Surrendering Autonomy: Can Cooperative Mobility Help?

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Abstract. In this paper, we develop a Cooperative Mobility Model that captures new salient features of collaborative and mission-oriented MANETs. In particular, the cost-benefit framework of our model is a significant advance in modelling heterogenous networks whose nodes exhibit the complete range of autonomy with respect to mobility. We then describe the design of CoopSim, a platform for conducting simulation experiments to evaluate the impact of parameter, policy and algorithm choices on any system based on the proposed Cooperative Mobility Model. We present a small but illustrative case study and use the experimental evidence derived from it to give an initial evaluation of the merits of the proposed model and the efficacy of the CoopSim software. In our case study, we propose studying the impact of the proposed model on improving the end-to-end communication based on the QoS parameter, namely BER.

Key words: Cooperative model, mobility, QoS, MANETs

1 Introduction

The potential applications of MANETs have led, perhaps not surprisingly, to a surge in research breakthroughs addressing the many technological challenges which stand in the way of their wide scale adoption. The many challenges include the limitations of wireless RF channels in terms of available bandwidth and relatively high bit error rates, energy-efficient communication to extend the network lifetime, QoS aware routing to meet application requirements, and the design of new protocols to support large networks and handle the limitations of the underlying wireless RF links.

On the applications side, the demanding requirements of end users in the military and public-safety sectors have led to the development of a variety of unmanned platforms [1]. More specifically, end-user demands have driven the development of Unmanned Ground Vehicles (UGVs) and Unmanned Air Vehicles (UAVs) for use within battlefield and public safety missions, e.g. the UAV-Ground Network [2]. These devices are mobile, mission capable, and can be deployed to serve as relay nodes, maintaining mobile communication, serving as mobile power supplies, since they can be easily deployed to travel to remote locations where power is most critically needed, or to support recharging of embedded devices and hardware carried by troops in the field.

The modern battlefield communications network is a MANET comprised of both manned and unmanned elements (e.g. UAVs), the question remains as to the role of cooperation between nodes. Certainly, task-oriented cooperation is to be expected in such a setting, e.g. coordinating the activity of UAVs to achieve a joint objective like radio source localization [3]. Here, however, we pose a more fundamental question: What role can cooperation play in supporting *communication itself?*

Prior work on the question of how cooperation can benefit communication (e.g. See [4–9] and others) has approached the issue from the vantage point of a node's willingness to forward messages to the next hop (toward the intended destination) along a multi-hop path. Almost all prior work was colored by the consumer model in which node mobility is considered the sacrosanct domain of the user, autonomously determined and non-negotiable. While this is an appropriate conception of current consumer applications (e.g. cell phone and laptop users) it fails to leverage the unique opportunities present in battlefield MANETs. In the latter setting, mobility is a fundamental resource of every MANET node, and cooperative nodes can potentially contribute their mobility towards the common good vis-a-vis systemic objectives. In this article, we develop a realistic model for cooperation in battlefield MANETs and evaluate the extent to which communications can be improved when constituent nodes are sometimes willing to *be moved*.

2 Budgeted Location-Based Cooperative Model

Our model begins with the model of Basu et al. [10], but extends it by postulating that future MANETs will not be homogeneous in terms of node autonomy. While Basu et al. consider networks consisting of robots and non-robots, we contend that the general setting requires us to consider *heterogenous* networks comprised of nodes which exhibit the entire spectrum of personalities: from defiant autonomy to self-sacrificial cooperativeness. We capture this viewpoint by adopting a cost model for mobility. To wit, every node is willing to move for the sake of the common good, but *for a price*. Each node is assigned a *movement cost* (proportional to distance moved)—this is the price it charges to be moved, say, per meter. Defiant autonomy is exhibited when a node declares this cost to be infinite; self-sacrificial cooperativeness is manifest when this cost is declared to be zero.

3 The CoopSim Platform

We have developed a simulation platform to investigate how parameter, policy and algorithm choices influence the efficacy of systems based on the proposed Cooperative Mobility Model. The CoopSim platform dynamically updates the communication infrastructure by manipulating its heterogenous constituent network elements; network nodes are assumed to have a wide range of characteristics, including mobility costs and available transmission power. CoopSim continuously seeks to fulfill concrete end-to-end QoS requirements for a set of application level (multi-hop) connections between given endpoint pairs. CoopSim achieves this by leveraging cooperative mobility: it determines new locations for cooperative battlefield MANET nodes, while adhering to its mobility budget constraints. In this exposition QoS requirements are stated in terms of maximum acceptable end-to-end connection bit error rates (BER), but we note that CoopSim can seamlessly integrate arbitrary, richer QoS definitions.

The CoopSim platform is implemented as a modular discrete event simulator that is naturally organized in layers. Fig. 1 presents a modular schematic diagram.

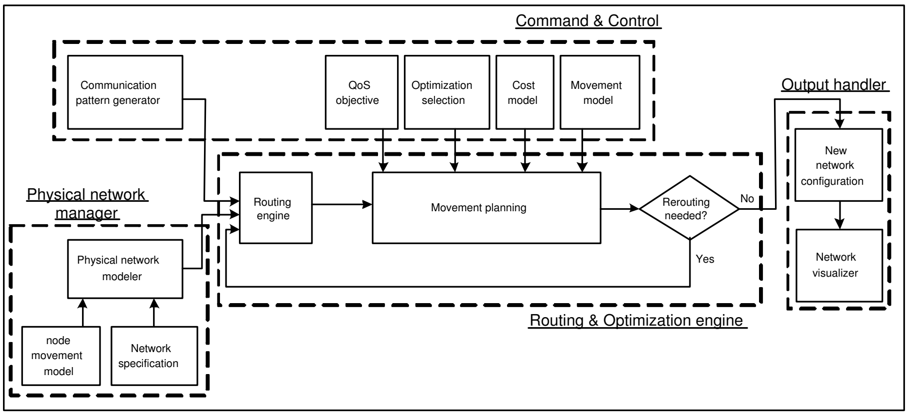

Fig. 1. CoopSim modular architecture

The *lowest layer* of CoopSim represents the **Physical Network Manager**, which consists of a collection of wireless components such as UGVs, manned tanks, etc. Important aspects of this layer include:

Network Discovery. These protocols are used to enable all nodes to discover their neighbors and establish wireless communication channels with them. The design of the network discovery protocol is beyond the scope of this article; a good reference can be found in [11]. For simulation purposes CoopSim assumes that a unidirectional channel connecting a transmitter to a receiver arises whenever the distance separating the two nodes is less than the communication range of the transmitter. A wireless channel forms between two battlefield MANET nodes whenever there is unidirectional channel in both directions.

Channel Characteristics. Suppose we have a pair of nodes at distance D communicating using transmission signal power P over a wireless channel L with noise power P_{noise} through a medium with propagation constant α. The relationship between wireless channel bit error rate (BER) and the received power P_{rcv} is a function of the modulation scheme employed. CoopSim considers non-coherent Binary orthogonal Phase Shift Keying (BPSK) modulation scheme, so $P_{rcv} = P/D^{\alpha}$, and the instantaneous channel bit error rate is [12–14]:

$$BER(L) = \frac{1}{2} e^{-\left(\frac{P}{D^{\alpha}}\right)\frac{1}{P_{noise}}}.$$

The **Routing and Optimization Engine** is the central layer of CoopSim. This layer is responsible for routing the set of connections that need to be maintained and repositioning the cooperative nodes in order to better provide the required QoS. Important aspects of this layer include:

Routing. Connections are routed along shortest paths in the graph using Dijkstra's algorithm, where the weight of link L is taken to be

$$w_L = -\log(1 - BER(L)).$$

It is easy to verify that shortest paths in this graph metric yield connections with minimal end-to-end BER. It is possible that in the course of the simulation two nodes move far apart, causing the channel between them to fail, and in turn causing some connections to break. CoopSim attempts to reroute connections that break due to link failures in this manner. The present version of CoopSim does not consider opportunistic rerouting of connections that are still intact but have become suboptimal because of node mobility.

Mobility. Manned nodes and tasked unmanned nodes move according to a Gauss-Markov model [15], as follows. In time interval n, node i travels with speed $s_{i,n}$ and direction $d_{i,n}$. The mean speed and direction of movement are taken as constants $\bar{s}_i$ and direction $\bar{d}_i$, respectively. Then a node's new speed and direction during the time interval $n+1$ are given by:

$$s_{i,n+1} = \alpha s_{i,n} + (1-\alpha)\bar{s}_i + \sqrt{(1-\alpha^2)s^*_{i,n}}$$
$$d_{i,n+1} = \alpha d_{i,n} + (1-\alpha)\bar{d}_i + \sqrt{(1-\alpha^2)d^*_{i,n}}$$

where α represents a continuity-determining constant, and $s^*_{i,n}$ and $d^*_{i,n}$ are random variables with a Gaussian distribution. The coordinates of node i at the end of time interval n are then easily computable as follows:

$$x_{i,n+1} = x_{i,n} + s_{i,n}\cos d_{i,n}$$
$$x_{i,n+1} = x_{i,n} + s_{i,n}\sin d_{i,n}$$

Nodes that are both unmanned and untasked are moved by a mobility planning algorithm. The design and evaluation of such algorithms remains an open area of investigation. Currently, the CoopSim uses our Resultant Algorithm to construct a movement plan; the details of the algorithm are presented in the next section.

The *topmost layer* of CoopSim is called the **Command and Control**. Important aspects of this layer include:

Connections. A connection is defined by a pair of distinct nodes which serve as the source and destination. The Application Layer can generate arbitrary connection topologies based on the structure of the distributed application that is being simulated. In this article, we consider applications in which communication needs are represented by a random set of source-destination pairs.

QoS Requirements. In this exposition, we consider QoS requirements to be defined in terms of maximum acceptable end-to-end BER, but we note that CoopSim can incorporate any computable definition of QoS.

Connection QoS. We compute the BER of multi-hop connections under an end-to-end retransmission scheme. The bit error rate of a connection C which traverses links L_1, L_2, ... L_k can then be computed as follows:

$$BER(C) = 1 - \prod_{i=1}^{k} 1 - BER(L_i).$$

Movement Costs. Command and Control maintains information about each node: whether it is a manned or unmanned asset. Unmanned nodes are further categorized as either tasked or untasked, with tasked nodes having priorities. Every node i declares its movement cost C_i. Manned vehicles and tasked unmanned vehicles are considered quasi-autonomous because they typically declare high movement costs and have their own objective-driven movement; high movement costs make it unlikely they will be moved by the Routing and Optimization Layer. Vehicles that are both unmanned and untasked are considered essentially cooperative; their declared costs reflect the relative logistical expense involved in their deployment.

Mobility budget. This is the amount of credit to issued by Command and Control to the Routing and Optimization Layer, for funding the movement of cooperative battlefield MANET nodes. The mobility budget is replenished periodically, every T_m time units. In the current simulation, mobility budgets do not accumulate across time intervals.

4 The Resultant Algorithm

Our approach to node mobility planning begins with the following Gedanken-experiment: Consider a single two-hop connection between a source node s and a destination node t, and assume that this connection goes through a cooperative node c. The following two observations are easily be proved by using the well-known Friis' formula [16]:

1. If node c is in line (s, t), then it moves towards s if $BER(c, s) \geq BER(c, t)$, and towards t otherwise; moving node c in a direction that is outside of line (s, t) yields worse connection performance.
2. If node c is not on the line (s, t), then it should move in a direction towards line (s, t).

Making the model more quantitative, we assign weights to the links (c, s) and (c, t); these weights $w(c, s)$ and $w(c, t)$ are taken to be proportional to $BER(c, s)$ and $BER(c, t)$, respectively. The cooperative node c repositions itself by moving in a direction that would improve the total end-to-end connection BER from s to t (see Fig. 2); the direction of movement depends on relative positions of the nodes, as well as the relative magnitudes of $w(c, s)$ and $w(c, t)$.

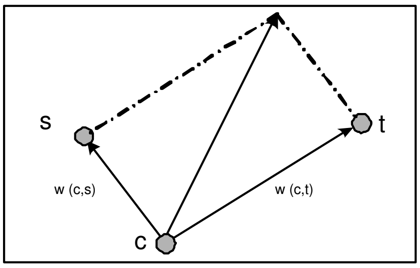

Fig. 2. A Gedankenexperiment on Node Mobility

The previously described Gedankenexperiment suggests a natural analogy between finding the cooperative node movement direction and the problem of resultant forces. Each node c experiences concurrent forces along all its incident links. The magnitude of the force along link L is proportional to $n_L \cdot BER(L)$, where n_L is the number of connections which transit over link L. Computing the resultant force can be done in many ways, including standard componentwise analysis by projection onto a set of orthogonal axes (see Fig. 3). After finding the resultant direction, the available movement budget can be used to move the cooperative node. There remains the problem of dividing a global mobility budget among the cooperative nodes. In this preliminary investigation, we consider uniform allocations: each of the N nodes receives $1/N$ fraction of the total mobility budget.

5 Case Study

In this section we give some experimental results to illustrate the types of investigations which can be conducted using the CoopSim platform.

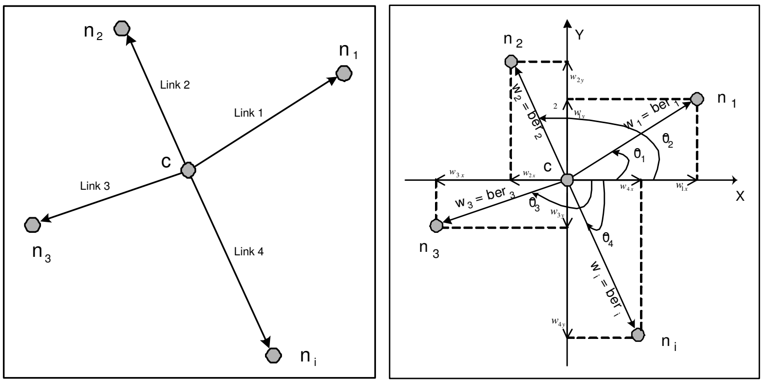

Fig. 3. Resultant Algorithm

The first experiment investigates the effects of increasing the total mobility budget while keeping the number of cooperative nodes fixed. The simulation setup for the top graph of Fig. 4 consists of 15 autonomous nodes moving according to a Gauss-Markov process, and 8 cooperative nodes with mobility cost equal to one unit per meter; all nodes reside inside a one square kilometer grid. Node transmit power and receiver sensitivities are set so that wireless channels arise whenever two nodes are at distance less than 100m. Command and Control establishes 7 random connections and sets their target Quality of Service to be 60% of their initial BER value of the connection. The top graph shows that having higher mobility budgets permits the routing and optimization layer to achieve lower connection BER over time. The bottom chart of Fig. 4 depicts this effect in greater detail by considering the same experimental scenario but with varying mobility budget. The graph shows that a mobility budget of 50 units permits the routing and optimization layer to lower average connection BER by almost 8%, and that increasing the mobility budget to 250 units enables BER reduction of almost 40%. The results indicate that connection BER can be improved almost linearly as the mobility budget increases, even under constant numbers of cooperative nodes.

The second experiment investigates the effects of increasing the number of cooperative nodes while keeping the total mobility budget fixed. The simulation setup for the graph in Fig. 5 consists of 15 autonomous nodes moving according to a Gauss-Markov process, and 0, 3 or 8 cooperative nodes with mobility cost equal to one unit per meter; all nodes reside inside a one square kilometer grid. The mobility budget is fixed at 250 units. Node transmit power and receiver sensitivities are set so that wireless channels arise whenever two nodes are at distance less than 100m. Command and Control establishes 7 random connections and sets their target Quality of Service to be 60% of their initial BER value of the connection. The top graph shows that having more cooperative nodes permits the routing and optimization layer to lower BER more effectively over time, even when the mobility budget is not increased. The bottom chart of

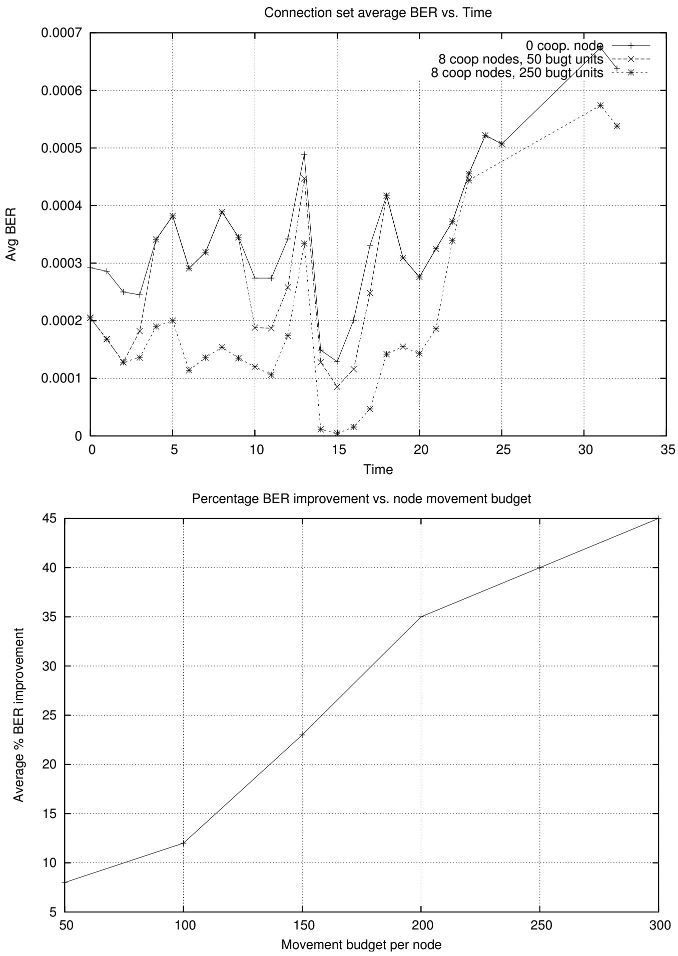

Fig. 4. The benefits of increasing the mobility budget.

Fig. 5 depicts this effect in greater detail by considering the same experimental scenario but with varying numbers of cooperative nodes. The graph shows that with 4 cooperative nodes, the routing and optimization layer can lower average connection BER by almost 8%, and that increasing the number of cooperative units to 12 enables BER reduction of almost 40%. The results indicate that connection BER can be improved almost linearly as the number of cooperative nodes increases, even under constant total mobility budgets.

6 Conclusion and Future Work

The cost-benefit framework of the Cooperative Mobility Model is able to capture MANETs in which nodes exhibit a wide range of autonomy with respect to

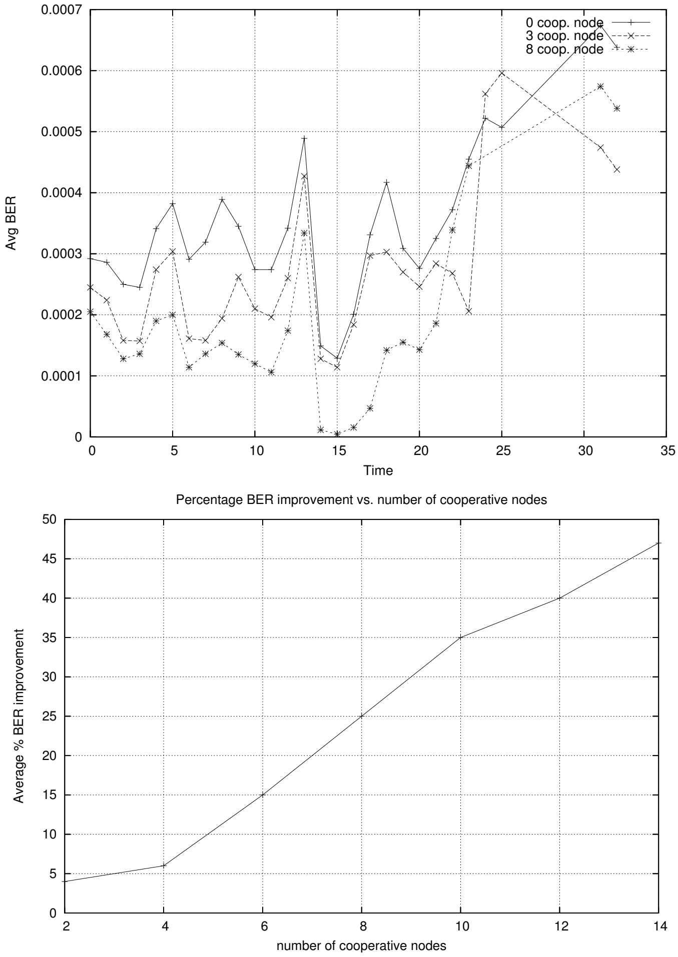

Fig. 5. The benefits of increasing the number of cooperative nodes.

their mobility. Initial experiments using the CoopSim software demonstrate that with even modest mobility budgets and a few cooperative nodes, it is possible to leverage communication-reactive mobility control in a way that significantly improves MANET communications. The Resultant Algorithm is a promising initial approach towards a distributed mobility planning scheme. Increasing mobility budgets increases the potential benefits of cooperation, while increasing the number of cooperative nodes improves the efficiency with which a mobility budget can be leveraged. Our results are a significant step towards improving MANET operations in battlefield, response & rescue, and contexts involving time-critical mission-oriented deployments of mobile users.

In future work, we will conduct systematic investigations using the CoopSim platform. We will design provably robust and distributed algorithms which leverage mobility in MANETs under the Cooperative Mobility Model, and further evaluate their scalability and performance using both analytic techniques and realistic simulation experiments.

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