A Model for Cooperative Mobility and Budgeted QoS in MANETs with Heterogenous Autonomy Requirements

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***Abstract*— Modern mobile ad-hoc networks (MANETs) frequently consist of nodes which exhibit a wide range of autonomy needs. This is particularly true in the settings where MANETs are most compelling, i.e. battlefield, response & rescue, and contexts requiring rapid deployment of mobile users. The time-critical nature of the underlying circumstances frequently requires deployment of both manned and unmanned nodes, and a coordination structure which provides prioritized tasking to them. Unlike consumer MANETs, these settings bring with them a common group purpose, making inter-node cooperation plausible. In this paper, we focus on how cooperation can improve MANET communications. We begin by taxonomizing all prior approaches and noting that no existing approach adequately captures networks where nodes exhibit a wide range of autonomy with respect to their mobility. To this end we present a new Cooperative Mobility Model, developing a cost-benefit framework which enables us to explore the impact of cooperation in MANETs where nodes are, to varying extents, willing to move for the common good. In the second half of the paper, we 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 model. Finally, 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.**

***Index Terms*— wireless ad-hoc networks, bit error rate, cooperative, QoS.**

I. INTRODUCTION

Mobile wireless ad-hoc networks (MANETs) are an important infrastructure building block, enabling the successful execution of both military and public safety operations. In the military setting, MANETs facilitate communication between mobile infantry units, command and control, field intelligence, aerial surveillance, etc. They can be built using Radio Frequency (RF) communication links both between and within infantry formations, ground armored vehicles (e.g., tanks), airborne units (e.g., fighters, bombers), and naval/amphibious platforms (e.g., destroyers, troop carriers). MANETs are particularly well-suited for rapid establishment of communications in battlefield and public safety settings, because they are comprised of mobile platforms that do not require a fixed infrastructure but rather operate over a shared wireless medium.

The modern battlefield communications network is a MANET comprised of both manned and unmanned elements (e.g. UAVs [15]), 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 [16]. 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 [9], [7], [12] 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 paper, 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.*

The remainder of the paper is organized as follows. In Section 2 we begin with a taxonomy of models for cooperation in MANETs. In Section 3 we use these models to motivate a novel Cooperative Mobility Model. In Section 4, we describe the design of the CoopSim platform that is used to evaluate and experiment with parameters of the proposed model. In section 5, we present a small case study to illustrate the richness of the model and the efficacy of the CoopSim platform. Finally, in Section 6 we draw conclusions and extrapolate the future trajectory of our research efforts.

II. A TAXONOMY OF COOPERATIVE COMMUNICATION MODELS

The notion of cooperative communication is itself quite old, appearing in the networking literature as early as the 1970's (e.g. papers on the relay channel model in information theory [5]). The phrase "cooperative communication" reflects the fact that each network node has two existential modalities:

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(i) a **selfish** existence in which it seeks merely to maximize the transfer of its own data, and
(ii) an **altruistic** existence in which it is willing to cooperate with the ambient system and aid in the transfer of data to and from other nodes.

Indeed, a large fraction of the corpus of literature on networking is, in some sense, concerned with achieving and maintaining a balance between these two modalities in an efficient manner that is mutually agreeable to all participants. In the next section, we describe the different categories of approaches to MANET node cooperation that have been considered to date.

In our view, a **model of cooperation** consists of two distinct components:

(i) A lexicon of actions by which to express its altruistic tendencies,
(ii) A set of objective criteria by which the benefits of a node's altruistic behavior are to be assessed.

Our focus in this paper is on mobile ad-hoc networks, and even within this narrow setting, several models of cooperation have been proposed to date (albeit at times only implicitly). Although these models came about in a somewhat ad-hoc manner over the past few years, each arose within concrete research efforts seeking to leverage some new observation or technological development, which in turn was motivated by the over-arching objective of making more efficient use of wireless network resources. In hindsight now, we are in a position to offer the following taxonomy of the models of cooperation that have been manifested in MANET research efforts so far.

1) **Relay Cooperation Models**. This fundamental class of models of cooperation begin with the central observation that if a transmitted signal is not strong enough to reach the intended destination, intermediate nodes may altruistically receive, process, and then retransmit (or relay) the signal toward the final destination. The lexicon of altruism is the willingness of a node to dedicate local resources (e.g. buffer storage, power and computational cycles) to engage in relay actions, while benefit is quantified in terms of the connection throughput of the network as a whole.

2) **Models of Cooperation using Spatial-Diversity**. The central observation underlying this class of models is that when multiple copies of a message are received by a node, a better estimate of the original signal can be determined by combining the received signals. These models refine the basic Relay Cooperation Models described above by extending the lexicon of altruistic behavior. Specifically, when acting as a relay, each node can determine whether to forward the entire received data or merely a part of it, as well as whether any compression should be applied before the forwarding. As before, the benefit of an altruistic act is quantified in terms of the connection throughput of the network as a whole. Most of the concrete schemes within this class operate at the physical or MAC layers.

3) **Cooperation Models for Reputation Management**. The central observation underlying this class of models is that the efficacy of any concrete instantiation of a Relay Cooperation Model can be easily subject to compromise and abuse by misbehaving nodes. Accordingly, this class of models extends the basic Relay Cooperation Model by augmenting the lexicon of altruistic behavior to include cooperation in identifying nodes which are not meeting communal expectations with respect to relaying responsibilities. Nodes that are not cooperating in the data forwarding process are often characterized in the literature [11], [4], [3] as "misbehaving" nodes, and their behavior is further classified as being either malicious or selfish in nature. A malicious node is one that does not cooperate because it wants to intentionally break the network functionality, while a selfish node is one that is simply not willing to spend local resources to forward data that is not intended for it.

4) **Cooperation Models for Power-based Topology Control**. The central observation underlying this class of models is that using new technologies [12], nodes can adjust their transmission power levels. The concomitant models of cooperation arising from this observation, all extend the lexicon of altruism to include inter-node coordination of transmission power. Clearly, changes in node transmission power impacts both the network topology and the network's total energy consumption. Most of the prior research in this area measures the benefit of altruistic behavior in terms of minimizing the total energy consumption of the network, or minimizing the maximum energy consumption (over the set of network nodes).

5) **Cooperation Models for Mobility-based Topology Control**: The central observation underlying this class of models is node mobility can ameliorate network communication properties. Until quite recently, relatively little effort has been directed to communication-reactive mobility control for ad-hoc networks. Movement control for fault tolerance was investigated in by Basu and Redi [1] using a model which considered moving subsets of nodes to new locations in order to achieve biconnectivity in the network graph.

6) **Cooperation Models for Distributed Control**. These models arise in the context of specific distributed applications, when application designers realize that coordination of node activities can facilitate the fulfilment of overall group objectives. These models have appeared frequently in recent years, partly in response to the prevalence of MANETs comprised of multiple independent dynamic nodes that are subject to coupled constraints. Such systems arise naturally in the context of dynamic control of group operations for UAVs, UGVs and robots, [17]. Altruistic action in such settings in-

volves the sharing of information regarding evolving group objectives. The benefits of altruistic behavior are typically measured in application-specific metrics.

In the next section, we present a new cooperation model for MANETs.

III. THE COOPERATIVE MOBILITY MODEL

We consider networks where mobility is a resource that can be used to ameliorate communication infrastructure. Our work begins with the model of Basu et al. [1], but rather than considering networks consisting of robots and non-robots, we consider the more general setting of *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 set to zero. The relative extent of cooperativeness exhibited by battlefield MANET nodes is reflected by the ratios of their associated movement costs.

We see mobility planning (for cooperative nodes) as a core function of the network routing layer, which becomes responsible for allocating a fixed (periodically renewed) **mobility budget** towards paying for the movement of cooperative nodes. The model assumes that a node will execute any mobility request that has been adequately funded by an allocation of the mobility budget; such requests are interpreted as being from higher-level supervisors whose objective is to maintain a communication network that best supports the overall mission requirements. Nodes that are autonomous (i.e. unwilling to be subjected to the movement requests of the routing layer) simply declare their movement costs to be infinite.

The central problem to be addressed then is how best to utilize the movement budgets of nodes to defray the cost of for moving them, in a way that leads to meeting the end-to-end QoS requirements of a set of connections. The QoS parameter we consider is bit error rate (BER) as it is gives a good estimate about the quality of the wireless connections. In short, if BER requirements are to be met, which nodes should be moved, and to where?

IV. THE COOPSIM PLATFORM

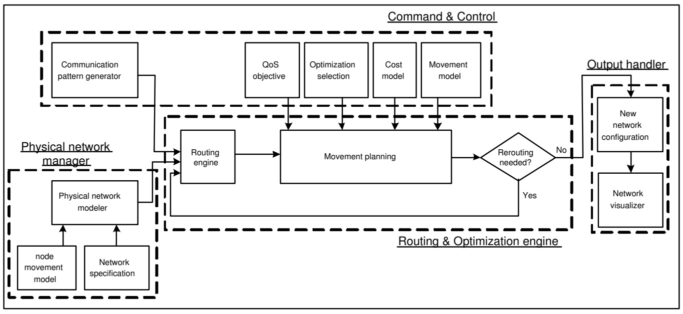

Fig. 1. CoopSim modular architecture

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. CoopSim can be used to evaluate both centralized approaches to mobility budget allocation (using global information) as well as distributed approaches that use only local information at each node.

The CoopSim platform is implemented as a modular discrete event simulator that is naturally organized in layers. Figure 1 presents a modular schematic diagram. Each modular building block that takes part in the discrete event simulation is called a simulation **entity**. Clearly, every battlefield MANET node is a simulation entity; in addition, there are the Physical Infrastructure Manager, the Routing Engine, Command & Control simulation entities. These correspond to each of the three layers. Additionally, an OutputHandler simulation entity serves as a collection point for the data recorded during a simulation experiment.

The *lowest layer* of CoopSim represents the **Physical Infrastructure Layer**, which consists of a collection of wireless components such as UGVs, manned tanks, etc. Within the CoopSim platform all functionality of the Physical Infrastructure Layer is implemented by a simulation entity called the **Physical Network Manager**. Important aspects of this layer/entity 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 paper; a good reference can be found in [18].

- **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) where $P_{rcv} = P/D^{\alpha}$, and the instantaneous channel BER is thus [8], [10], [14]:

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

The *middle layer* depicts the **Routing and Optimization Layer**, which forms the core 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. Within the CoopSim platform, the functionality of the Routing and Optimization Layer is implemented in a simulation entity called the **Routing and Optimization Engine**. Important aspects of this layer/entity 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.

- **Mobility**. Manned nodes and tasked unmanned nodes move according to a Gauss-Markov model, 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:

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

  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:

  $$\begin{aligned} x_{i,n+1} &= x_{i,n} + s_{i,n}\cos d_{i,n} \\ x_{i,n+1} &= x_{i,n} + s_{i,n}\sin d_{i,n} \end{aligned}$$

  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 platform uses a distributed heuristic algorithm to construct a movement plan for cooperative nodes.

The *topmost layer* depicts the **Application Layer**. This layer is responsible for generating a set of connections and associated QoS requirements. Within the CoopSim platform, the functionality of the Application Layer is implemented in a simulation entity called the **Command & Control**. Important aspects of this layer/entity 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.

- **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:

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

- **Movement Costs**. Command & 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 & 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.

The CoopSim platform also implements an **Output Handler** simulation entity, which interacts with the Network Manager, Routing Engine, and Command & Control to analyze the evolving topology and network characteristics.

V. CASE STUDY

In this section we present the results to two experiments to illustrate the types of investigations which can be conducted using the CoopSim platform. Both experiments share the following features: (i) All nodes reside inside a one square kilometer grid, (ii) Node transmit power and receiver sensitivities are set so that wireless channels arise whenever two nodes are at distance less than 100m, (iii) Command & Control establishes 7 random connections at the outset of the experiment, and sets the target Quality of Service (BER) of each of these connections to be 60% of its initial value.

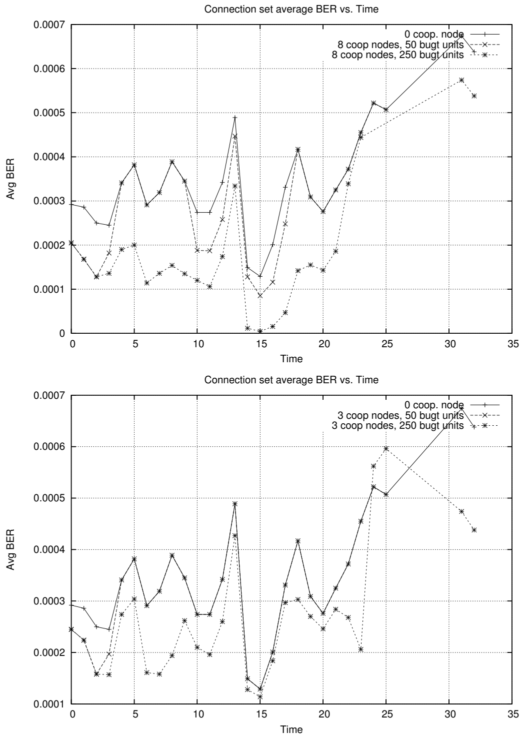

Fig. 2. The benefits of increasing the mobility budget.

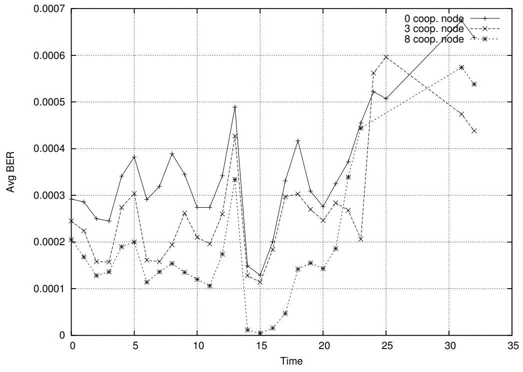

Fig. 3. The benefits of increasing the number of cooperative nodes.

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 Figure 2 consists of 15 autonomous nodes moving according to a Gauss-Markov process, and 8 cooperative nodes having mobility costs equal to one unit per meter. The graph shows the average BER of the 7 connections as a function of time. The results indicate that a mobility budget of 50 units permits the routing and optimization layer to lower average connection BER by almost 10%, and that increasing the mobility budget to 250 units permits more consistent BER reduction frequently in excess of 50%. The bottom graph in the same figure shows that if the number of cooperative nodes is decreased from 8 to 3, the Routing and Optimization Layer is not able to use cooperative mobility as effectively.

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 Figure 3 consists of 15 autonomous nodes moving according to a Gauss-Markov process, and 0, 3 or 8 cooperative nodes having mobility cost equal to one unit per meter. The graph shows the average BER of these 7 connections as a function of time. The results indicate that having more cooperative nodes permits the Routing and Optimization Layer to better leverage cooperative mobility, even when the mobility budget is not increased proportionately.

VI. 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 their mobility. Initial experiments show 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. 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 robust distributed algorithms which leverage mobility in MANETs under the Cooperative Mobility Model, and evaluate the scalability and performance of these algorithms using both analytic techniques and realistic simulation experiments.

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