Scaling MANETs using Long-Range Radios and Protocol Adaptation*

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***Abstract*— In this paper, we present a solution to the problem of scaling MANETs beyond 100 nodes, while providing service levels comparable to cellular networks. Flat MANETs are limited to about 100 nodes due to the high overhead of control traffic and the high inefficiency of multi-hop forwarding (Gupta-Kumar bound). Hierarchical (such as cellular) networks scale indefinitely, but do not provide uniform geographic coverage, and require pervasive infrastructure. Assuming a minimal infrastructure consisting of a fixed long-range radio, we have developed a networking system called MIANET that efficiently exploits the limited resources of this infrastructure. Specifically, MIANET drastically limits the control traffic overhead by (1) identifying "operating regimes" within the MANET that share common network and application requirements; and (2) tailoring data forwarding protocols based on the operating regime. Moreover, MIANET maximizes the benefits of fixed wireless radio by selecting to forward over this radio the data and control traffic requiring the most MANET resources (such as longest MANET paths). We have shown in emulation experiments that MIANET increases the maximum MANET size providing acceptable goodput from 100 to at least 500 nodes, compared to standard MANET forwarding using link-state routing or flooding.**

Keywords – MANET, Scaling, Fixed Wireless, network operating regime, protocol tailoring, hybrid networks, MIANET.

I. INTRODUCTION

Tactical networks rely on mobile ad-hoc networks (MANETs) where fixed infrastructure is unavailable. The proliferation of specialized MANET protocols adapted to particular operating conditions (with none of them scaling significantly beyond O(100) nodes for all conditions) suggests that no single MANET protocol can support a large-scale deployment without significant tailoring. There are three main obstacles to MANET scaling. First, large non-hierarchical networks require long average paths between nodes ($O(\sqrt{N})$ for 2D mesh networks with N nodes), and thus the average goodput in a MANET with uniformly distributed flows decreases as $O(1/\sqrt{N})$ (Gupta-Kumar bound).

Second, MANETs are unable to support the accumulated control signaling overhead that occurs in large dynamic networks (link state traffic grows as $O(NMF)$ per node, where M is the average number of neighbors per node, and F is the frequency of link state updates). When control signaling is intentionally scoped, imprecise data forwarding caused by the reduced signaling counters any achieved gains. A third problem is that network performance is highly dependent on user, topology, and operational conditions. No single or hybridized solution can accommodate the range of situations. Therefore, stable solutions are required that can efficiently incorporate multiple MANET algorithms and manage their use in appropriate operational regimes.

Cellular networks achieve unlimited scaling by using fixed wireless connected by wired infrastructure, and by limiting the wireless portion of end-to-end paths to only one or two hops. However, this solution is designed for serving concentrated populations, while tactical MANETs are required to cover large geographical areas. Adding a fixed wireless infrastructure with long range radios to MANETs can provide such coverage. But the limited capacity and limited geographic placement of such radios (unlike the ubiquitous cellular towers) eliminate the simple (cellular) solution of all traffic being serviced through the infrastructure. An efficient solution would combine MANET forwarding with selective use of the fixed wireless infrastructure, and with specific adaptation to network conditions and traffic characteristics.

In this paper, we present the principles, design and performance of the "Mobile Infrastructure-assisted Ad-hoc Network" (MIANET) system we developed to address the above challenges and provide MANET scaling to 500-5000 nodes. The MIANET architecture combines multiple data-sharing protocols, aligns their signaling to match local conditions, efficiently exploits fixed wireless infrastructure, and supports unicast and multicast on standard and legacy IP-based applications. Based on team research [M11], our central innovations (1) identify "operating regimes" within the MANET that share common network and application requirements; and (2) tailor protocol control signaling and data dissemination algorithms based on the operating regime.

We have demonstrated regime identification and quantified the initial performance gains obtained through protocol tailoring. Specifically, we developed local and global regime classification algorithms that efficiently distinguish between quasi-stable and dynamic network regions. Based on the classification, each node selects in real time the most efficient strategy for data forwarding that is effective in those network conditions. This approach significantly increases scalability over a "one size fits all" solution. Specifically, we demonstrated substantial gains with only a limited set of data forwarding strategies: stateful routing and stateless flooding. Using a 500-node EMANE-based wireless emulator, MIANET tailoring of forwarding strategies demonstrated 3x gains over any single homogenous forwarding strategy. Moreover, adding fixed infrastructure demonstrated 2x additional performance gain by reducing control-signaling overhead for the MANET radios. An additional 2x to 4x throughput gain was observed when long-range selective data forwarding over a fixed wireless radio is introduced.

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Many MANET algorithms have been proposed over the past two decades [A02][A05][A09], aiming to reduce control traffic in mobile networks with limited capacity. Flooding algorithms use no control state, but are very inefficient in large networks. Multi-path forwarding provides partially redundant transmission that mitigates losses due to inaccurate forwarding in fast-changing MANET topology. In our recent work [F10], [F12-1], [F12-2], we have developed integrated routing-transport systems (CONCERTO, BRAVO) based on the concept of network coding and multi-path forwarding that showed several-fold gains in goodput compared with a standard OLSR/SMF/NORM systems in networks up to 35 mobile nodes. [D12] combines OSPF single-path routing with localized flooding in areas of high mobility. Their results showed that adapting the protocol to the changing network can provide performance gains in 30-node networks. None of the above systems scaled beyond 100 nodes in highly mobile networks, and did not consider the addition of long-range radios.

Hybrid networks combining MANETs with additional fixed infrastructure were considered in [D02], [L03], [T04], [Z05]. These efforts assume a single flat, connected MANET and do not consider control plane overhead, which has been shown to be costly and to significantly impact data plane performance in stateful protocols [P00], [A04], [T10]. MIANET exploits infrastructure links for data plane transfers, but does so in a unified utility-based framework that includes signaling and control overhead, and the need to bridge to nodes that would otherwise be disconnected without infrastructure use. The use of infrastructure to partition a large MANET into a set of interconnected (by infrastructure) smaller MANETs, also has advantages in the control plane. Link state broadcast and other network-wide services (e.g., name translation and content-location) are locally scoped to the individual MANET, when they are then served using infrastructure. This avoids full MANET-wide broadcast that is known to cause scaling problems [A04]. Approaches such as Fisheye routing [P00], [A04] mitigate this problem for routing state, but still perform MANET-wide link-state broadcasts for each node (at lower rates) and cannot be used for additional network services such as content location. MIANET's use of infrastructure links for control traffic reaps the additional advantage of having a quasi-centralized network view for operating regime identification [M11] and consistent routing [J08].

In the next section, we detail our approach based on network regime identification, protocol tailoring and selective use of fixed, long-range radio, and outline the architecture and design of the MIANET system. Section III introduces the performance evaluation framework based on network emulation, and in Section V we present and analyze a representative set of our results. Section VI concludes with a summary and future work.

II. The MIANET Approach

The MIANET system aims to address the three main problems with scaling MANETs discussed earlier. The fixed wireless infrastructure can mitigate the inefficiency of long MANET paths and the routing control overhead, but using it to relay all traffic is not possible, given its limited capacity. Later in this section, we describe how MIANET selects the data and control traffic with the highest utility to forward over the fixed wireless radio.

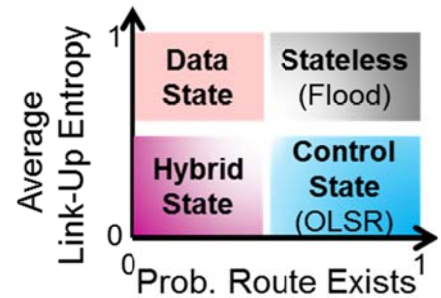

Figure 1: Network state strategies best suited for various network conditions.

While MANETs exhibit high variations in user, topology, and operational conditions, significant performance gains can be achieved if forwarding strategies are adapted to such conditions. This observation is based on our team's recent research [M11] that categorized the performance of stateful and stateless ad-hoc protocols in various network conditions (Figure 1, adapted from [M11]). When links change frequently, link-state signaling (e.g., in OLSR) can overwhelm the network, resulting in poor data plane performance [A04]. Hence, flooding (shown in the higher right quadrant of Figure 1) is attractive. Conversely, when paths are stable, stateful MANET routing incurs relatively low overhead and delivers data more efficiently than flooding. For this reason, stateful routing (e.g., OLSR) is preferred.

The above observations were drawn from characterization of entire networks and from performance analysis of each protocol controlling that network. A principal MIANET innovation is to use multiple protocols simultaneously, each active in different parts of a network. Specifically, MIANET (1) identifies the operating regime of each network region, (2) maps each regime to a particular forwarding protocol, and (3) activates that protocol in the corresponding network region. Thus, MIANET uses the most efficient protocol for each network region, providing an average network goodput higher than any single protocol controlling the entire network, as we show in Section V.

In the first phase of MIANET design, we have focused on adapting the local forwarding protocol to the frequency of change of local topology. Specifically, we have defined the following *Dynamicity* metric to characterize the degree of change of a node's links at a given time:

$$Dynamicity(node\ i, time\ t) = \frac{\sum_j LQ_{i,j}(t)}{\sum_j 1_{LQ_{i,j}>0\ at\ t-1}}$$

where $LQ_{i,j}(t)$ is the link quality measured between nodes *i* and its neighbor *j* at time *t*.

The MIANET network classifier is a distributed algorithm, executed in each node. It gets its $LQ_{i,j}(t)$ inputs from measurements performed by an OLSR instance running at that node. Given that OLSR reports link quality as a moving average of instant measurements (effectively a time integral), the MIANET algorithm compensates by using the time derivative of the local Dynamicity:

$\partial\, Dynamicity(n,t)/\partial t > \tau$ ➔ n's neighborhood is *dynamic*,

where τ is a threshold depending on the frequency of link state measurements. For nodes classified as *dynamic*, MIANET assigns a flood forwarding strategy, otherwise it activates forwarding using routing (shortest path). This hybrid strategy enables MIANET to provide network-wide connectivity with a low rate of link-state updates. This low frequency is sufficient for accurate routing in non-dynamic regions, while flooding in dynamic regions avoids losses from incorrect paths. MIANET uses the typical update frequency of once every 5 seconds, which generates approximately 80Kb/s of control traffic in a network of 5000 nodes, with an average neighborhood size of 4 links per node (the typical size of link state information is 12 Bytes per link). This level of control traffic is less than 1% capacity of typical MANET radios, and thus not an issue for MANET scaling.

Mixing routing and flood forwarding in the same network presents practical issues, solved in MIANET as shown in Figure 2. We use the OLSR extensible framework for combining routing and flooding in the same system and using OLSR's link quality calculations as inputs to the MIANET classifier. Once the classification decision is made, one of the forwarding strategy is activated and the data path is directed to that module. Shortest path routing is native to OLSR, while flooding is performed by the BMF (Basic Multicast Forwarding) plugin. We use BMF's mechanism for duplicate packet detection and suppression even when routing is active, since duplicate packets can come from neighbors using flooding.

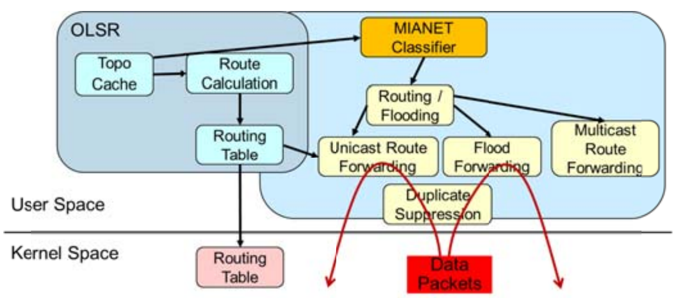

Figure 2: MIANET design of hybrid forwarding using the OLSR plugin framework.

The multitude of applications hosted in large MANETs (100-5000 nodes) requires service that can amount to 100Mb/s to 10Gb/s of user goodput. Forwarding all this traffic over the fixed wireless (cellular strategy) that has a typical capacity of 10-50Mb/s is not an option. The hybrid strategy adopted in MIANET is to forward only the highest-cost flows (longest hop paths using the most network Tx per delivered packet) over the fixed radio node, leaving the short-path flows forwarded in MANET. This strategy maximizes the efficiency of MANET forwarding, as measured by the total transmissions per packet delivered, averaged over all MANET traffic.

The mechanisms used in MIANET to selectively forward data and control traffic over fixed wireless are shown in Figure 3.

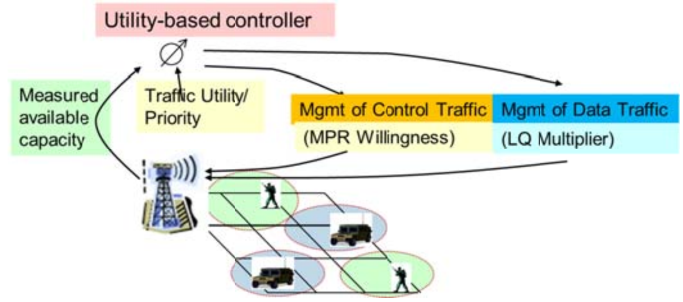

Figure 3: Design of MIANET traffic control over the fixed wireless radio.

The OLSR default behavior (shortest-path routing) is to pass all flows through the fixed wireless node since in this case all paths have two hops. In order to have only long-path flows routed over fixed wireless, MIANET increases the cost of the fixed wireless links by lowering their LQ. This is achieved by setting the *LQmultiplier* parameter (available in OLSR configuration) to a value smaller than 1. For example, a value of 0.3 makes flows having MANET paths shorter than 10 hops avoid the fixed wireless node. A real-time adaptive mechanism under development uses a feedback controller that measures the available capacity of fixed wireless node and adjusts its links' LQ multiplier with the goal of achieving a fixed wireless utilization of a given level (80% in our case). As in any control system, stability is an issue to be considered, and we are designing a PID controller to address it.

Control traffic (OLSR Topology Control [TC] messages containing link state updates) can also be steered to be forwarded through fixed wireless. This strategy increases overall network efficiency if the fixed radio has some broadcast capability. For example, in a network with *N* nodes, *M* neighbors per node and *F* link state updates per second, in a pure MANET (without fixed infrastructure), each node gets at least *NMF* bits/s and transmits the same, for a total of *2NMF* per node. If fixed wireless gets all link state updates and relays to all nodes via omni broadcast, then each node gets the same *NMF*, but only transmits *MF* bits/s, for a total of *(N+1)MF*, a significant savings compared to above. If the fixed radio is directional with a certain beamwidth, it needs *S* (=360°/beamwidth) transmissions to broadcast to all nodes. Still, each MANET node only requires *(N+1)MF* load, since only one (out of *S*) directional Tx occupies its channel. Another benefit of using the fixed radio to broadcast control messages occurs in MANETs using CDMA radios with uncoordinated Tx schedules, where losses due to hidden terminal collisions are common. In this case, the short (two-hop) dissemination of link state is much more efficient than multi-hop flooding.

In MIANET we assume that the fixed radio has both directional and omni Tx capability, and thus, steering control traffic through the fixed wireless is beneficial. MIANET achieves this (Figure 3) by adjusting the OLSR's MPR (Multi Point Relay) willingness parameter to a high value (for example the maximum value 7). The effect is that all OLSR in all other MANET nodes will direct the flooding of the TC messages to the MPR with the highest willingness, namely the fixed wireless node.

III. EVALUATION FRAMEWORK

In the rest of this paper, we present an experimental evaluation of the MIANET system in several configurations with an increasing feature set, compare it with single-protocol forwarding, and show its scalability in a set of mobile network scenarios with sizes from 100 to 500 nodes.

A. *Emulation System*

We performed our experiments in an emulated wireless mobile network (Figure 4) consisting of Extendable Mobile Ad-hoc Emulator [EMANE] distributed wireless emulation software running in a set of Linux-based platforms connected with high-speed LAN. Each mobile node has a MANET radio using 802.11 configured in peer mode (without a base station) and using local broadcast (RTS/CTS disabled), and a radio connected to the fixed wireless station. Various MANET scenarios are realized through a set of pathloss files that describe radio propagation characteristics between any two nodes as function of time.

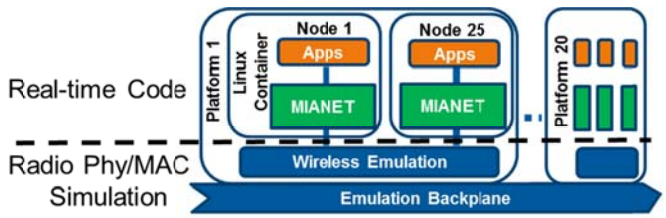

Figure 4: Emulation system for MIANET performance

In order to scale our experiments to 500-node networks, we configured our emulation with 25 nodes per platform. Each node's software (including MIANET routing, forwarding, and applications) runs in a Linux container, thus enabling separate routing tables without the use of heavy-weight virtual machines. We also customized the EMANE Over The Air (OTA) wireless packet processing module to not transmit packets from a node outside its platform, if all the nodes that can receive a node's signal are emulated inside that platform. This improved EMANE's capacity to simulate wireless traffic by 5x.

B. *Scenarios*

We have generated a set of mobile network scenarios, where regions of stable topology alternate with regions of high mobility. For example, in Figure 5, we show a network of 100 nodes, where two 5x5 grids are static and the other two are mobile. In the same figure, we show MIANET's characterization of each node: nodes classified *dynamic* are in red. We observe that some static nodes (neighboring mobile nodes) are classified as dynamic, which is correct, since dynamicity is a property characterizing a node's links, and not its movement.

We performed emulation experiments with a range of network sizes (100, 225, 400 and 500 nodes) having a number of flows proportional to their respective size. Figure 6 shows the topology of a 500-node network with static and mobile regions and the distribution of application flows, including both short- and long-MANET routes, and traversing both static and mobile regions. Neighbor nodes are at an average distance of 50m and mobile nodes have an average speed of 70Km/h.

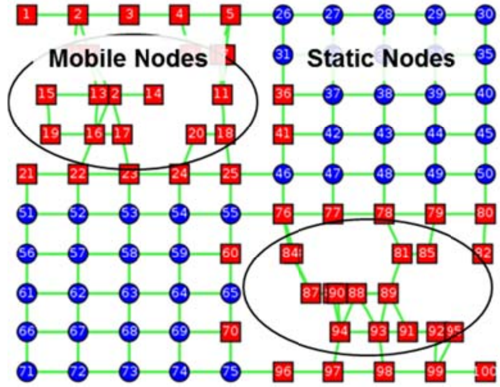

Figure 5: 100-node network with diverse mobility and traffic

Each node has a 802.11 radio at 11Mb/s and 60m range, and the fixed wireless has a capacity of 20Mb/s and 20Km range. Data traffic is composed of 16 video flows between nodes uniformly distributed in the network. Of this, 12 flows are "short," with average source-destination distance of 280m and 8 MANET hops, and 4 flows are "long," with average path length of 1100m and 30 hops.

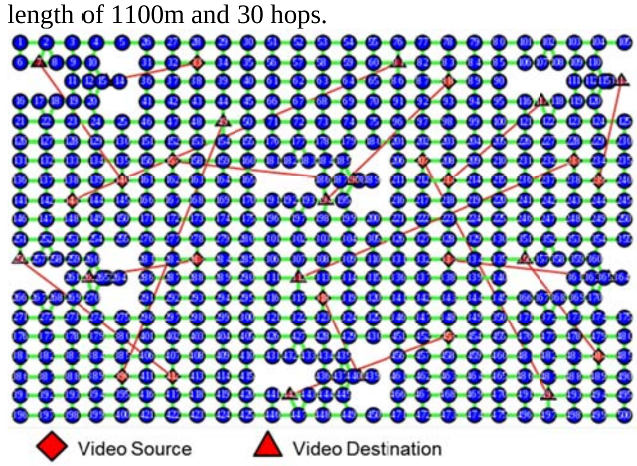

Figure 6: 500-node network with diverse mobility and traffic

IV. RESULTS AND ANALYSIS

In the following, we show the performance of MIANET servicing the flows in the above scenarios, compared with uniform, single-protocol configurations. First, in the network of 100 nodes (Figure 5) with 4 short and 2 long UDP flows, we configured the same protocol (routing or flooding) throughout the network. All flows had the same send rate, varied between experiments from 8 to 80Kb/s (X axis in Figure 7). We measured the received rate and plotted on the Y axis the average goodput ratio (received/send) over all flows and duration of experiment.

First, we observe that OLSR routing has the lowest performance, due to the high frequency of link changes in the dynamic regions, producing incorrect routes for link state update interval of 5 seconds. Flooding provides high goodput at low-flow rates (8 and 16Kb/s) since packets are transmitted over any existing path. As expected, flooding performance drops rapidly for higher flow rates, as the network is saturated by the aggregate flooding transmissions.

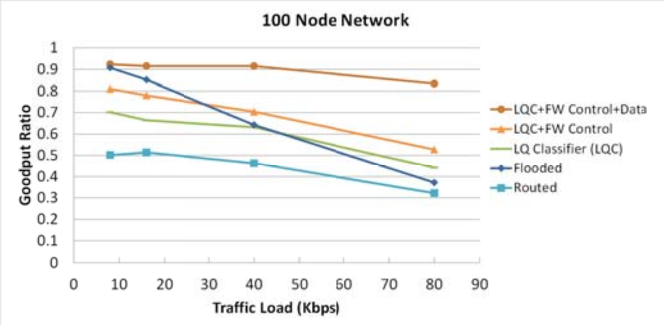

Figure 7: Performance of MIANET and homogeneous protocol deployment in 100-node network.

MIANET, using the network classifier and protocol selection ("LQ classfier" in Figure 7), is able to provide a goodput ratio higher than routing because using flooding in the dynamic zones avoids losses from incorrect routes. Still, flooding is better at low rates, as it avoids all possible losses from incidental route changes at dynamic zone boundaries. MIANET is more efficient at high flow rates, by using routing in the static regions.

When we added control forwarding over fixed wireless to the MIANET classifier ("LQC+FW Control" in Figure 7), the performance increased for all flow rates, as some MANET resources were freed. Still, performance deteriorates at high rates mainly because the long flows take significant MANET bandwidth along many hops, and they are more likely to lose packets from collisions over the high number of hops. These problems are addressed by further adding selective forwarding of long flows over fixed wireless ("LQC+FW Control+Data"), and MIANET achieves acceptable goodput ratio for all flow rates.

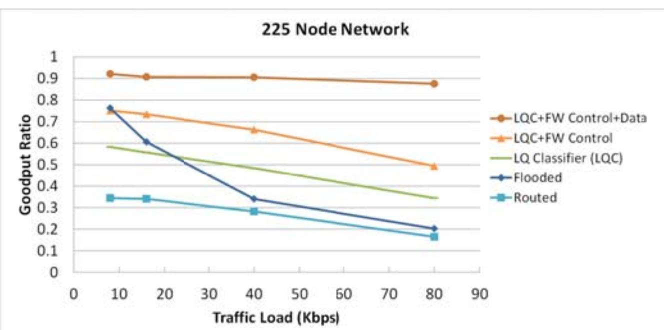

Figure 8: Performance of MIANET and homogeneous protocol deployment in 225-node network.

Our 225 node scenario was based on a 15x15 grid with three mobile regions, 6 short and 3 long flows, with the same send rates and similar path lengths as above. In Figure 9 we show the average goodput ratio achieved by single-protocol configurations and MIANET. We observe similar trends as in the 100-node network scenario, but the MIANET advantage is increased. The routing performance has decreased due to the increased control traffic in the larger network. Flooding performance has decreased as well, given that an aggregate of more flows contend to the same radio capacity at each node. MIANET using only network classifier and protocol selection ("LQ classifier" line) provides almost the same goodput as in the smaller network, because flooding traffic is isolated to each dynamic region and thus does not compound to a network-wide larger load. The small performance degradation is due to the higher control overhead (link state updates) in the larger network. Therefore, moving control traffic to the fixed wireless ("LQC+FW Control") results in average goodput close to the 100-node case. Similarly, routing the long flows over fixed wireless ("LQC+FW Control+Data") provides near-optimal goodput, since the aggregate of the long flows is within the fixed wireless capacity, and the short flows are well served by the regional flooding.

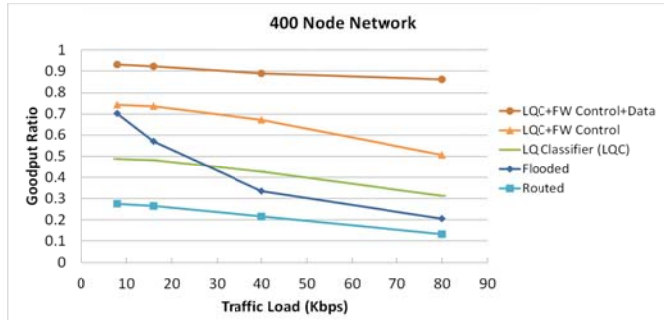

Figure 9: Performance of MIANET and homogeneous protocol deployment in 400-node network.

In the 400-node scenario (20x20 nodes, 4 mobile regions, 8 short flows, 4 long flows), we observe a continuation of the above trends. Homogeneous routing or flooding provide very low goodput given the large overhead of control traffic or the large aggregate of all flows flooding the entire network. MIANET continues to provide almost the same average goodput as for the smaller networks, and the benefit of the single fixed long-range radio continues to apply to this larger network.

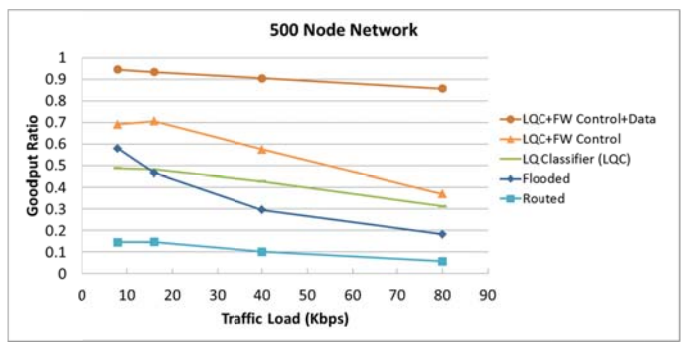

Figure 10: Performance of MIANET and homogeneous protocol deployment in 500-node network.

In the 500-node network (25x20 nodes, 6 mobile regions, 12 short flows, 4 long flows), we observe the highest MINAET benefit (Figure 10). Homogeneous routing or flooding continue to degrade in performance compared to 400-node case, given their increasingly high overhead of control or aggregate flooding traffic. On the other hand, MIANET's assignment of protocols to regional conditions ensures average goodput almost unchanged from the 400-node case. Adding routing control over fixed wireless frees significant MANET resources, again providing high average goodput similar to the 400-node case. Routing the long flows over fixed wireless ensures high-transport success probability by avoiding collision loss over paths with a large number of hops.

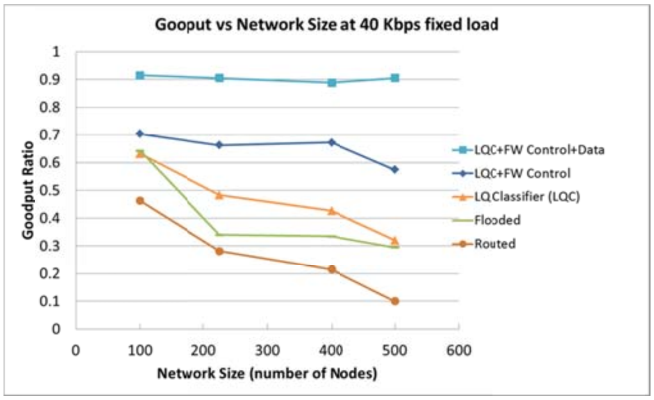

Figure 11: MIANET provides MANET scaling to 500 node networks

In Figure 11, we show a consolidated set of results across all network sizes, for the same traffic rate per flow of 40Kb/s. We observe MIANET with protocol selection ("LQ classifier") outperforming both homogeneous routing and homogeneous flooding. Combining this with selective routing of control and long-path data traffic over fixed wireless provides MANET scalability to 500 nodes and possibly beyond.

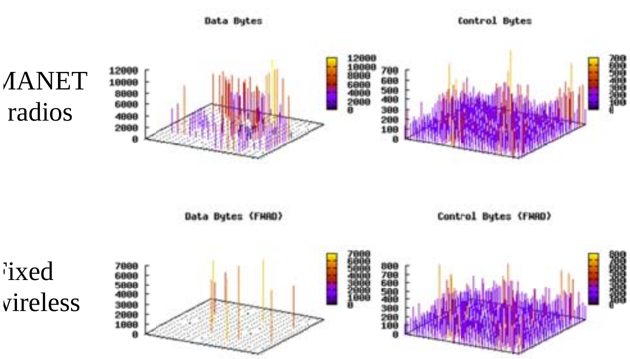

Figure 12: Sample of traffic distribution for MIANET in "LQC+FW Control+Data" configuration, 500 node network

In Figure 12, we show histograms of traffic samples (Bytes/s) per node, in the 500-node network. We observe that data traffic is using MANET radios at relatively low rates, and is concentrated around the dynamic zones that use regional flooding. Data traffic is using fixed wireless sparingly, in the few nodes that are source/destination of long flows. Control traffic is also at relatively low rate (200 to 600Bytes/s) and equally distributed between MANET and fixed wireless. The MANET radios distribute local information (local link quality in TC messages and link probes in Hello messages) between neighbors. The transmissions to the fixed wireless communicate the same local information, and thus have a similar low rate. Only the transmission to all nodes from the fixed wireless node (not shown in this Figure) has a higher rate (approximately 200KB/s), as it broadcasts the aggregate link state updates from all 500 nodes.

V. CONCLUSION

In this paper, we presented our approach to scaling MANETs beyond 100 nodes by adapting forwarding protocols to local network conditions, and by adding modest fixed-wireless infrastructure. We have shown that local, distributed network classification and protocol selection is a much more efficient method for data forwarding in large networks than homogeneous routing or flooding, and its performance advantage increases with network size. In addition, by introducing a single long-range radio with modest capacity further improves data forwarding. Specifically, if control traffic is routed over fixed wireless, it enables network-wide connectivity with no MANET overhead, while consuming approximately 1.6Mb/s of its bandwidth. Selected data traffic with long-hop MANET paths further benefit from fixed wireless by receiving near-optimal goodput while saving MANET resources capable of serving many more local flows.

Based on our analysis we expect additional performance gains when using finer-grain protocol decisions. For example, per-flow type forwarding decision can extract more efficiencies than topology-based classification. Flows with multiple destinations (multicast) in a region can benefit more from flooding than unicast flows. Locality of content interest can be exploited for reducing wasteful downloads. We will explore these refined MANET scaling methods in a future work.

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