node randomly generated topology, as a function of packets generated from each node.

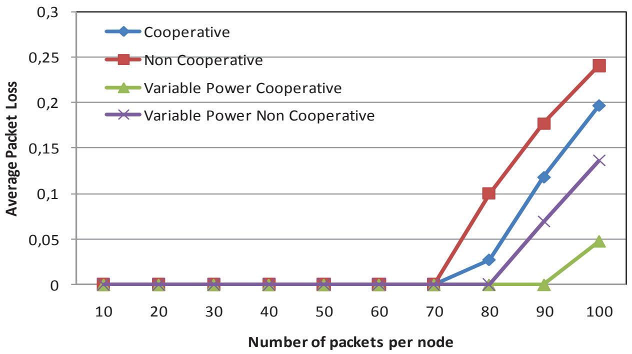
2) *Enabling variable transmission power*

In the experiments that follow we compare four routing methods resulting from the Cooperative and Non-cooperative version of *CAMERA*; where the nodes can adjust or not their transmission power. In the former case, nodes use for their communication the minimum required transmission power, using the equations presented in Section III. The results were obtained for the case of 16 nodes placed on a connected grid topology, as a function of the number of packets generated from each node.

Figure 5.a shows that when node cooperation is combined with variable transmission power, the *CAMERA* algorithm makes better use of the nodes' available energy reserves. Also, in comparison to Figure 3.a, we observe that for the connected 4x4 grid topology, the use of the Cooperative version of the *CAMERA* algorithm, results in larger average nodes residual energy after all the packets have been evacuated, than when the Non-cooperative *CAMERA* is used. This is mainly because cooperation in a non-connected network leads to larger energy consumption, since virtual links and corresponding paths have to be used so as to achieve communication between otherwise disconnected nodes. On the other hand, node cooperation when applied in a connected network results in more choices regarding the paths that can be chosen for a given source-destination pair and in the end in more energy- efficient path selections. In the same context, in Figure 5.b we observe that the Cooperative *CAMERA* algorithm with variable transmission power results in more packets reaching their destination.



(a)



(b)

Figure 5: (a) The nodes' average residual energy and (b) the average packet loss for the Cooperative and Non-cooperative versions of the *CAMERA* algorithm, with and without variable transmission power capabilities. The results were obtained for the case of 16 nodes placed in a connected grid topology, as a function of the number of packet generated from each node.

VII. CONCLUSIONS

We presented a Cooperative Multi-criteria Energy-Aware Routing Algorithm (*CAMERA*) for performing routing, relay selection and power allocation (for the case of adjustable power) in wireless ad-hoc networks. It is the first time that multi-criteria optimization is applied to ad hoc networks using the cooperative transmission technique. Our results show that *CAMERA* makes better use of the nodes' energy reserves, being able to deliver a larger number of packets to their destination over shorter paths than when cooperation is not used. When nodes are able to adjust their transmission power these results are improved even further. In addition, we showed the way the network connectivity degree affects the performance of cooperative routing algorithms. In case of a loosely connected network, cooperation results in more packets reaching their destination but increases the nodes' average energy consumption. On the other hand, when a network topology is strongly connected, cooperation leads in more path choices and in better use of the available energy.

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