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Using Multiple Radios for Ad Hoc Backbone Construction and Maintenance

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***Abstract*—We investigate the performance of a new distributed protocol for setting up and maintaining a backbone for multi-hop mobile networks with multiple radio interfaces. Our solution, termed MM-Backs, is effective in producing backbones with limited size, while being robust and reliable in the face of node mobility. We compare our protocol with a solution for mobile backbones running in single-radio networks that has been shown to outperform previous backbone formation protocols. MM-Backs provides backbones of reasonable size, with superior connectivity, shorter route lengths, higher resilience and lower maintenance-related overhead.**

***Keywords*-Multi-hop wireless networks; mobile multi-radio ad hoc networks; backbone construction and maintenance.**

I. INTRODUCTION

In this paper we present the result of a simulation-based performance evaluation of protocols for mobile, multi-hop and multi-radio networks that build and maintain a *backbone*, i.e., a communication structure formed by selected ad hoc nodes and by the links among them. The typical *raison d'être* of a backbone in a multi-hop network is that of providing a hierarchy among the network nodes that, by creating a smaller communication structure, enhances network scalability. The topic has been investigated intensively throughout the years and, more recently, backbone construction has been perfected to efficiently deal with node mobility.

The focus of our study is the evaluation of the benefits obtained by multiple radio vs. using only one radio, as customarily done. In particular, we consider a recent backbone construction and maintenance protocol introduced by Nanni and Basagni [1], termed M-Backs for mobile backbones, that has been shown to outperform previous solutions with respect to critical backbone metrics. M-Backs has been redefined and optimized to work with multiple radios, and the resulting protocol has been termed *MM-Backs* for Mobile Multi-radio Backbones [2]. The version tested in this paper concerns nodes with two radio interfaces with different transmission radii, r and R, with $r < R$. While exchanging HELLO packets over the topology formed by r, backbone links are formed and maintained over the longer range radio. MM-Backs achieves all properties that are desirable for efficient backbone construction: The protocol does not require nodes to be synchronized; information is carried over packets (the HELLO packets) that are needed anyway for basic network operations; the size of the HELLO packets remains manageably small; the protocol is based on very simple code, and produces and maintains a backbone in constant time, i.e., in a time that does not depend on the number of nodes in the network; nodes in the backbone are the best suited for the job (this may dynamically change in time); the protocol does not require extra hardware (e.g., GPS) and does not constrain the mobility of the nodes.

The performance of MM-Backs has been evaluated through ns-2/MIRACLE-based simulations. We compare MM-Backs and M-backs in terms of the characteristics of the backbones they produce, such as size, how long they are connected, how resilient and robust they are to link failure, and the length of their routes. We observe that MM-Backs remarkably outperforms M-Backs (which in turn has been shown to perform better than previous solutions in [1]).

II. MM-BACKS VS. M-BACKS

In order to assess the effectiveness of building backbones over multi-radio nodes we compared the performance of MM-Backs with that of its single-radio counterpart, M-Backs (see [1] and [2] for protocol definition and comparison with previous solutions for single-radio nodes). Running on a single-radio network G_r, M-backs needs to build backbone links between backbone nodes (called *head nodes*, HNs) that are at most three hops away by choosing intermediate nodes, called gateways nodes (GNs). Therefore a "virtual" M-Backs link is implemented through at most three physical links on G_r. As a consequence, for GN selection, HELLO packets contain additional information on the actual composition of routes between pairs of HNs [1].

We implemented MM-Backs and M-Backs in the VINT Project *ns-2* Simulator [3] and its extension ns-MIRACLE [4]. We consider nodes with two radios, one with high data rate and shorter range and one with lower data rate but longer transmission radius. The high data-rate interface is set to perform as a 802.11g card with transmission radius $r = 150$m and data rate 18Mbs. The second wireless interface simulates a 802.11b card, with a much lower data-rate (1Mbs) and a transmission range of about 450m.

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Transmissions on the two interfaces occur on orthogonal (i.e., non-interfering) channels. Our experiments concern networks with 200 to 500 nodes initially scattered uniformly and randomly over a square area with side $L = 1000$m. Nodes then move according to the Gauss-Markov mobility model [5]. This model is designed to adapt node movements to different levels of randomness via one tuning parameter α. Totally random values (or Brownian motion) are obtained by setting $\alpha = 0$, while linear motion is obtained by setting $\alpha = 1$. Intermediate levels of randomness are obtained by varying the value α between 0 and 1. Results shown here have been obtained by setting $\alpha = 0.5$. Nodes move at the average speed of 2.5m/s. The *HelloPeriod* is set to 2s. If a node does not receive a HELLO packet from a neighbor for 6s or more their link is considered dead, and that neighbor entry is removed from the node neighbor table. Simulations run for 10000s. Nodes start their operation randomly during the first 50s of simulation. Metrics are measured after the first 100s of simulations. Each point has been obtained by averaging over 100 different runs for each network size, which allows us to achieve 95% statistical confidence within 5% precision.

We considered the following metrics.

- *Backbone size*: The number of nodes in the backbone (HNs in MM-Backs, HNs and GNs in M-Backs).
- *Backbone connectivity*: The percentage of simulation time when the backbone is connected.
- *Backbone resilience*: The number of links that should be removed in order to disconnect the backbone.
- *Backbone robustness*: The minimum number of links that should fail for disconnecting the backbone.
- *Route length*: The length (in hops) of the shortest route between any two nodes, passing through the backbone.

For this set of metrics measures are collected by taking a network snapshot every second of the simulation time after the first 100s. Results are shown in Figure 1.

Figure 1(a) depicts the average backbone size as the number of network nodes increases. MM-Backs clearly takes advantage of interface I_R that allows it to build smaller backbones. Their size is quite contained, being always between 40 and 57 nodes, i.e., always below one fifth of the number of nodes in the network. M-Backs needs to select GNs to build a connected backbone: Its size ranges between 97 and 153 nodes. Therefore, using multiple radios leads to a reduction of the backbone size of about 59% for networks with 200 and of 63% in denser networks ($n = 500$).

In Figure 1(b) we show the average percentage of simulation time when the backbone is connected (being the flat network topology also connected). Connectivity of MM-Backs backbones is maintained in more than 90% of the simulation time, because of the longer lasting I_R links when nodes move. M-Backs is able to maintain the backbone connected only for 82% of the simulation time in sparser networks, and for 94% of the time in networks with $n = 500$. The reasons why MM-Backs backbones are sometimes disconnected (even when the flat network topology is connected) are the time it takes to a node to react to topology changes (it takes 6s to declare a link dead and take care of it), and, more rarely, to repeated collisions.

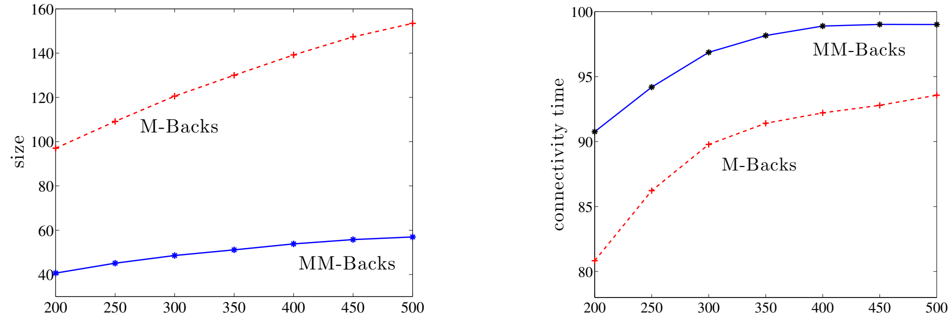
Figure 1(c) depicts the average backbone resilience, i.e., the average number of links that should fail in order to disconnect the backbone. MM-Backs backbone resilience ranges between an average of 170.42 links ($n = 200$) and 450.12 links ($n = 500$). M-Backs, instead, goes from an average of 63.98 backbone links in sparse networks to 291.1 links in the denser ones. The ratio between MM-Backs resilience and the M-Backs one ranges from 2.6 in smaller networks down to 1.54 in the larger ones, reflecting the larger number of 3-hop routes with respect to those 1 or 2 hops long that are needed to form M-Backs backbones in smaller networks than in larger ones. The robustness (i.e., the minimum number of link to be removed for disconnecting the backbone, not shown here) of MM-Backs backbones ranges approximately between 5.05 and 6.58. Less than two links are needed, on average, to disconnect a M-Backs backbone, whose robustness ranges between 1.21 and 1.77. In other words, MM-Backs is more robust to link failures, and needs the failure of over 5 (I_R) links to loose connectivity. M-Backs backbones, instead, are out of commission with just two (I_r) broken links.

MM-Backs backbone show superior results also for what concerns average route lengths. Routes are fairly short in MM-Backs. Their average length (in hops) ranges between 1.98 in networks with 200 nodes, and 1.95 in networks with 500, as depicted in Figure 1(d). Clearly, the shorter radius r used by M-Backs imposes longer routes: Their length averages always above 4 hops, independently of the network size. The reduction in route length enabled by MM-Backs is therefore always above 60%. As we show in the next section this has very notable consequences when routing is supported by MM-Backs backbones.

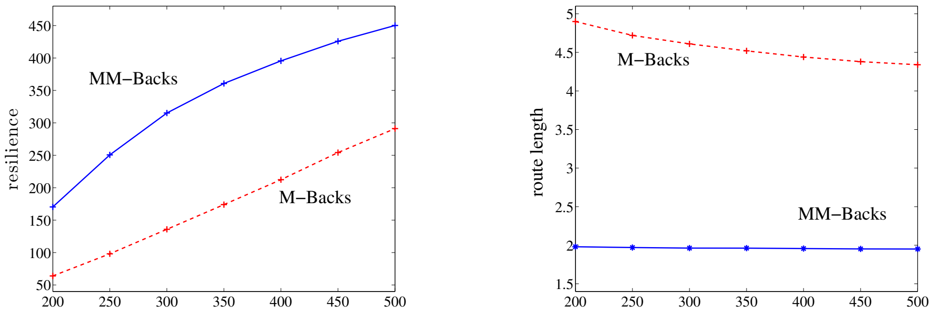
III. DISCUSSION AND FUTURE DIRECTIONS

MM-Backs is a protocol that by using a second radio achieves remarkable improvements over single-radio backbone protocols. The following considerations provide further insights and future directions on MM-Backs research.

Transmission radii relationship. MM-Backs backbones are connected if $R \geq 3r$. This is a sufficient condition to guarantee (at least from a theoretical, protocol design point of view) that if the flat network topology is connected, so is the backbone. The condition is not necessary, as verified by experiments (not shown here): Connected backbones can be obtained even when $r < R < 3r$, both in static and mobile scenarios. Future directions in this realm concern a more accurate analysis and experiments on backbone connectivity and routing support when the two radii exhibit different ratios, especially when $\frac{R}{r} < 3$.



(a) Size. (b) Connectivity.



(c) Resilience. (d) Route length.

Figure 1. Backbone metrics vs. increasing network size.

Challenging network parameters. Lack of space prevented us to show a more complete set of simulation results obtained by varying more than the network size. Our original set of experiments includes different node speeds (from 1m/s to 10m/s), different *HelloPeriod* duration (1 to 3 seconds) as well as different values of the time to declare a link dead. We also tried different values for the parameter α that regulates node movements according to the Gauss-Markov mobility model. The results reported here have been chosen in that they show, better than the others, the advantage of using multiple radios. Not all possible directions have been explored yet. Next steps include evaluating the sensitivity of MM-Backs (and M-Backs) to different mobility models, and the possible advantages (if any) of using a higher number of radio interfaces.

IV. CONCLUSIONS

We demonstrated the effectiveness of a multi-radio approach to backbone construction by comparing the performance of MM-Backs with its single-radio counterpart, M-Backs. Our experiments show that MM-Backs outperforms M-Backs in terms of backbone size, connectivity time, resilience to link breakage and route length.

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