On the Performance of Metro-Scale Ad Hoc Networks

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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. In this paper, we investigate the use of wireless networks large enough to span a campus or a town. To make these networks reliable, we propose mixed networks which are mostly ad hoc networks with a few infrastructure nodes, i-nodes. These i-nodes are interconnected with point-to-point, p2p, links in addition to Wi-Fi capability. We modify an existing ad hoc routing protocol to incorporate the relatively stable p2p links with the broadcast type Wi-Fi channels in finding routes. We have simulated several ad hoc and mixed networks using the Glomosim simulator. Our results show that adding a small number of i-nodes with p2p links can improve the performance dramatically with throughputs increasing by a factor of 3 or more. Our results also indicate that using too many i-nodes beyond a certain limit does not improve the performance and that reducing radio transmission power can significantly reduce radio interference and improve throughput significantly.**

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. Even with a few tens of nodes, ad hoc networks have low network performance [3], [9], [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, or i-nodes, and mobile wireless nodes, or m-nodes, which denote users. All nodes are capable of using a standard wireless technology such as the Wi-Fi. In addition, the i-nodes have p2p links among them. These networks can take advantage of

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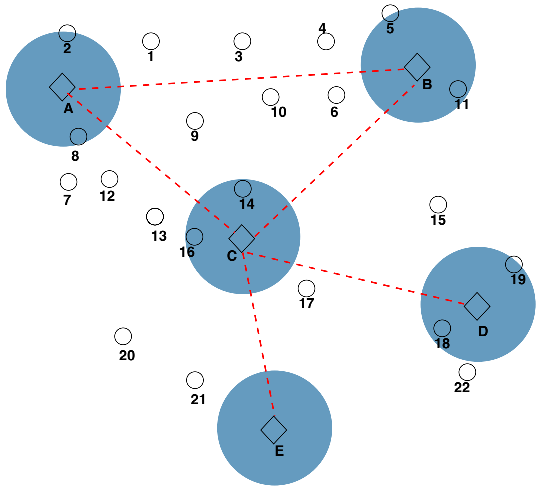

Fig. 1. A mixed network with mobile user and fixed infrastructure nodes, denoted by circles and diamonds, respectively. The infrastructure nodes are interconnected by point-to-point links, denoted by dashed lines, for infrastructure support and to provide multiple paths. All nodes are capable of using 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.

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 current technologies, it is inexpensive to design the proposed mixed networks. The IEEE 802.11 has already been a popular medium access control (MAC) protocol for ad hoc wireless networks. The 802.11 is a short haul (for distances less than 376 m) wireless link protocol. The fixed infrastructure nodes

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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 10 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 using a suitable 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 of mixed networks [2], [12], [14], [4].

In this paper, we are interested in evaluating the suitability of mixed networks for city-wide wireless connectivity. We simulated and evaluated the performances of 200- and 1000-node ad hoc and mixed networks. We varied the number of i-nodes and transmission power of radios (used for the wireless links) to see the interaction of ad hoc networking and stable infrastructure of p2p links. 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 tripled even when p2p links have low bandwidth. Furthermore, adding too many i-nodes is not beneficial since the wireless interface at these nodes tends to be a bottleneck. Reducing the transmission power of short-haul radios is beneficial when there is a significant overlap in the areas covered by the i-nodes.

II. Routing in Mixed Networks

Several current Internet/intranet routing algorithms for Internet such as Routing Information Protocol (RIP) [10], Open Shortest Path First (OSPF) [15] do not work well for wireless networks, while the Ad hoc On demand Distance Vector (AODV) [16], Dynamic Source Routing (DSR) [11] 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 mixed network with p2p and wireless links, 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 event 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. A dynamically computed trigger threshold is used to decide when an update needs to be triggered. 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 p2p links among i-nodes. In ADVS, these control packets are broadcasted via wireless interface to inform wireless neighbors and unicasted via wired interfaces (if it is an i-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.

III. Performance Analysis

We used the Glomosim simulator, version 2.03 [1] for performance analysis of ad hoc 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 [9]. 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 [17]. Node speeds are chosen to vary uniformly between 1 m/s and 9-29 m/s. We use 0-second pause time, which corresponds to continuous motion.

Types of Networks. We simulated ad hoc and mixed networks with 1000 nodes in a 6×6 Km^2 field. For ad hoc networks, all nodes are mobile nodes, and for mixed networks, there are $1000-n^2$ m-nodes and $n \times n$, $n = 3, 5, 8, 10$, i-nodes, arranged in a 2-dimensional grid centered in the middle of the field. The adjacent i-nodes are separated by a distance of $6/n$ Km and are interconnected by p2p links. We also simulated several 200-node networks in a 2×2 Km^2 field.

We modified Glomosim 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 propagation delay. 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. Later we varied the radio range of wireless links to show the benefits of reduced interference on network performance.

For route selection purposes, we varied the p2p link to wireless link ratio, r, from 5 to 10, but the results are identical. So, $r = 10$ unless otherwise specified.

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. We also used TCP traffic generated by up to 50 HTTP or FTP connections. The i-nodes are neither sources nor destinations of any of the connections simulated.

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.

Performance Metrics. We use throughput, average packet latency, and routing overhead over wireless links to evaluate the routing protocols and networks. In addition, we also examined secondary metrics such as MAC layer network allocation vector, which indicates channel contention, hop counts, and the rate of broken routes to understand the performance differences among routing protocols and networks.

ADVSnF denotes the ADVS routing protocol in a mixed network with n i-nodes. ADV and AODV are used to denote ADV and AODV routing protocols in ad hoc networks. 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.

A. Large Network Simulations

Figure 2 gives the CBR traffic throughputs of ADVSnf, where $n = 3, 5, 8,$ or 10, ADV and AODV. The maximum throughput achieved with ad hoc wireless networks is 753 Kb/s by ADV. In the mixed network, the peak throughput with 9 i-nodes is 1272 Kb/s, 69% higher, and with 25 i-nodes 2356 Kb/s, 213% higher. It is noteworthy that even though the p2p link bandwidth is 2 Mb/s, adding 25 i-nodes and 40 p2p links among them triples the throughput.

With 25 i-nodes, the minimum distance between adjacent nodes' radio covered areas (henceforth, radio areas) is $6000/5 - 376 * 2 = 448$ m. Despite significant gaps in the radio coverage by the i-nodes, the performance is high, since m-nodes that are not within the radio range of an i-node use ad hoc routing effectively to reach the nearest i-node. Also, if the communicating nodes are within each other's radio range, then they communicate directly using the radio links. In contrast, 9 i-nodes are not enough due to the gap of nearly 1.25 Km between the radio areas by adjacent i-nodes. So the 9f mixed network with behaves mostly like an ad hoc network.

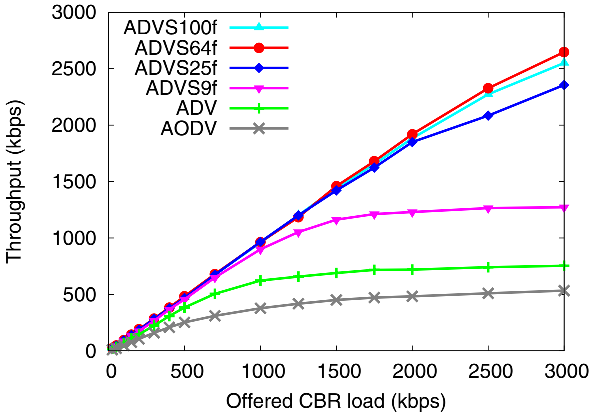

Fig. 2. Throughputs achieved for CBR traffic on 1000-node ad hoc networks.

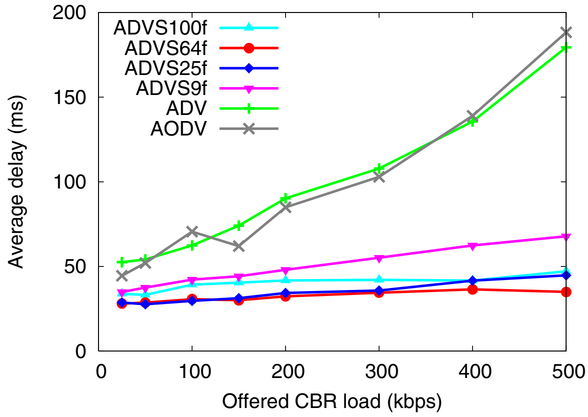

Fig. 4. Average delays achieved for low CBR traffic load on 1000-node ad hoc networks.

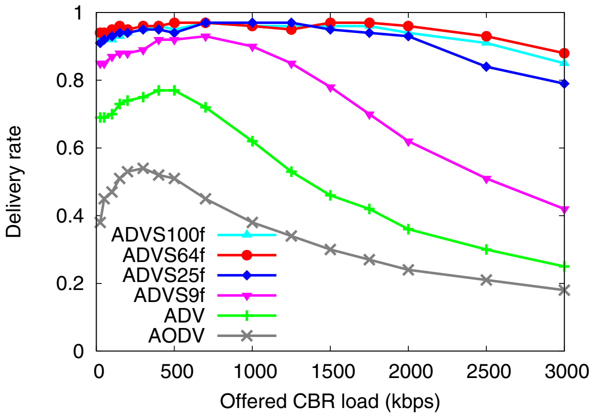

Fig. 3. Delivery rates for CBR traffic on 1000-node ad hoc networks.

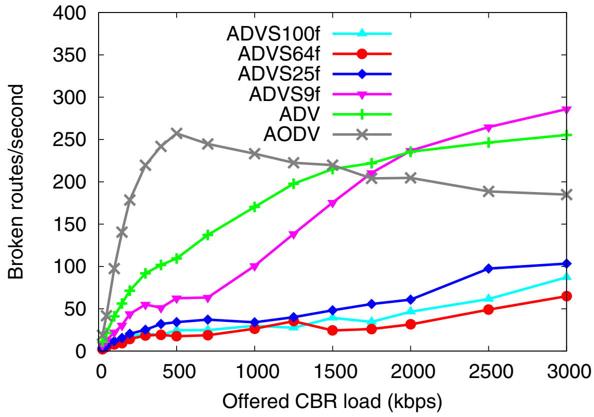

Fig. 5. Average broken routes in CBR simulation on 1000-node ad hoc networks.

Adding more i-nodes and p2p links does not give a corresponding increase in performance. With 64 i-nodes, the radio ranges of adjacent nodes overlap by $2 * 376 - 6000/8 = 2$ m. However there are gaps in the radio coverage by the i-nodes due to the circular shape of radio coverage. Our results show that the performance increases slightly compared to the 25f case only when the network load is high. With more i-nodes, however, there will be enough overlap in the radio areas covered by them to eliminate most of the gaps. Owing to the distributed and shared nature of ad hoc networking, this increases the radio interference and the number of nodes exposed to neighbors' transmissions. So the performance suffers slightly, for the 100f case. With a large number of i-nodes (about 10% of total nodes in our example network), the network can be operated as an infrastructure-based wireless network, similar to the metro-scale Wi-Fi projects by several municipalities. However, the price-performance ratio may not be in favor of these infrastructure wireless networks if the density of m-nodes is low.

Even more illustrative are the delivery rates in mixed and ad hoc networks given in Figure 3. For the ad hoc network, ADV is able to perform adequately, delivering up to 77% of injected packets prior to saturation. AODV does not perform well and saturates much more quickly with a peak throughput of 533 Kbps. Even at low loads, its delivery rate is less than 55%. Mixed networks, however, achieve 90-95% peak delivery rates which indicate substantially higher reliability of routes.

Figure 4 gives packet delays prior to saturation. At low loads (less than 50 Kbps), all networks have comparable delays. As the load increases, mixed networks provide significantly lower latencies. At a load of 300 Kbps, AODV and ADV have 4 times higher packet delays compared to the 25f mixed network. Our results indicate that the average packet latencies are manageable with mixed networks, but are too high with ad hoc networks to facilitate interactive applications such as voice over IP or online gaming.

Using i-nodes with p2p links benefits the network performance by using fewer wireless hops for data packets. First, this frees up wireless links for more data packets and also reduces contention for wireless channels. With 25 i-nodes, the average number of wireless hops taken is about 4.5, while it is 9.5 to 11.5 hops in ad hoc networks, depending on the routing protocol, prior to saturation. The second factor, perhaps the more significant one, is the improvement in the stability of routes. The rate of broken routes is shown in Figure 5. 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 network). 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 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. (ADV does not have the same problem since the number of control packets is limited to at most 2/node/second.) 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.

TCP Traffic. We have simulated TCP traffic using varying number of HTTP connections. The Glomosim simulator has a builtin HTTP traffic generator with client and server traffic load modeled using Zipf distribution [13]. Figure 6 shows the throughput achieved for the case where each HTTP server serves five clients. We simulated multiple clients per server to capture a more realistic traffic pattern and also to evaluate the impact of traffic hot-spots.

The HTTP traffic has variable size transactions between client and servers. This traffic pattern together with TCP sliding window mechanism to retransmit lost packets seem to further amplify the advantages–stable routes and freer wireless channels–of mixed networks over ad hoc networks. With 25 i-nodes, the mixed network provides throughput about 5 times that of ADV for the ad hoc network. AODV performs significantly worse than ADV for the reasons elaborated in the case of CBR traffic.

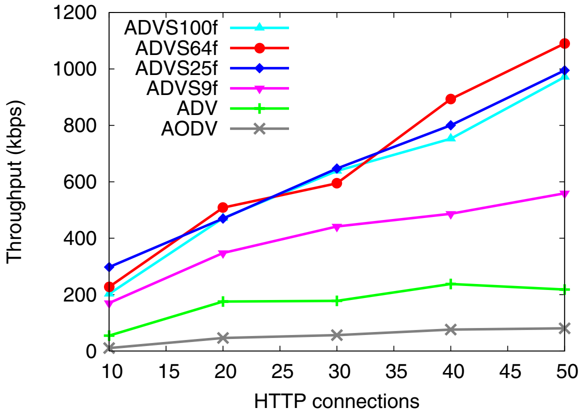

Fig. 6. Throughputs achieved for HTTP traffic on 1000-node ad hoc networks. Each server has five clients.

B. *Small Network Simulations*

We varied the wireless to p2p link cost ratio from 5 to 10, but the performance is unchanged. In another set of simulations, we varied the p2p link BW, but there is only a marginal improvement in throughput. As shown above, the throughput does not improve with increase in the number of i-nodes beyond a certain limit. The primary reason for this performance limit is the wireless interfaces at i-nodes become the bottlenecks. Since Glomosim is not designed to simulate multiple wireless channels, we experimented with radio transmission power to reduce the number of nodes within the radio area of a node. For easier simulation, we use a 200-node network in a 2×2 Km^2 field. The number of i-nodes is 9 or 81. We used two radio ranges: 376 m as in the large network simulations and 126 m, which is denoted as *sr* for short radio range. We simulated TCP traffic using up to 50 HTTP connections as described for the larger network. We also simulated FTP connections with infinite backlog.

The performances of different mixed networks are shown in Figures 7 and 8. (We did not simulate the *sr* case with 9 i-nodes, since the network will be disconnected and no meaningful throughput can be obtained.) With a shorter radio range, the mixed network performs extremely well. For FTP, the performance is up to 7 times higher. It is interesting to note the underperformance by the *sr* case when the number of HTTP connections is 30 or less. Our analysis revealed that with $r = 126$ m, m-nodes depend primarily on i-nodes to communicate. The number of wireless hops per data packet is slightly over 2. Since a minimum of 2 wireless hops is required to communicate through i-nodes, there is almost no ad hoc networking effect. There are 200 nodes in a field of 4 Km^2, which gives a density of $200 \times \pi r^2/4$, where r is the radio transmission range in Km, nodes/radio area. For $r = 0.126$ Km, the node density is about 2.5 nodes per radio area. This is too sparse for effective ad hoc routing. In contrast, the node density is 12.3 in the 1000-node, 36 Km^2 field case, and it does facilitate ad hoc networking. With $r = 0.376$ Km, however, the 200-node network has a density of 22.5 nodes/radio area. This high density is detrimental at higher traffic loads, and the network does not perform well.

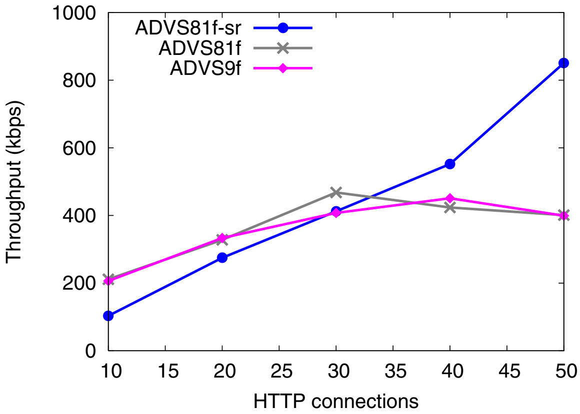

Fig. 7. Throughputs achieved for HTTP traffic on 200-node ad hoc networks. Each server has five clients.

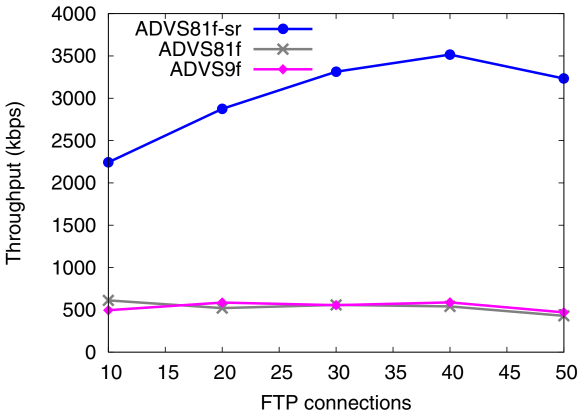

Fig. 8. Throughputs achieved for FTP traffic on 200-node ad hoc networks. Each server has ten clients.

IV. Conclusions

Pure ad hoc networks using wireless technologies such as Wi-Fi (IEEE 802.11) are useful in 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 investigated mixed networks that are primarily ad hoc wireless networks with some fixed nodes and p2p links in order to provide better performance and reliability.

We have shown using simulations for UDP and TCP traffic that mixed networks perform significantly better than ad hoc networks.The mixed networks can provide significantly higher throughput and lower packet delays. The key result of our study is that while pure ad hoc networks are unusable, adding a few infrastructure nodes with p2p links offers high throughput and low delays.

We have shown that using too many i-nodes beyond a limit does not improve the performance. In such cases, reducing the transmission power to reduce the radio range and hence contention for wireless channels can significantly improve the network performance.

In future, we intend to explore the benefit of using multiple wireless channels by fixed nodes.

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