Multigrid Techniques for Movement Planning in MANETs with Cooperative Mobility

Bilal Khan
Dept. of Mathematics and Computer Science,
John Jay College of Criminal Justice
899 Tenth Avenue
City University of New York, NY., 10019
bilal@bilalkhan.org

Ghassen Ben Brahim and Ala Al-Fuqaha
Dept. of Computer Science, Western Michigan University
Kalamazoo, MI., 49009
gbenbrah@cs.wmich.edu,
alfuqaha@cs.wmich.edu

ABSTRACT

Rapid-deployment mobile ad-hoc networks (MANETs) are frequently characterized by common over-arching mission objectives which predicate a cooperativeness on the part of constituent nodes. In this article we present a new strategy to improve MANET communications based on node cooperation with respect to mobility. We present our model for cooperative mobility, and use this cost-benefit framework to explore the impact of cooperation in MANETs where nodes are—to varying extents—willing to be moved for the common good. We develop an effective centralized algorithm for mobility planning based on multigrid techniques. Our simulation results are compelling and demonstrate that the communication infrastructure—specifically, connection bit error rate— can be significantly improved by leveraging this proposed scheme.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.4 [**Computer Systems Organization**]: Performance of Systems

General Terms

Algorithm, Design, Performance

Keywords

wireless ad-hoc networks, bit error rate, cooperative, Quality of Service.

1. INTRODUCTION

Mobile wireless ad-hoc networks (MANETs) are an important infrastructure building block, enabling rapid deployment of a flexible communication infrastructure, e.g. in military and public safety operations. In the military setting, for example, 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).

These technical challenges facing MANETs stem from their intrinsic limitations, specifically (i) bandwidth scarcity and high bit error rates of wireless RF channels, and (ii) limited battery capacities which mandate energy-awareness to extend the network lifetime. These limitations have hindered the development of truly scalable QoS-aware routing, and to cope with them much effort has been undertaken to leverage the power of *cooperation* between MANET nodes.

While prior work on the question of how cooperation can benefit communication (e.g. see [6], [5], [3], [4], [8], [7] and others) has principally considered the node's willingness to forward messages as it's cooperative contribution, we explore the ramifications of treating a node's physical mobility as a contributable resource. The assumption, while not applicable in the consumer MANET setting, is quite reasonable in in MANETs where participants have a common (e.g. mission) objective; these rapid deployment settings are precisely the ones where MANETs are most compelling anyway.

2. COOPERATIVE MOBILITY MODEL

The model of networking has evolved significantly over time. Classical networking presumed that link structure is essentially static and predetermined, with users at fixed locations. The cellular network paradigm, in contrast, allowed each user to roam and extend the classical network by making wireless connections to nearby base station nodes. In the purely mobile ad-hoc (MANET) setting, the classical network disappeared altogether; links are formed entirely by dynamic peer-to-peer wireless connections between users. Arising from historical context of consumer MANETs, users are envisioned in this model as being entirely autonomous with respect to their mobility. What we propose here is a significant modification of the conventional mobile ad-hoc network 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 *hetero-*

IWCMC'07, August 12–16, 2007, Honolulu, Hawaii, USA.

geneous 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 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?

3. THE MULTIGRID APPROACH

An initial approach to finding the optimal solution to the nodes location problem might consider using continuous function minimization techniques. However, several difficulties arise immediately: (i) the dimensionality of the space is large ($2N$ dimensions for networks of N nodes), (ii) the objective function (mean bit error rate per connection) is highly non-linear, and (iii) the objective function has many local minima. One way to systematize the search process is to discretize the search space. However, in discrete approaches, the grid resolution parameter introduces an inefficient tradeoff between solution optimality and compute time. We seek to mitigate this tradeoff using grids of varying resolution.

Multigrid (MG) techniques have gained significant popularity in computing numerical solutions for differential equations [2]. Following the general MG pardigm, we define a hierarchy of successively finer grids, based on an original "fine" grid. This process of defining the finer grids inverts the standard MG process of agglomeration [9]. At each phase, all cooperative nodes (that are part of any connections requiring optimization) successively consider moving to nearby grid locations. Specifically, here we assume that each cooperative node may consider moving to one of the four corners of its surrounding grid cell. Once all cooperative nodes have considered moving, the grid is refined (if necessary) according to a *grid refinement schedule.* In this paper, we consider an arithmetic grid refinement schedule, by considering a sequence of grids having $n, n+c, n+2c, \ldots$ cells; in phase i, we consider a grid of $\sqrt{n+ic}$ by $\sqrt{n+ic}$ cells the grid has $n+ic$ cells .

In the next section, we present more details about the multigrid algorithm.

3.1 Node Control Logic

Before we describe the procedure that each cooperative node follows to select its next location, we define the notion of *slack* of a connection:

$$\textit{slack} = \text{ current BER} - \text{ required BER.}$$

This is depicted in Figure 1.

When a node contemplates moving to a new location, it considers two quantities: its current slack, and the slack it will have if it moves to the new location; the latter quantity is referred to as the *projected* slack. The *slack differential* for a proposed move is defined by:

$$\begin{aligned}\text{slack differential} &= \text{current slack} - \text{projected slack},\\ &= \text{current BER} - \text{projected BER}.\end{aligned}$$

We distinguish between scenarios based on whether a node sees a connection having negative or positive projected slack. On the one hand, if the projected slack is positive, two sub-possibilities arise: if the slack differential is positive, the projected cooperative node movement will result in better connection performance; if the slack differential is negative, moving the cooperative node to the new location will result in worse connection QoS. On the other hand, a negative projected slack indicates that the proposed movement will yield an improvement in the connection bit error rate that will *exceed* the required QoS. In such settings, the algorithm tries to minimize the *magnitude* of negative slack using minimal movement budget. The scenarios are depicted in Figures 1 and2.

The procedure to select the next location of the cooperative node is illustrated by the following pseudocode. The new location of the cooperative node is chosen in a way that results in an overall improvement of the bit error rate of all underlying connections while utilizing a minimum amount of the movement budget.

Begin
for each each coop. node C part of any connection **do**
  Find C's boundary cell.
  for all grid cell's four corners **do**
    (1) Compute projected BER of connections that transit C.
    (2) Compute slack differential of all connections that transit C.
  end for
  Find new location of coop. node C such that:
  (1) Sum slack differential (over all transit connections) is positive and significant, and
  (2) There is sufficient movement budget to make projected move.
  (*) If more than one candidate corner exists, we choose the one which minimizes the sum of (the magnitudes of) the negative slacks.
end for
Move C to the best corner, if one was found.
Decrease the residual movement budget suitably.
End

Failure to find a grid cell corner that satisfies (1) implies that average BER cannot be improved by moving. Failure

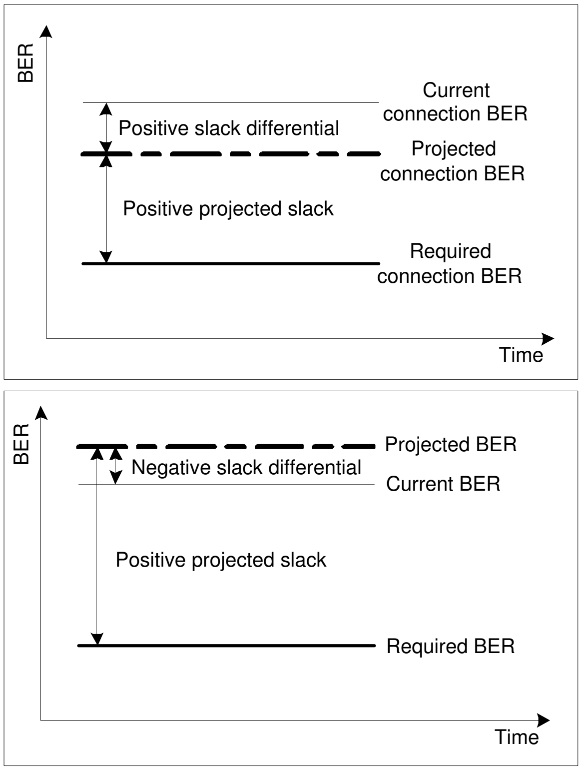

Figure 1: Positive projected slacks

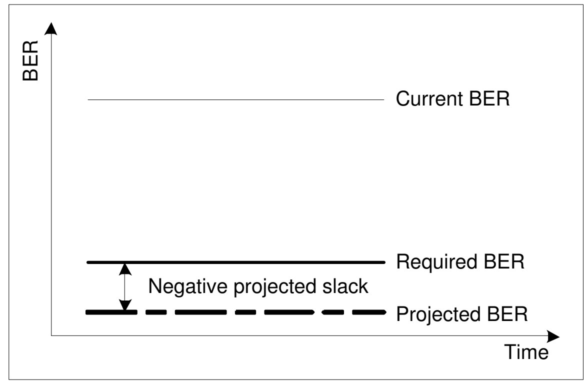

Figure 2: Negative projected slack

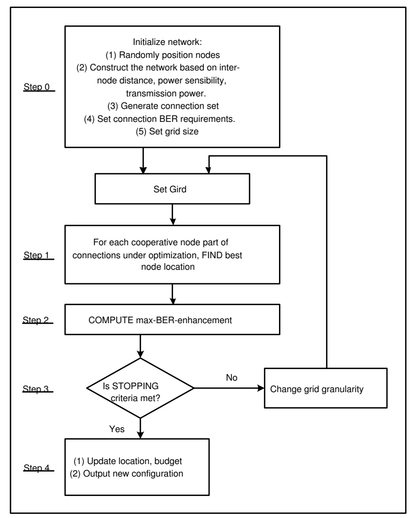

Figure 3: Flowchart of the multigrid algorithm

to find a grid cell corner that satisfies (2) implies that insufficient movement budget is available. In the event that multiple grid corner's satisfy (1) and (2), the condition (*) is used to break ties, ensuring that we minimize the extent to which connection QoS is oversatisfied. If a node fails to find a corner satisfying both (1) and (2), the node leaves the optimization process. We formalize each node's stopping criteria in pseudocode as follows:

Begin
IF for all four grid cell corners:
(1) Average slack differential (over all transit connections) is negative/insignificant OR
(2) Not enough movement budget is available THEN
Node exits optimization process
ELSE
Increase grid granularity and re-iterate
End

In practice, the stopping criteria procedure is implemented by interpreting the phrase *"significant"* to mean a threshold encoding the notion of convergence. In our experiments convergence was assumed for a node when its slack differential was less than μ =1% of the *initial* slack at the beginning of the entire optimization process.

Initially, we divided the whole space into a grid of $n \times n$ cells. Within a phase, the movement of a cooperative node is restricted to be to one of the surrounding corners of the grid cell in which it resides, according to the previously described logic. If not all nodes have left the optimization process yet, the algorithm is rerun again over a successively finer granularity grid, as mandated by the refinement schedule. Figure 3 illustrates the algorithm.

3.2 Multigrid algorithm complexity

In this section, we study the complexity of the proposed algorithm in terms of the number of cooperative nodes in the connection set (N) and the number of connections (m).

Since in each phase, a node is guaranteed to reduce its slack by $\mu = 1\%$, the number of rounds required is bounded $1/\mu$. In each round, a node performs $O(m)$ work evaluating the four corners of its grid cell. Thus the algorithm converges in sequential time $O(Nm/\mu)$; a parallel implementation in which nodes operate concurrently requires $O(m/\mu)$ time. Note that the run time of the algorithm is independent of the initial grid size (n), and increment (c) which determine the grid refinement schedule; these parameters affect the quality of the solution because they alter the algorithm's susceptibility to local minima; they do not significantly impact upper bounds on the convergence time.

4. RESULTS

In this section we give some experimental results to illustrate the performance of the proposed multigrid approach. The scenario consists of an average network size of 30 uniformly distributed nodes, where 15 autonomous nodes are moving according to a Gauss-Markov process, and 15 coop-

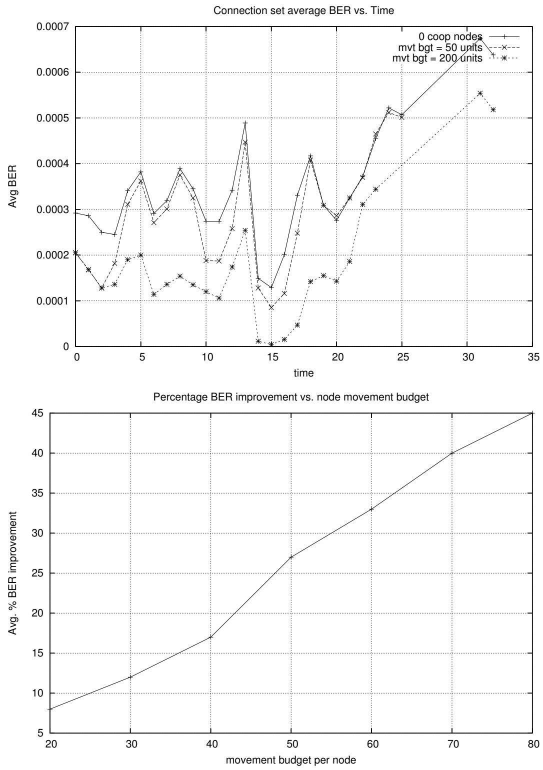

Figure 4: The benefits of increasing the mobility budget

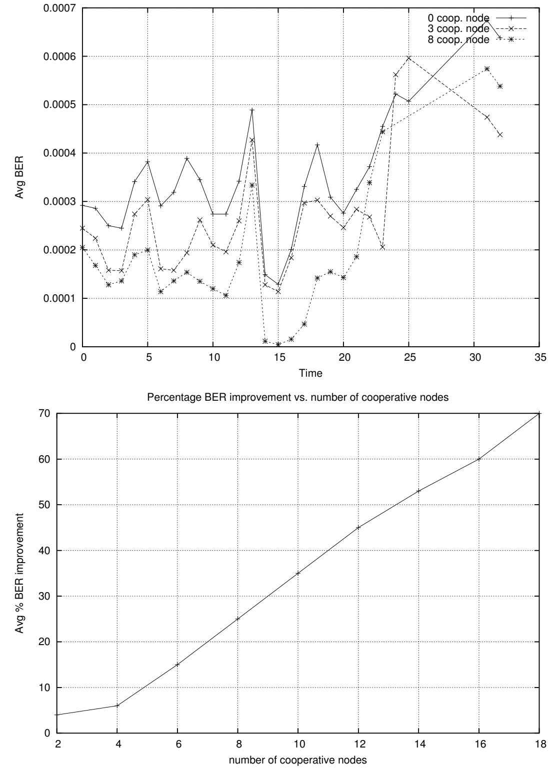

Figure 5: The benefits of increasing the number of cooperative nodes

erative nodes operate, each with a uniform mobility budget; 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 $100m$. We establish 15 random connections that we propose BER requirements for the connections equal to 60% of their initial values. We consider an initial grid size equal to 10.

The first experiment investigates the effects of increasing the total mobility budget while keeping the number of cooperative nodes fixed. 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 Figure 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 200 units enables BER reduction of almost 40% over time. 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 Figure 5 consists of 15 autonomous nodes, 0, 3 or 8 cooperative nodes, mobility budget is fixed at 200 units, and a total of 7 random connections with a target Quality of Service to be 60% of their initial BER value for each 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 Figure 5 depicts this effect in greater detail by considering the same experimental scenario but with varying numbers of cooperative nodes. For example, with 4 cooperative nodes, we can lower average connection BER by almost 8%, while 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.

The next experiment investigates the impact of the proposed scheme on improving the average BER of the connection set. The top curve in Figure 6 represents the average BER of an ad-hoc network where the cooperative nodes remain stationary over time. The bottom curve represents the same measure in the presence of cooperative nodes manipulated according to the proposed multigrid scheme. By looking at the *slope* of the bottom chart, we conclude that the routing and optimization scheme were able to maintain a fairly constant low connection set BER. By analyzing the difference of both curves, we conclude that with our proposed scheme, we were able to achieve an improvement of the overall connection set BER by almost 300%.

The next experiment investigates the effects of increasing the node mobility budget and number of connections. The network is constructed in the same manner as before but the same autonomous movement node sequence is responded to by cooperative node which have mobility budget of $50m$ (top curve) and $20m$ (bottom curve). By considering the *difference* between the curves curves of the top graph, we no-

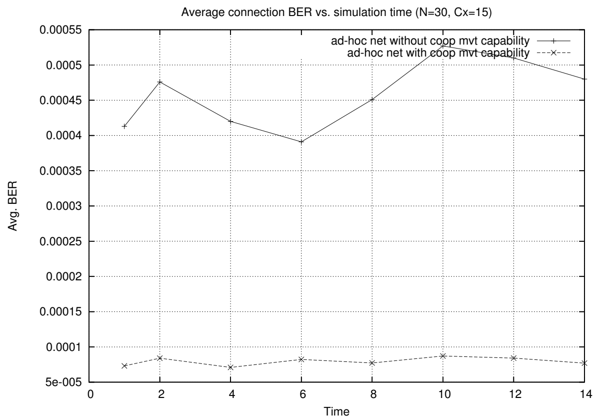

Figure 6: Using the multigrid scheme to reduce the average BER

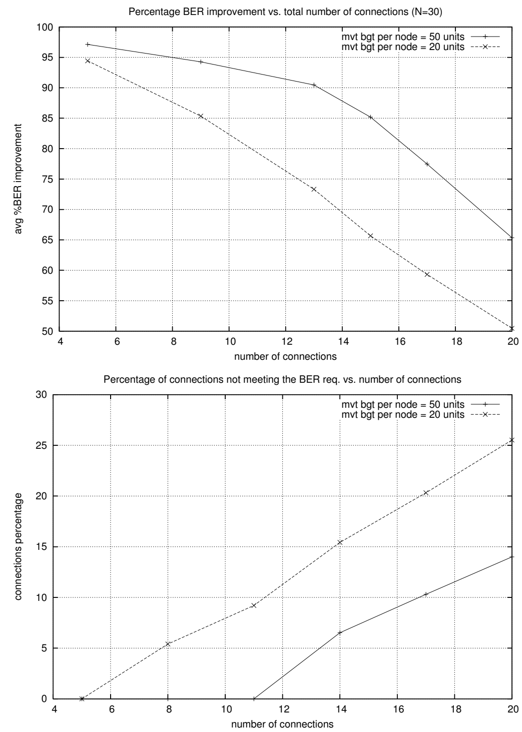

Figure 7: The benefit of increasing the mobility budget

tice that for a higher node movement budget corresponds a better improvement in the overall percentage BER improvement. For example, for a connection set size, corresponds a 35% improvement when using 50 units of budget compared to the case where each node has only 20 units. Considering the *slope* of the curves in the top graph, we conclude that the average percentage BER improvement decreases as the connection set size increases.

The bottom graph of Figure 7, illustrates the impact increasing the movement budget on the percentage of the connections that do not meet the BER requirement by the time the optimization terminates. By looking at the *slopes*, we conclude that this percentage increases as the connection set size increases. For example, 13% of the connections did not meet the BER requirement when the connection set size equals to 17. By considering the *difference* between both curves of the bottom graph, we conclude the percentage of connections that did not meet the BER requirement is much less in the case of higher movement budget available per node. For example, for 17 connections, increasing the movement budget from 20 to 50 units results in a 50% improvement in the percentage of connections not meeting the BER requirement.

5. CONCLUSION AND FUTURE WORK

In this paper, we consider how cooperation between nodes can improve communication in mobile ad-hoc networks. We propose a new cooperative mobility model based on location management scheme under budget constraints aiming to the improvement of the QoS of a connection set. The main contribution of this paper is the design and implementation of an effective multigrid scheme for computing dynamic node placements. Simulation experiments indicate conclusively that the resulting approach is scalable and succeeds at efficiently moving cooperative nodes in a manner which optimizes connection bit error rates.

Several extensions to this work are presently being considered. First, we seek to quantify the impact of the grid refinement schedule on the quality of the solutions derived. In addition, we will design distributed implementations of this scheme, under the presumption of effective clock synchronization protocols.

6. REFERENCES

[1] P. basu and J. Redi. Movement Control Algorithms for Realization for Fault-Tolerant Ad-Hoc Robot Networks. IEEE Network, July 2004.

[2] A. Brandt. Multi-level adaptive solutions to boundary-value problems. volume 31, pages 333–390, 1977.

[3] S. Buchegger and J. Y. L. Boudec. Cooperative routing in mobile ad-hoc networks: Current efforts against malice and selfishness. of Mobile Internet Workshop. Informatik 2002., Dortmund, Germany, October 2002.

[4] M. Gerharz, C. de Waal, P. Martini, and P. James. A cooperative nearest neighbors topology control algorithm for wireless ad hoc networks. IEEE, 2003.

[5] A. Khoshnevis and A. Sabharwal. Network channel estimation in cooperative wireless networks. Canadian Workshop on Information Theory, Waterloo, Ontario, May 2003.

[6] N. Li, J. C. Hou, and L. Sha. Design and Analysis of an MST-Based Topology Control Algorithm. IEEE INFOCOM, 2003.

[7] A. Nosratinia, T. E. Hunter, and A. Hedayat. Cooperative Communication in Wireless Networks. IEEE Communication Magazine, October 2004.

[8] C. Politis, T. Oda, N. Ericsson, S. Dixit, A. Schieder, H. Lach, M. Smirnov, S. Uskela, and R. Tafazolli. Cooperative Networks for the Future Wireless World. IEEE Communication Magazine, September 2004.

[9] V. E. H. William L. Briggs and S. F. McCormick. *A Multigrid Tutorial, Second Edition*. SIAM, 2000.