A Hybrid Approach to Internet Connectivity for Mobile Ad Hoc Networks

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***Abstract*— Mobile Ad Hoc networks are autonomous, infrastructureless networks that support multihop communication through IP routing. This paper examines the use of Mobile IP in order to provide global Internet connectivity to ad hoc networks that use an on-demand routing protocol. We present a hybrid scheme that uses techniques such as TTL scoping of agent advertisements, eavesdropping and caching agent advertisements to combine the advantages of proactive and reactive approaches to providing connectivity. We present simulation results to show that our approach achieves excellent connectivity while keeping overhead costs low.**

I. Introduction

THE biggest challenge to the deployment and acceptance of mobile applications is the need for better connectivity. The use of solutions such as Mobile IP [1] has extended the sphere of connectivity to include nodes with a wireless last hop. In comparison, an ad hoc network is generally viewed as a stand-alone network, where communication is only supported between nodes in the network. The lack of connectivity to the wired infrastructure enables simple management and deployment, but limits the applicability of ad hoc networks to scenarios that require connectivity outside the ad hoc network. A bridge between ad hoc networks and the Internet would expand the communication base of an ad hoc network, but also require the concept of last hop mobility management to include multiple wireless hops between the mobile node and the base station. The challenge to enabling such support stems from the need to provide good connectivity in a dynamic, resource poor (i.e limited power and bandwidth) environment. The goal of our research is to understand the tradeoff between connectivity and overhead in various ad hoc networking environments.

Two classes of approaches have been proposed to support connectivity between ad hoc networks and the Internet. Proactive schemes flood advertisements from nodes acting as Mobile IP foreign agents through the whole ad hoc network [2], [3], [4]. Such approaches provide good connectivity, but impose a high overhead, especially when not all the nodes in the ad hoc network require external connectivity. Reactive schemes allow the mobile nodes to broadcast solicitations to find foreign agents as they are needed [5], [6]. Such approaches tie the overhead of maintaining connectivity to external traffic patterns but negatively impact the mechanisms necessary for Mobile IP such as agent discovery and movement detection.

The contribution of our work is the design and evaluation of a hybrid scheme that combines proactive and reactive techniques to provide good connectivity with reduced overhead. In our approach, agent advertisements are flooded within a limited number of hops from the foreign agent. Nodes that are outside this hop limit use reactive techniques to solicit foreign agents when needed. A hybrid approach combines the advantages of both proactive and reactive approaches and provides good connectivity while keeping overhead costs low.

The remainder of this paper is organized as follows. Section II provides an overview of Mobile IP and on-demand routing protocols and examines the tradeoffs between using proactive and reactive approaches. In Section III, we describe our protocol and optimizations. The performance of our approach is detailed in Section IV and Section V concludes the paper.

II. Connectivity for Mobile Ad Hoc Networks

The characteristics of an ad hoc network differ substantially from that of the fixed Internet. In this section, we examine some of the solutions proposed for the integration of Mobile IP and ad hoc networks, and lay the foundation for our hybrid proactive-reactive approach.

A. Mobile IP and On-Demand Routing Protocols

The Mobile IP [1] protocol provides transparent routing of IP datagrams to mobile nodes in the Internet, enabling users to maintain connections as they roam in different networks. Gateways, called foreign agents periodically broadcast *Agent Advertisements* to advertise their presence to visiting mobile nodes. Alternatively, mobile nodes may actively solicit foreign agents, causing foreign agents to respond with advertisements unicast to the node. On receiving an advertisement, a mobile node registers with their home network by sending a *Registration Request*, and the registration expires after a *registration lifetime*. The mobile node must re-register with the home network before the lifetime expires. The mobile node acquires a *care-of address* that is valid on the foreign network. This care-of address may be that of the foreign agent, in which case the foreign agent serves as the point of contact for the mobile node, or may be obtained by the mobile node by other means. Datagrams are tunneled by the home network to the care-of address of the mobile node. Mobile IP relies on proactive mechanisms such as the broadcasting of advertisements and solicitations for agent discovery, movement detection and reachability of the mobile node.

In mobile ad hoc networks (MANETs), on-demand routing protocols have been proposed to provide connectivity within the network (eg.DSR [7], AODV [8], [9]). *Route Request* (RREQ) messages are broadcast when a mobile node requires

This work was supported in part by the National Science Foundation under grant NSF-CCR-0086094

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a route. The destination or intermediate nodes that know a fresh enough route to the destination, respond with *Route Reply* (RREP) messages, effectively setting up the route. This reactive approach provides good connectivity within the MANET while reducing the overhead costs when the network is idle.

The basic design of Mobile IP and on-demand routing protocols makes integration difficult. Adjusting Mobile IP to operate in an on-demand fashion will cause nodes to have less up-to-date information about foreign agents, causing poor handoffs and bad connectivity. On the other hand, a pure proactive approach, such as that used by Mobile IP, results in excessive control overhead. Furthermore, nodes that do not require Internet connectivity are unnecessarily burdened with the traffic imposed by repeated flooding. In the next section, we discuss some of the solutions that have been proposed to achieve this synthesis.

B. Proactive and Reactive Approaches

A proactive approach to providing Internet connectivity to a MANET relies on ensuring that all nodes are registered with a foreign agent at all times. Mobile IP relies on link-layer broadcasts to provide foreign agent information to interested nodes. However, these broadcasts can prove to be extremely expensive in a MANET where a broadcast translates to the packet being flooded throughout the network. Some of the solutions proposed for interconnecting MANETs to wired infrastructure also rely on this periodic flooding [2], [3], [4]. [2] uses a proactive routing protocol to maintain connectivity within the MANET. The other approaches rely on on-demand routing in the MANET to maintain connectivity information. To reduce the flooding of advertisements, these schemes increase the *beacon interval* (i.e. the interval between successive advertisement floods).

In a purely reactive approach, mobile nodes obtain foreign agent information by sending out agent solicitations only when data needs to be sent to a node outside the MANET. To limit the flooding of these solicitations, solicitations may be piggybacked on RREQ messages [5], or an expanding ring search may also be used [6]. Although [4] is essentially a proactive approach with periodic flooding, intermediate nodes are allowed to reply with a route to the foreign agent, which reduces overhead.

An ideal solution should provide Internet access to MANETs while attempting to balance the proactive and reactive approaches. There are many benefits to a hybrid approach. A proactive solution allows mobile nodes to find the foreign agent closest to them and enables better handoffs, which in turn leads to lower delay. Periodic registrations in such a proactive scheme help foreign agents track the mobility of the mobile node. However, if not all the nodes in the MANET require connectivity, the repeated broadcasting of agent advertisements and solicitations can have a negative impact on the MANET due to excessive flooding overhead. A hybrid approach combines the advantages of both approaches so that the required information is received in a timely fashion and the MANET's scarce resources are not further burdened with Mobile IP overhead.

III. Protocol Design

Our protocol is designed to provide nodes in a MANET with access to the Internet using Mobile IP. The protocol uses foreign agents to track and forward data to and from the mobile node. Using foreign agents provides Internet access to the entire MANET using a single care-of address. This approach also alleviates the need for address allocation schemes for the MANET, since nodes use an arbitrary address within the MANET and use the care-of address provided by the foreign agent for external communication. Our design assumes the use of an on-demand ad hoc routing protocol to deliver packets between the foreign agent and the mobile nodes.

A. Route Discovery and Transmission of Packets

A mobile node uses the route discovery mechanisms of the ad hoc routing protocol to determine if the node lies in the MANET or on the wired Internet, similar to mechanisms used in [3], [4]. A route discovery is initiated for the node. If the node lies in the MANET, it responds with a RREP message. Otherwise if a foreign agent receives the request and finds that it does not have an explicit route entry for the node (i.e. if the node is not registered with the foreign agent), the foreign agent sends back a special route reply (FA-RREP [4]). If no route reply is received, other than from the foreign agent, the node is assumed not to lie in the MANET.

The packets to destinations on the Internet (i.e. the correspondent host) are encapsulated and routed to the foreign agent that the mobile node is currently registered with, which then forwards to the destination using standard IP forwarding. Packets destined for the mobile node arriving from nodes on the Internet are tunneled from the home network to the foreign agent, which decapsulates them and forwards them to the mobile node using the ad hoc routing protocol.

We detail the procedure for locating and registering with foreign agents in the following sections.

B. Agent Advertisements

Foreign agents periodically announce their presence on the MANET by broadcasting agent advertisements. When a mobile node receives an agent advertisement, it records the address of the foreign agent, the advertisement sequence number and advertisement lifetime in a list of foreign agents. Agent advertisements also set up reverse routes to the mobile nodes. These reverse routes allow mobile nodes to update their routes to the foreign agent if the advertisement arrives along a shorter path and to refresh the route entries if the route is already known. A unique broadcast ID is used to prevent the broadcast of advertisements that a node has already seen before. The broadcasting of agent advertisements is randomly delayed to prevent collisions.

To limit the flooding of advertisements, the TTL-field in the IP header of the advertisements can be set, thereby flooding the advertisement in a n-hop neighborhood. In this way, nodes that are closer to the foreign agent obtain up-to-date information about the foreign agents while nodes further away rely on the agent discovery mechanisms explained in the next section.

This is useful when the primary aim is to provide good coverage to mobile nodes that are close to the foreign agent as well as provide "dead spot" coverage to nodes that are far from the foreign agents. Furthermore, flooding in the n-hop neighborhood of the foreign agent reduces the number of solicitation messages that the foreign agent must respond to, decreasing the processing overhead at the agent. On hearing advertisements, nodes update their routes to the foreign agents, reducing broadcast overhead from RREQ messages to find foreign agents when Registration Request messages or data packets need to be transmitted.

C. Registration

Upon receiving an advertisement, nodes may unicast a Registration Request to register with a foreign agent. The foreign agent and the home agent process the Registration Request as described in [1]. Home agents create an entry for the mobile node, and set a registration lifetime for this entry. Mobile nodes must periodically register with the home agent to refresh this entry. Foreign agents forward Registration Reply messages they receive from the home agent back to the mobile node. Mobile nodes receive the reply and set the lifetime field in the entry for the foreign agent. To maintain the registration, the mobile node must re-register before the lifetime expires.

To further reduce overhead, nodes do not re-register each time they hear an advertisement. Instead, they cache the advertisement and wait until 75% of the registration lifetime has elapsed. To detect and move to new foreign agents, the protocol uses the MMCS Cell Switching Algorithm [3].

D. Solicitations

Since advertisements are only flooded within the n-hop neighborhood, there may be certain nodes that never receive an advertisement from a foreign agent. These nodes may broadcast a solicitation to discover a foreign agent. When an intermediate node receives a solicitation, it checks the list of foreign agents that it has heard from recently. If the intermediate node has received an advertisement during the last beacon interval and has a current route to the foreign agent, the intermediate node replies to the mobile node with a unicast advertisement. On receiving this unicast advertisement, the mobile node may send a registration request to the foreign agent. To reduce flooding overhead due to solicitations, the Expanding Ring Search Method [9] is used, in which solicitations are initially sent out with a TTL of 1 and the TTL is increased by 2 after every interval in which no reply is obtained, until it reaches 7, after which the solicitation is sent using flooding. Solicitations also set up reverse routes to the nodes that they originate from, ensuring that unicast advertisements sent out in response do not generate unnecessary RREQ messages.

E. Eavesdropping

Nodes that desire Internet connectivity also eavesdrop on agent advertisement messages in the MANET. If a unicast advertisement is overheard by a node that is not the intended destination, it may still derive the location and the address of the foreign agent from the advertisement and will not need to subsequently send out a solicitation when its registration with the home agent expires.

Beacon Interval	10secs
Registration Lifetime	30 secs
Agent Advertisement Lifetime	30secs
Time between solicitations	5secs
Simulation Time	600 secs

TABLE I
SIMULATION PARAMETERS

This optimization is especially useful for nodes that do not lie in the n-hop neighborhood of the foreign agents. With eavesdropping, a single solicitation can potentially benefit all of the nodes that are close to the node that broadcasts the solicitation, as well as those nodes that lie along the path to the requesting node.

The combination of flooding in an n-hop neighborhood, allowing intermediate nodes to reply to solicitations, the expanding ring search for solicitations and allowing eavesdropping for advertisements combines the advantages of the proactive and reactive approaches for providing Internet connectivity to MANETs. The use of Mobile IP broadcast traffic such as advertisements and solicitations to set up routes further helps to reduce the number of RREQ's that are needed, thus reducing on-demand routing protocol overhead.

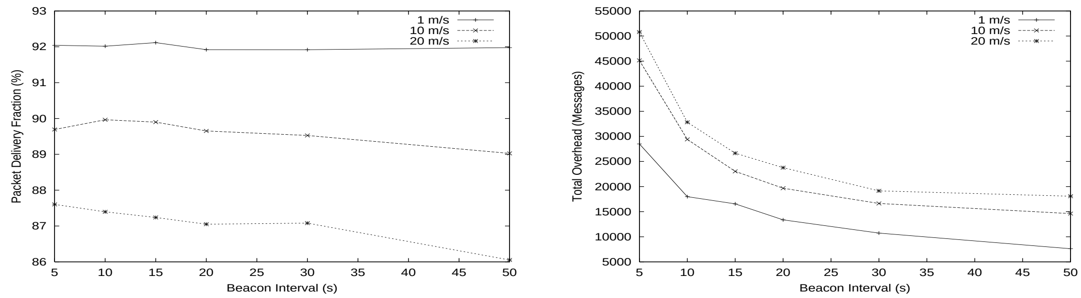
IV. SIMULATION RESULTS

To evaluate the proposed approach, we have implemented a prototype in the Network Simulator [10] with mobility extensions. Although our approach could work equally well with any on-demand routing protocol, we extend the Ad-Hoc On Demand Distance Vector (AODV) routing protocol [9] for routing within the MANET.

We study two topologies, a 50 node network over a 1000mx1000m square area and a 100 node network in a 2000mx2000m area. Two foreign agents are placed at opposite corners of the square areas in both scenarios. The mobile nodes move according to the random waypoint model. The maximum speeds as well as the number of registering nodes are varied for different simulations. Communication is carried out between wireless mobile nodes and correspondent nodes with traffic directed towards and away from the MANET. CBR sources and sinks sending 512 byte packets at 10 pkts/s are randomly placed at different nodes in the network. The pause time is fixed at 10 seconds. Each data point represents an average value of 5 runs with the same traffic models, but randomly generated mobility scenarios. Table I summarizes other parameters used in the simulation.

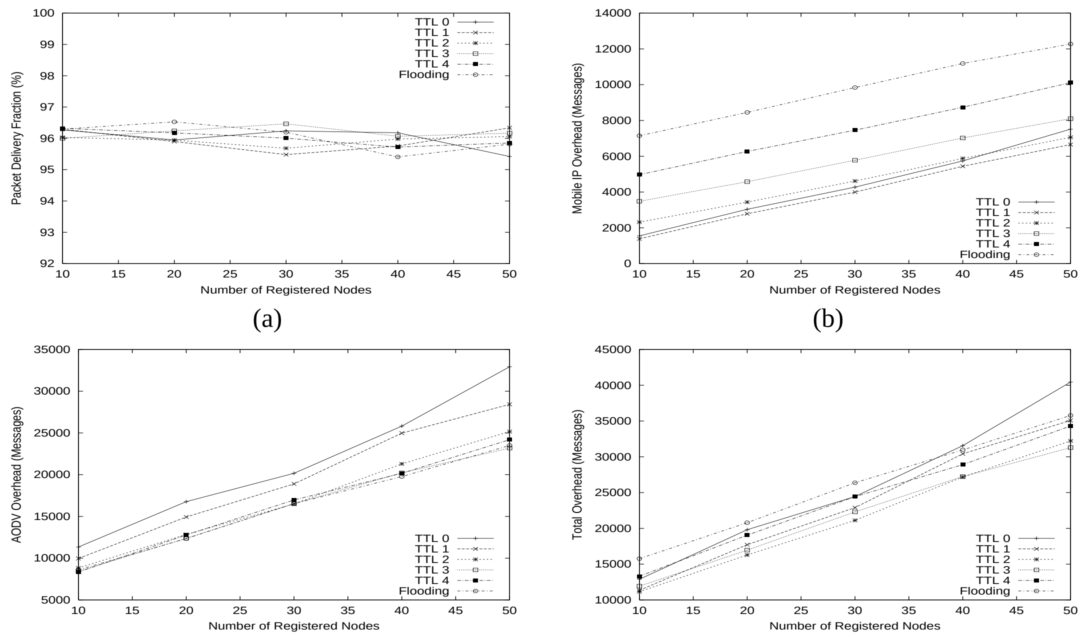
A. Optimal Beacon Interval

A simple way to reduce the effect of the repeated broadcast of agent advertisements would be to reduce the frequency of this flooding. To determine an optimal beacon interval so as to reduce overhead while not sacrificing connectivity, we simulated a 50 node network (1000mx1000m area) with



(a) (b)

Fig. 1. Effect on Connectivity and Overhead by varying Beacon Intervals



(c) (d)

Fig. 2. Varying the Number of Registered Nodes

varying mobility. Figure 1(a) shows that connectivity drops off as the beacon interval is increased, while Figure 1(b) shows a drop off in total overhead as the beacon interval is increased. From these results, we can see that a beacon interval of 10-15 seconds would be ideal since connectivity is high and the overhead also decreases significantly. We choose a beacon interval of 10 seconds for the remainder of the simulations.

B. Effect of the Number of Registered Nodes

To show the effect of varying the number of registered nodes, we perform simulations on a 50 node network in a 1000mx1000m area. Figure 2(a) shows that there is little or no effect on the packet delivery fraction as the number of registered nodes is increased, irrespective of the TTL of the advertisements. The packet delivery fraction is always above 95%. Also, the connectivity for the scenario when advertisements are flooded, (i.e a purely proactive solution) is much the same as that when only solicitations are used. Figures 2(b) and 2(c) show the effect of the number of registered nodes on the Mobile IP and AODV overhead. The Mobile IP overhead includes the overhead of all Mobile IP messages, including agent advertisements, solicitations, registration requests and replies. The AODV overhead is the total number of RREQ and RREP messages that are sent in the network. We calculate each transmission of the message as a separate message in the network.

As expected, the Mobile IP overhead increases rapidly for advertisements with larger TTL, while AODV overhead is higher when advertisements are not flooded. Also, as the number of registered nodes increases, both AODV and Mobile IP overhead increase. Figure 2(d) shows the total overhead and this indicates that neither a pure proactive solution nor a pure reactive solution are desirable in terms of total overhead imposed on the MANET. In a pure proactive solution, the repeated flooding of advertisements leads to high Mobile IP overhead, while in a solution where no flooding is carried out, the AODV overhead increases since advertisements are unicast. We see that although it may still be possible to

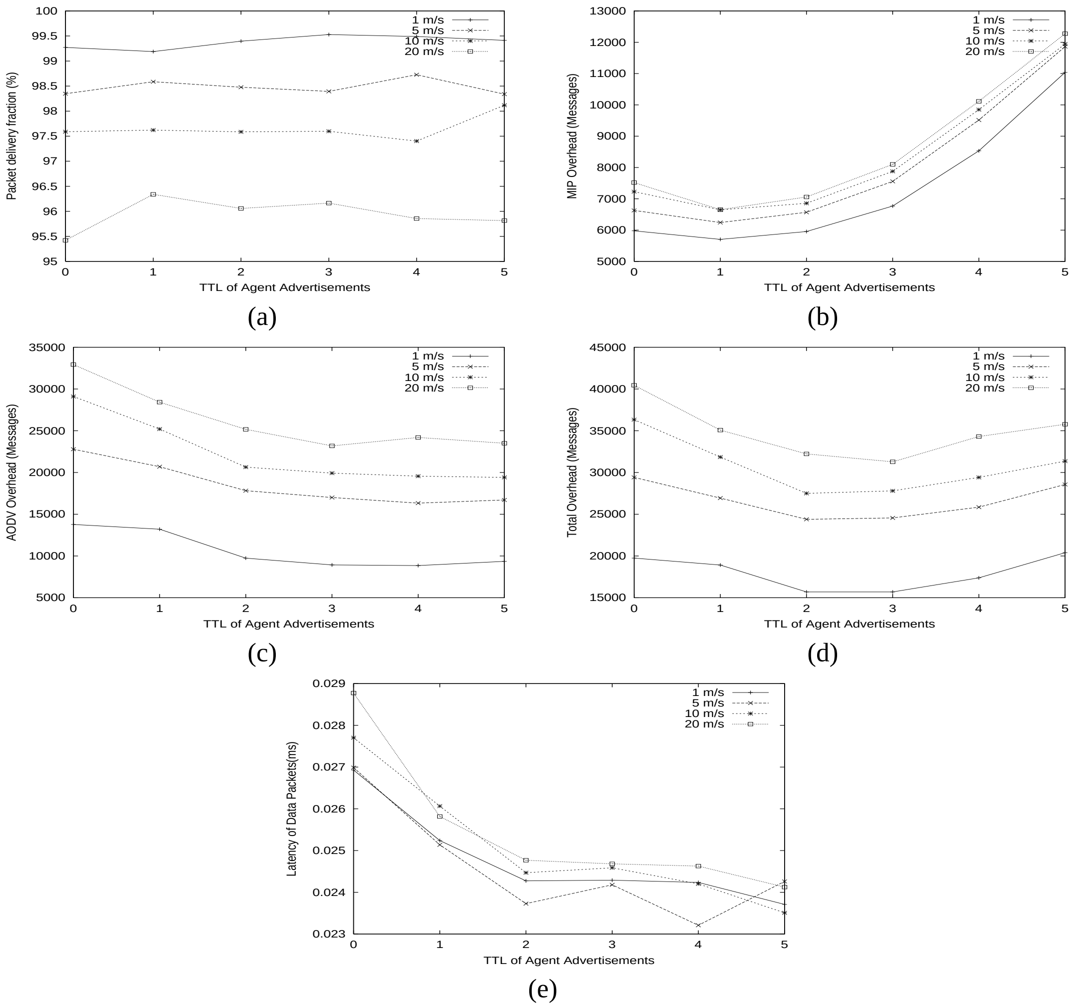


Fig. 3. Varying the TTL of Agent Advertisements (50 nodes,1000mx1000m)

use a purely reactive solution when few nodes register, as the number of registered nodes increases, a move towards a more proactive solution becomes necessary. We find that a hybrid solution with a flooding of only upto 2 hops is the best, achieving good connectivity while maintaining the lowest overhead.

C. *Optimal TTL for Agent Advertisements*

Figure 3 shows the impact of varying the TTL of the advertisements flooded by the foreign agents on the packet delivery fraction and the overhead imposed on the MANET. Scenarios with different maximum speeds are simulated to understand the effect of mobility. We observed that a TTL of 5 was equivalent to flooding the entire network, since all the nodes received the advertisement. From Figure 3(a), we can see that although the packet delivery fraction is considerably lower for higher mobility scenarios, the TTL of the advertisements does not have an appreciable effect on the connectivity of the mobile nodes. However, as can be seen from Figure 3(b), as the TTL is increased, Mobile IP overhead increases dramatically due to the flooding of the advertisements. Figure 3(c) shows that AODV overhead, on the other hand, decreases since the flooding of advertisements sets up reverse routes and fewer advertisements are unicast in response to solicitations. Finally Figure 3(d) gives the total picture. We can see that a TTL of 2 for a scenario of 50 nodes in a 1000mx1000m area imposes extremely low overhead and provides high connectivity. Furthermore, Figure 3(e) shows a sharp drop-off in the delay of data packets as we move towards a more proactive solution, and a TTL of 2 achieves delay comparable to a solution based on flooding advertisements.

We also simulated a 100 node network in a 2000mx2000m area. It was our observation that a TTL of 15 was equivalent to flooding the network. Figures 4(a)-(d) show the impact on connectivity and overhead in this scenario. Connectivity marginally improves as the TTL of the advertisements increases. Mobile IP overhead at first decreases sharply as the TTL is increased due to reduced solicitations as advertisements are sent out with a limited TTL. Mobile IP overhead increases as the TTL of advertisements becomes higher. AODV overhead, on the other hand, decreases with an increased TTL, due to the broadcast Mobile IP traffic setting up routes. From the curves for total overhead, we can see that a TTL of 2-3 is no longer optimal but a larger TTL is required for maintaining

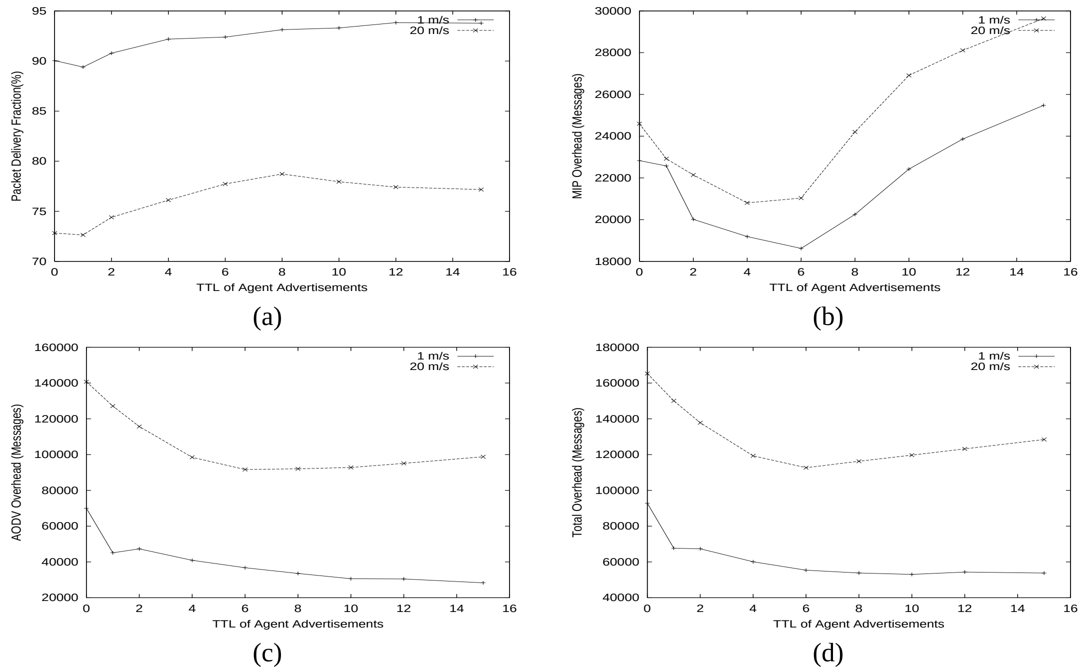


Fig. 4. Varying the TTL of Agent Advertisements (100 nodes, 2000mx2000m)

good connectivity, while keeping overhead to a minimum. A TTL of 4-6 seems to be ideal for this condition at different speeds.

Our simulation results show that a purely reactive or a purely proactive solution may provide the desired connectivity but at higher overheads than our hybrid solution. The overhead for a purely reactive solution increases rapidly as the number of registered nodes increases. For a solution based on the flooding of advertisements, although AODV overhead is reduced, Mobile IP overhead is large, causing high total overhead. We see that the scoping of advertisements, coupled with eavesdropping and allowing intermediate nodes to reply with advertisements leads to lower overhead, while maintaining high connectivity.

V. Conclusion

Mobile IP and on-demand routing protocols in a MANET can work together to set up multihop paths to a foreign agent in the network, allowing Internet connectivity. We present a hybrid approach that uses a combination of techniques including TTL scoping of agent advertisements, eavesdropping of advertisements and allowing intermediate nodes to reply with a route to the foreign agent. This hybrid approach combines the advantages of previous proactive approaches that rely on the flooding of agent advertisements and reactive approaches that rely completely on the reactive mechanisms of on-demand routing to obtain connectivity

Our simulations show that our hybrid approach achieves high connectivity while keeping overhead costs low. We have simulated different network configurations and find that the optimal TTL for agent advertisements can differ based on network area and density. We believe that this hybrid scheme is the best way to achieve an optimal mix of the advantages of the proactive and reactive approaches to providing connectivity to MANETs, and is a step closer to making the large-scale deployment of MANETs a reality.

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