Designing Ad Hoc Networks with Limited Infrastructure Support

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Abstract—**Ad hoc networks based on IEEE 802.11 (Wi-Fi) wireless links are viable for small regions with a few tens of mobile nodes, but such networks suffer from frequently broken routes and low network utilization. We investigate the benefits of adding a few infrastructure nodes to an otherwise ad hoc network to improve its performance. These infrastructure nodes are interconnected among themselves with point-to-point (p2p) links in addition to Wi-Fi capability. To evaluate the benefit of ad hoc networks with mixed broadcast wireless and point to point links, we modify an existing ad hoc routing protocol to automatically discover routes emphasizing p2p links and simulated several ad hoc and mixed networks using the Glomosim simulator. Our results show that adding a small number of point-to-point links makes a significant difference in performance with 2-3 times higher throughput and up to 2-3 times lower packet delays.**

Keywords. Ad-Hoc and Sensor Networks, Network Protocols, Wireless Networks.

I. Introduction

A mobile ad hoc network (MANET) is a collection of wireless mobile nodes dynamically forming a temporary network without the use of any existing network infrastructure or centralized administration. A MANET consists of mostly homogeneous wireless links, based on a standard medium access control (MAC) standard such as IEEE 802.11 [6]. Owing to the limited radio propagation range of the wireless devices used, messages among non-neighbor nodes go through multiple intermediate nodes to reach destinations.

Because of the multi-hop communication even for short geographical distances (say, 1 km) and random movement of mobile nodes, applications of ad hoc wireless networks are mainly restricted to small wireless *islands*, which can be useful for military or limited intranet applications. Even with a few tens of nodes, ad hoc networks have low network performance [3], [4], [5]. Without the reliability comparable to that of a wired network, and access to the Internet, these ad hoc networks are not useful for general purpose networking.

We believe that ad hoc networks with mixed point-to-point (p2p) and wireless links are suitable as medium range networks spanning, for example, a metropolitan area. Such mixed networks will have two types of nodes: fixed or relatively stationary infrastructure nodes with wireless capability and p2p links among them, and mobile wireless nodes, which denote users. These networks can take advantage of the higher reliability and bandwidth of p2p links as well as the flexibility and low-cost of wireless links using ad hoc networking concepts. Because these networks make use of ad hoc networking, there is no need for fixed nodes to cover all the desired area with wireless links. When a fixed node is not available, a mobile node can send its data through other mobile nodes to the destination or to the nearest fixed node. An example mixed network is shown in Figure 1. Even in this small network, infrastructure nodes with p2p links will significantly improve the routing distances and reliability of communication among user nodes.

With the advent of new technologies, it is feasible to design the proposed mixed networks. The IEEE 802.11 has already been a popular MAC protocol for ad hoc wireless networks. The 802.11 is a short haul (for distances less than 376m) wireless link protocol. The fixed infrastructure nodes and p2p links among them are not difficult to set up. The p2p links can be wired links or long haul wireless links. For example, the new IEEE 802.16 [7] and soon to be standardized IEEE 802.20 [8] are examples of long haul (for distances less than 50 Km) wireless link protocols. The infrastructure nodes can be already existing fixed nodes connected via p2p links (for example, access points connected to the Internet) or semi-permanent nodes that remain stationary for a few hours and have p2p links implemented via a different wireless technology. More importantly, elaborate design and implementation to ensure complete geographical coverage by fixed nodes is not necessary, since gaps in the coverage can be managed using ad hoc networking provided there is enough node density. Recently, a few researchers have started investigating the benefits

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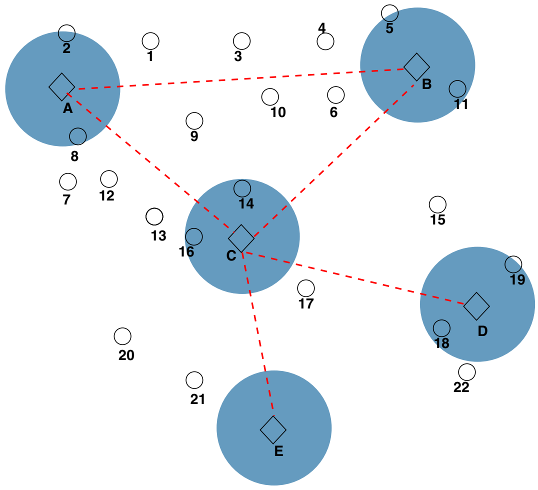

Fig. 1. A mixed network with mobile user and fixed infrastructure nodes, denoted by circles and diamonds, respectively. The infrastructure nodes are interconnected by point-to-point wired links, denoted by dashed lines, for infrastructure support and to provide multiple paths. All nodes are capable of using a common wireless technology, such as 802.11; the radio range of infrastructure nodes is indicated by a circular shaded region. A network of this type can provide multiple paths among user nodes. For example, node 8 in the upper left portion of the network can go through 12, and 13 or A and C to reach node 16. Ad hoc routing is used in cases when a user node is not near an infrastructure node. For example, node 10 can reach node 4 via node 6.

of mixed networks [2], [11], [12].

In this paper, we are interested in designing a suitable routing protocol for mixed networks and exploring the performance benefits of p2p links in ad hoc networks. We simulated and evaluated the performances of 60- and 1000-node ad hoc and mixed networks. Our results indicate that mixed networks provide significantly better throughput and packet delays. With a few p2p links added to an otherwise ad hoc network, the throughput can be doubled or tripled even when p2p links have low bandwidth.

The rest of the paper is organized as follows. Section II describes a routing protocol suitable for both ad hoc networks and mixed networks. Section III presents simulation analysis of mixed networks and ADVS. Section IV concludes the paper.

II. Routing in Mixed Networks

Several current Internet/intranet routing algorithms for Internet such as Routing Information Protocol (RIP) [9], Open Shortest Path First (OSPF) [13] do not work well for wireless networks, while the Ad hoc On demand Distance Vector (AODV) [14], Dynamic Source Routing (DSR) [10] and Adaptive Distance Vector (ADV) [3] focus only in ad hoc wireless networks and do not take advantage of p2p links.

In this section, we describe a new routing protocol for the mixed network with both wired and wireless capability, called ADV Static (ADVS). ADVS is based on the Adaptive Distance Vector (ADV) [3]. ADVS behaves like ADV for ad hoc wireless networks, but can utilize the p2p links to improve throughput and routing stability. We use p2p links and wired links synonymously for easier description of the protocol.

Adaptive Distance Vector

The Adaptive Distance Vector (ADV) is a combination of proactive and on-demand techniques. ADV shows proactive characteristics by disseminating routing information among all neighbor nodes using triggered or periodic updates like in a distance vector routing protocol. It varies the frequency and the size of the routing updates according to the network conditions.

Unlike typical distance vector (DV) protocols which advertise and maintain routes for all nodes in the network, ADV maintains routes to only active receivers to reduce the number of entries advertised. A node is an active receiver if it is the receiver of any currently active connection. At the beginning of a new connection, the source broadcasts (floods) network-wide with an InitConnection advertising that its destination node is an active receiver. A node that receives InitConnection packet marks the target of InitConnection as active receiver and start advertising the routes to the receiver in future updates. The destination node, upon receiving the InitConnection packet, responds, if it is not marked as an active receiver already, by broadcasting network-wide with a ReceiverAlert packet. A similar flooding mechanism is used by pure on demand routing protocols such as AODV and DSR. The main difference is ADV uses it only once for each new receiver.

The feature that makes ADV proactive is it refreshes routes using periodic and triggered updates as in other distance vector protocols. However, ADV adaptively triggers partial and full updates such that periodic full updates are obviated. With ADV, a node may trigger an update for three primary reasons: (a) if it has some buffered data packets due to lack of routes, (b) if one or more of its neighbors make a request for fresh routes, and (c) it is a forwarding node and received a fresher route to destination. The impact of each events that requires a triggered update is quantified and captured in a variable called trigger meter. ADV adjusts the trigger meter based on the value of several other parameters associated with the three conditions mentioned above. The trigger meter is reset to zero after scheduling any update. A trigger threshold is used to decide when an update needs to be triggered. This trigger threshold is changed dynamically based on the recent history of trigger meter values at the time of previous partial updates. To avoid too frequent triggered updates, a limit of 2 updates/second is imposed. This plays a crucial role in limiting the control overhead.

ADV Static (ADVS) Routing Algorithm

ADVS is an enhanced version of the ad hoc network routing protocol ADV described above. So, ADVS uses InitConnection and ReceiveAlert to learn new routes and routing Updates to disseminate and maintain routes. The difference is the additional logic to take advantage of wired links among fixed nodes. In ADVS, these control packets are broadcasted via wireless interface to inform wireless neighbors and unicasted via wired interfaces (if it is a fixed node) to inform all wired neighbors. ADVS routes the data packets the same way as ADV does.

To promote the use of wired links in discovering and maintaining routes, we assign costs to wireless and wired links. Wired links have a cost of 1 and wireless links r, $r > 1$. The cost of a route is the sum of costs of all links used in the route. Routes with lower costs are preferred. By varying r, we can easily change the characteristics of routes selected.

Preferring wired links in route selection

When there is a choice, ADV selects routes with higher sequence number and lower cost (among routes with the same sequence number). ADVS uses an additional criterion: among the routes with the same sequence number and cost, the route with higher wired link count is selected since that such a route is likely to be more stable. By preferring routes via wired links, ADVS can improve stability of routes significantly. So InitConnection and ReceiverAlert control packets keep track of the number of wired links traversed. In addition, the number of wired links in a route are kept for each route indicated in the routing table.

III. Performance Analysis

We used the Glomosim simulator, version 2.03 [1] for performance analysis of ADVS and mixed networks.

Node Mobility Model. The Glomosim simulator has a built-in random node mobility model called random waypoint (RWP). The RWP model is used extensively in ad hoc network simulations [4]. We modified the mobility model slightly to let nodes wrap around and reenter the field from opposite side when they reach an edge of the field. This avoid the clustering in the middle effect observed for RWP [15]. Node speeds are chosen to vary uniformly between 1 m/s and 29 m/s. We use 0-second pause time, which corresponds to continuous motion.

Types of Networks. We simulated ad hoc and mixed networks with 60 nodes in a 1.5×1.5 Km^2 field and 1000 nodes in a 6×6 Km^2 field. For the small mixed networks, we used 4 or 9 fixed nodes arranged in a square grid pattern in the middle of the field with a distance of 750 m or 500 m, respectively, between adjacent fixed nodes. For the large mixed networks, we used a grid of 9 or 25 fixed nodes with a distance of 2 Km or 1.2 Km, respectively. Adjacent pairs of fixed nodes have a p2p link between them. For pure ad hoc networks, all nodes are mobile. All nodes have wireless capability.

We modified the Glomosim simulator so that a specified list of stationary nodes can be placed at predetermined locations, while the remaining nodes are placed randomly in the field with the specified mobility model.

Types of Links. We used two types of links for simulations: single rate 802.11 wireless links with 2 Mb/s bandwidth (BW) and 376 m radio range, and p2p full-duplex wired links with 2 Mb/s BW and 2.5 μsec. We limited the BW of wired links to 2 Mb/s to show that even with such low BW, mixed networks can outperform ad hoc wireless networks significantly. We also used 6 Mb/s p2p links for one mixed network for comparison purposes. For route selection purposes, we set the wired link to wireless link ratio, r, to 10.

Traffic Models. We used UDP traffic generated by 25 constant bit rate (CBR) connections among 50 mobile nodes. We vary the network load by varying the packet rates of the CBR connections. The packet size is fixed at 512 bytes.

For each data point, 5-10 600-second simulations with different initial placement of nodes is run and results are averaged to minimize the impact of a particularly bad or good scenario.

Routing Protocols. We implemented ADVS in Glomosim. We used ADVS for all types of networks. For ad hoc wireless networks, ADVS is the same as ADV. In addition, we also simulated an compared AODV routing protocol for ad hoc wireless networks (distributed with Glomosim code) to illustrate that the results obtained with ADV are representative of the performance achievable in wireless ad hoc networks.

Metrics and Parameters. We use throughput, average packet latency, and routing overhead over wireless links to evaluate the routing protocols and networks.

A. Small Networks

Figure 2 gives the throughputs and packet latencies of various networks. ADVS4F and ADVS9F denote ADVS routing protocol in a 60-node network with 4 and 9 fixed nodes, respectively. The performances of ADV and AODV in ad hoc networks are denoted by their names. The maximum throughput achieved with ad hoc wireless networks is 339 Kb/s and with mixed networks 705 Kb/s, twice as much. It is interesting to note that increasing the number of fixed nodes does not improve the performance significantly. Since four nodes are sufficient to cover most of the simulated field, increasing the number of fixed nodes is not beneficial. We also simulated the four-fixed node case with 6 Mb/s p2p links. The performance is virtually identical to the 2 Mbps links case presented here. The performance of mixed networks is limited the Wi-Fi channels around the fixed nodes.

B. Large Networks

To explore the benefits of mixed networks further, we evaluated large mixed and ad hoc networks with 1000 nodes in 36 Km^2 square field. ADVS25F denotes ADVS routing protocol in a 1000-node network with 25 fixed nodes and ADVS9F 9 fixed nodes. ADV and AODV are used to denote ADV and AODV routing protocols in networks with 1000 mobile nodes.

Figure 3 give the CBR traffic throughputs of ADVS25F, ADVS9F, ADV and AODV. The maximum throughput achieved with ad hoc wireless networks is 835 Kb/s by ADV. In the mixed network, the maximum throughput with 9 fixed nodes is 1359 Kb/s, 63% higher, and with 25 fixed nodes 2421 Kb/s, 190% higher. It is noteworthy that even though the wired link bandwidth is 2 Mb/s, adding 40 p2p links among 25 fixed nodes nearly triples the throughput.

Even more illustrative are the delivery rates in mixed and ad hoc networks given in Figure 4. For the ad hoc network, ADV is able to perform adequately, achieving 70% or higher delivery rates prior to saturation. AODV does not perform well and saturates much more quickly with a peak throughput of 608 Kbps. Even at low loads, its delivery rate is less than 56%. Mixed networks, however, achieve 90-95% peak delivery rates which indicate substantially higher reliability of routes.

Figure 5 gives average packet delays prior to saturation by ad hoc networks. At low to moderate loads (less than 150 Kbps), all networks have comparable delays. For moderate loads, which do not congest the networks, mixed networks provide lower latencies. As the load increases beyond 500 Kbps (not shown), the wireless networks saturate and packet delays grow rapidly. Since mixed networks saturate at much higher loads, their packet latencies do not grow as fast as those in ad hoc networks. For interactive applications such as voice over IP or online gaming, mixed networks are more suitable than pure ad hoc networks.

To understand the reasons for this increase in performance, we examined the number of wireless hops taken by data packets (see Figure 6). Let us consider the performance when the offered load is 2000 Kb/s. The mixed network with 9 fixed nodes delivers a throughput of 1315 Kb/s with an average of 6.9 wireless hops per delivered data packet. In contrast, the ad hoc network with no fixed nodes delivers a throughput of 778 Kb/s with an average of 9.4 hops (all hops are wireless in this network) per delivered data packet. So $\frac{9.4-6.9}{9.4}$ = 28% of the wireless hops are saved by adding 12 extra wired links. This accounts for some of the 57% throughput increase we observed.

The rest of the improvement in throughput with p2p links is due to two factors: (a) reduced interference to transmissions on wireless channels due to reduced wireless link usage; (b) fewer broken routes and more stable routes due to the use of p2p links as much as possible. To show that using p2p links in mixed networks reduces interference on wireless channels significantly, we examined the network allocation vector (NAV) at the MAC layer [6]. This NAV indicates the duration wireless channel is reserved at any instant of time; smaller NAV means reduced contention. We sampled NAV each time MAC protocol needs to transmit a packet and calculated the average NAV. Figure 7 presents the average NAV observed for various protocols and networks. The average NAV is indicative of performance before the network is saturated. Based on this, we see that the average NAV for mixed network is about 50% smaller than that of the wireless networks. To examine the second factor, we calculated the rate of route breaks in each type of network. The rate of broken routes is shown in Figure 8. Mixed networks have much fewer broken routes than the ad hoc network. It is particularly interesting to compare ADV (for ad hoc network) and ADVS (for mixed net-

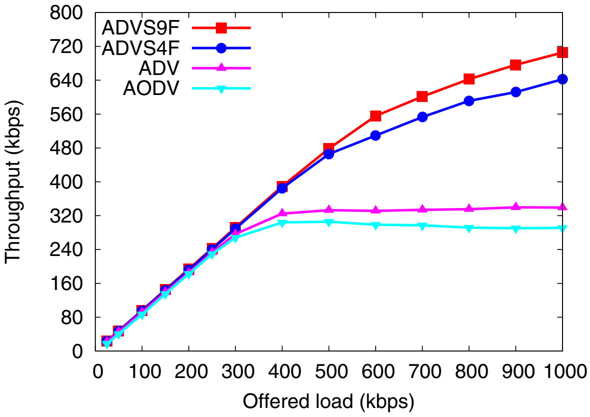

Fig. 2. Throughputs achieved for CBR traffic on 60-node mixed and ad hoc networks.

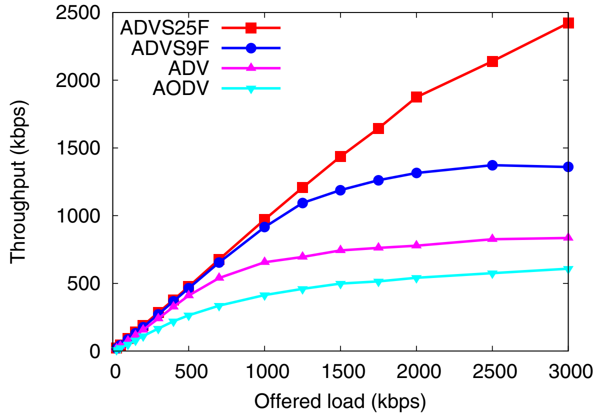

Fig. 3. Throughputs achieved for CBR traffic on 1000-node mixed and ad hoc networks.

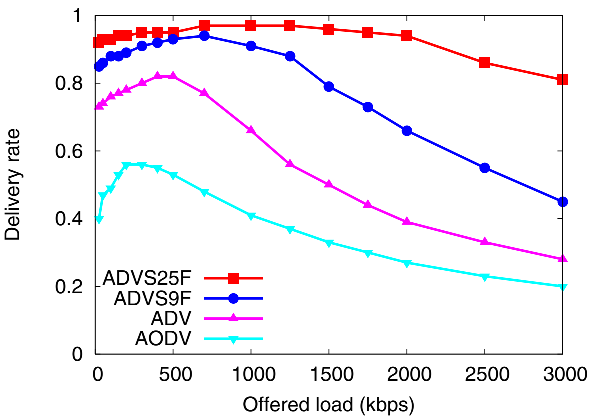

Fig. 4. Delivery rates for CBR traffic on 1000-node networks.

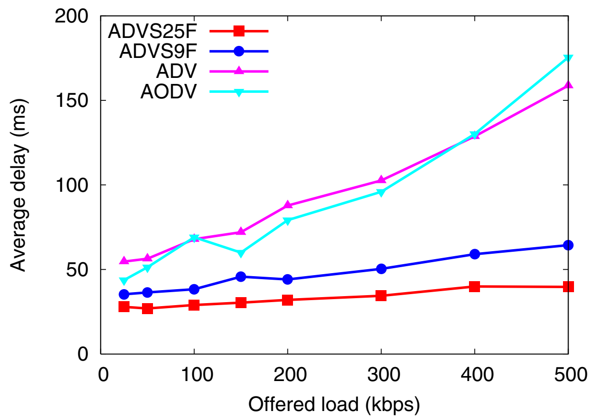

Fig. 5. Average delays (offerloads from 0 to 500 Kbps) achieved for CBR traffic on 1000-node networks.

work). The rate of broken routes increases rapidly for loads beyond 600 Kbps for ADV, while it is more gradual for ADVS. The key reason is ADV needs to repair routes with a large number of wireless hops compared to ADVS.

Between the two ad hoc routing protocols ADV and AODV, the latter has an extremely high rate of broken routes. Even at low traffic loads, and the network saturates quickly; this rate is bounded in saturation because, by now, the routing protocol is repairing only connections with shorter paths, effectively giving up on longer path connections. Since AODV uses network-wide floods to repair broken routes, repairing routes is expensive. In large networks, control packets dominate the wireless channel BW when AODV is used. It can be seen from Figure 9, which gives control packet overhead on wireless links. ADV does not have the same problem since the number of control packets is limited to at most 2/node/second. Hogging the wireless BW for control packets increases radio interference at nodes transmitting data packets, which could lead to additional route repairs. While AODV has been shown to perform well for small ad hoc networks [5], our results indicate that it does not work well for large ad hoc networks.

IV. Conclusions

Pure ad hoc networks using wireless technologies such as Wi-Fi (IEEE 802.11) are useful for small or military applications, but do not have the reliability expected by a user accustomed to broadband access to the Internet and wired networking infrastructure. So for general purpose mobile networking, it is necessary that wireless networks provide reliability and performance comparable to that of a wired network.

We have proposed mixed networks that are primarily ad hoc wireless networks with some fixed nodes and p2p links to provide better performance and reliability. We have modified an existing ad hoc routing algorithm, denoted ADVS, to exploit the availability

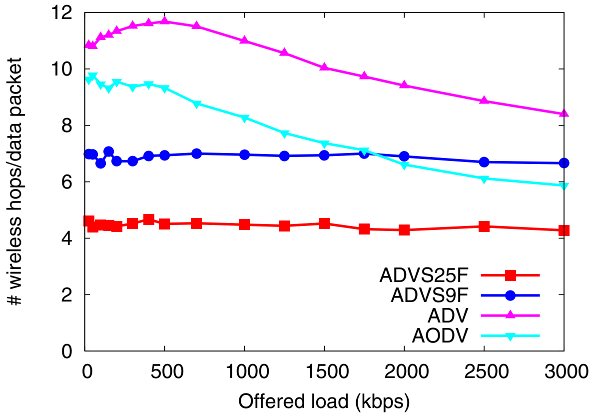

Fig. 6. The number of wireless hops taken by a data packet in 1000-node networks.

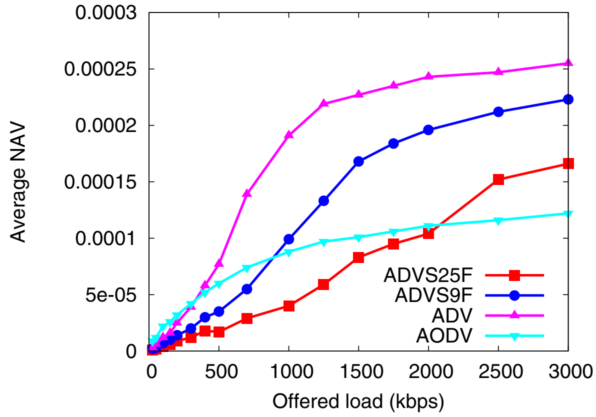

Fig. 7. Average Network Allocation Vector(NAV) value for various 1000-node networks.

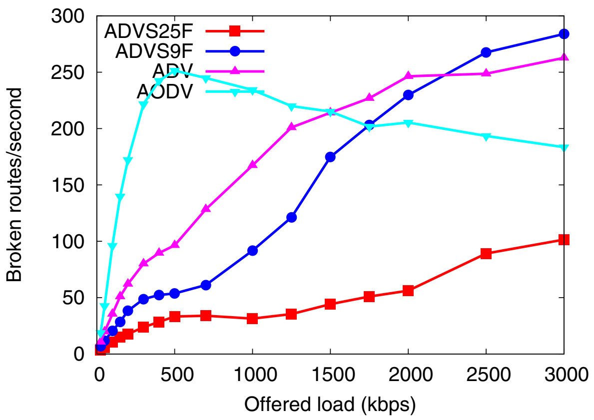

Fig. 8. Average broken routes in CBR simulation on 1000-node networks.

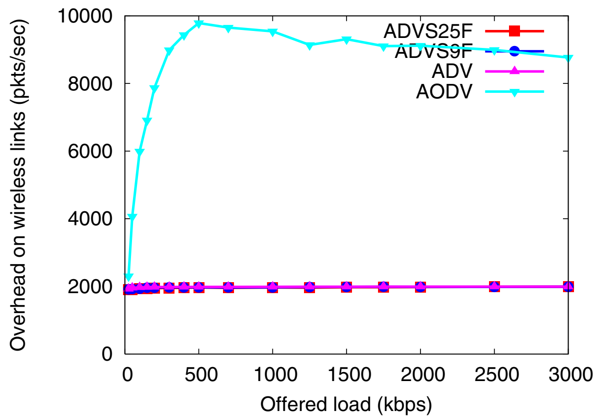

Fig. 9. Overheads on wireless links achieved for CBR traffic on 1000-node networks.

of more reliable p2p links in mixed networks. We implemented ADVS in the Glomosim simulator.

We have shown using simulations that mixed networks can provide significantly higher throughput and lower packet delays.

In future, we intend to investigate the performance of multimedia applications on mixed networks. Another interesting topic to explore is optimal placement of fixed nodes and links and using multiple wireless channels by fixed nodes.

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