# Application-Oriented Routing in Hybrid Wireless Networks

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***Abstract*— Hybrid wireless networks are a viable networking solution to combat the limitations of *infrastructured* wireless networks and provide Internet connectivity to *ad hoc* networks. This paper first analyzes the requirements for deployment of hybrid networks under different application scenarios. Then two routing schemes designed for different traffic patterns in hybrid networks are proposed to achieve optimal performance. Simulation results show that with a large percentage of short web-based traffic sessions, using a gateway as a default router results in better performance with lower latency, fewer routing table entries, and manageable control overhead. When traffic locality is high and Internet traffic is only an occasional occurrence, the reactive routing scheme results in better performance, yielding low control overhead and higher throughput.**

## I. Introduction

*Infrastructured* wireless networks and *ad hoc* networks are two popular types of wireless networks. In infrastructured wireless networks, mobile nodes communicate directly with an access point to the wired network. An ad hoc network, on the other hand, is comprised of mobile nodes that communicate solely over the wireless medium. One difficulty of installing infrastructured wireless networks is to avoid *dead zones* (areas without coverage). Additionally, unidirectional links, which are a common occurrence in wireless networks, can make direct communication with the access point impossible for mobile nodes if the access point has a greater transmission range than the mobile nodes. The limitation of ad hoc networks is that there is typically no connectivity between the fixed network and the mobile nodes, due to the lack of preexisting infrastructure. With the continued growth of interest in ad hoc networks, it is inevitable that global connectivity will be required for mobile wireless devices in the near future.

To overcome the limitations of infrastructured wireless networks and to provide mobile nodes in ad hoc networks Internet connectivity, hybrid wireless networks can be built to broaden usage of wireless networks. As shown in figure 1, multi-hop paths between mobile nodes and access points can extend the coverage of the network and provide Internet connectivity to mobile devices.

While these two types of wireless networks have been extensively studied individually, hybrid wireless networks bring new challenges in protocol design and performance evaluation. Traffic in hybrid networks can be both within the ad hoc network, and to or from nodes in the wired Internet. Applications for hybrid networks include conference environments. Conference attendees can communicate with each other in a spontaneous network using their mobile devices, and they can also perform Internet-centric tasks such as web browsing or email checking. In a sensor network, sensor nodes can cooperate with each other by exchanging data, while some designated or powerful nodes may transmit this data back to an Internet repository. Other applications include personal networks and many collaboration scenarios.

Because different applications have different configuration and performance requirements, traffic patterns in these scenarios will vary. To deploy hybrid networks, it is important to understand the required elements in terms of hardware and protocols. Further, because the routing protocols for infrastructured networks are based on direct transmission range of the access point, they cannot be directly applied to the multihop environment. It is important to investigate new routing schemes that can better adapt to the hybrid networks with different traffic composition and application requirements.

In this paper, we propose two routing schemes for hybrid wireless networks, and evaluate the performance of the protocols based on different application scenarios. Both solutions entail the integration of the Mobile IP protocol [4] and Ad hoc On-Demand Distance Vector (AODV) protocol [6]. Our results show that with a large percentage of Internet traffic and real-time applications, routing schemes that utilize a default gateway provide better performance with lower transmission latency; on the other hand, if most traffic is confined to the ad hoc network and the application is not particularly delay-sensitive, on-demand routing schemes are preferred because they generate less control overhead.

## II. Related Work

Two initial related studies are presented in [3] and [1] to provide Internet connectivity in ad hoc networks. Both approaches integrate Mobile IP with ad hoc routing protocols to forward data between the wired network and ad hoc network. Specifically, [3] uses a modified version of the Routing Information Protocol (RIP) and [1] uses DSR for ad hoc routing.

An alternative solution, MIPMANET, is presented in [2]. In this approach, nodes in an ad hoc network that require

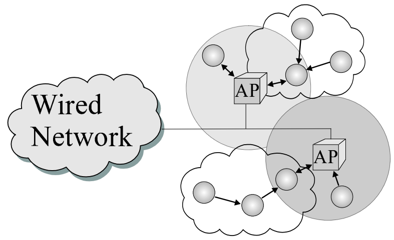



Fig. 1. A Hybrid Wireless Network.

Internet access register with the foreign agent and use their home address for all communication. Mobile nodes tunnel all packets destined for the Internet to their Mobile IP foreign agent. The AODV routing protocol is used to discover routes between mobile nodes and the foreign agent.

Our previous study [8] uses a similar mechanism by integrating Mobile IP with AODV. However, in this approach, data forwarding between the gateway and mobile nodes does not necessitate tunneling. This work also examines the effect of varying beacon intervals on the protocol performance, and proposes a mechanism for mobile nodes to obtain co-located IP addresses without the existence of Mobile IP.

## III. Routing in Hybrid Wireless Networks

In this section, we investigate routing protocols for hybrid wireless networks. It is first important to analyze the required elements for the deployment of hybrid networks. As described in section I, in addition to the mobile ad hoc network, the access point serving as the Internet gateway, where one or more mobile nodes are within its transmission range, are the basic requirements to deploy hybrid wireless networks. Mobile nodes with arbitrary pre-assigned IP addresses can obtain globally addressable co-located IP addresses for Internet communication [5]. On the other hand, if a node wants to keep its original IP address, Mobile IP can be utilized; a Mobile IP foreign agent can be deployed at the gateway to provide Internet access to and from the hybrid networks. Finally, it is desirable to use ad hoc routing protocols for traffic within ad hoc networks to obtain optimal routing paths with less traffic centralization at the gateway.

Since multi-hop paths typically exist between mobile nodes and the gateway, as well as between pairs of mobile nodes, the primary issue is to effectively find routes to destinations whether they are inside the ad hoc network or reachable through the wired network. Because the general location of the destination is not initially known, the optimal design of the routing protocol is likely to be affected by the requirements of the application. We will examine these effects in section IV. The following describes routing approaches for hybrid networks.

### A. Gateway/FA Discovery

It is important for mobile nodes to know the existence of the Internet gateway or the Mobile IP foreign agent, so that the gateway can be utilized to communicate with wired correspondent nodes. In this paper, we focus primarily on networks with Mobile IP capability. Similar mechanisms can be applied to non-Mobile IP access point/gateway operation.

In infrastructured wireless networks, foreign agent discovery is achieved through periodic Foreign Agent Advertisements. Mobile nodes can also proactively solicit advertisements from available foreign agents. Because these messages can only reach nodes within one hop, they cannot be directly applied to the multi-hop environment.

There are two basic mechanisms for mobile nodes to discover a gateway that is multiple hops away [2]. In the first approach, mobile nodes rebroadcast the Agent Advertisement messages so that the advertisements periodically flood the entire ad hoc network. This approach has the advantage of informing new nodes of the presence of the foreign agent, refreshing paths to the foreign agent, and enabling nodes a faster discovery of a foreign agent with lower transmission delay, fewer hops, etc. In the second approach, mobile nodes that require Internet connectivity proactively solicit the foreign agent and advertisement messages are unicast to these mobile nodes.

Previous work [2] has shown that as the number of nodes that desire Internet connectivity increases, the total control overhead of the unicast approach increases and surpasses the rebroadcasting approach. Further, the determination of the better approach for foreign agent discovery depends on the traffic pattern and application requirements. This will be examined in section IV.

### B. Routing for Hybrid Networks

Because traffic can be either within the ad hoc network or to and from the Internet, a routing scheme is needed that can operate seamlessly in either scenario. Recent studies [9] show that a large percent of the traffic in a local-area wireless network is comprised of web sessions, FTP and mail traffic. Web-surfers often visit one or two sites in a single session and initiate many sessions. No traffic analysis studies for hybrid networks have been performed, but we can predict Internet traffic and application models in hybrid networks will follow similar patterns. Additionally, usage of hybrid networks will also entail scenarios such as the conference scenario, as described in section I. These web-centric applications require real-time user interaction with low latency, which demands low communication and processing overhead. Sometimes the sessions are short-lived and a large number of web sessions can target many different web sites, so the processing overhead for discovering and maintaining a large number of routing entries may also be an important issue because of the scarce resource of mobile devices. In other applications, such as the sensor network scenario described in section I, Internet traffic may not require short latencies, and the destinations may not frequently change over a short period of time.

Considering the different application requirements, we propose two routing schemes for hybrid wireless networks. The routing schemes can be built on top of any on-demand ad hoc routing protocol with minor changes. For simplicity, we utilize AODV as an example to illustrate the protocols.

*Routing Scheme 1:* When there is a large percent of traffic traversing the wired/wireless gateway, and applications are short web-oriented sessions, it is desirable for mobile nodes to always have a default route to the gateway. This will significantly reduce the route acquisition latency, thereby reducing the data transmission latency. Minimal delay is important to web users, because users cannot tolerate frequent long waiting times for web page retrievals. Also, web users typically visit web pages at multiple domains. Lack of a default gateway would require a route discovery each time a new web server was queried. Further, by using a default route, the processing and caching overhead is significantly reduced, thereby saving the limited resources of mobile devices. The first scheme is geared towards web-centric traffic patterns and provides efficient routing to this type of applications.

In this scheme, foreign agents periodically broadcast Agent Advertisement messages, and all the mobile nodes rebroadcast these messages. Each mobile node is required to register with the foreign agent. Mobile nodes can also use advertisements to initialize and update the route between the foreign agent and themselves. In high mobility scenarios, where the route freshness cannot be guaranteed solely by beacon messages, mobile nodes can use ad hoc routing protocols to acquire a route to the foreign agent.

Each mobile node maintains the gateway as its default router. When a node has data to transmit, it sends the data directly to the gateway by either tunneling or loose source routing. The gateway, after receiving the packet, forwards the packet to the intended destination on the wired network. Because all mobile nodes are required to register with the gateway, the gateway can check whether or not the packet's destination is within the ad hoc network. If the destination is inside the ad hoc network, the foreign agent returns an ICMP redirect message notifying the source node to perform route discovery to find a route within the ad hoc network. As a result, the routing scheme can work efficiently with different traffic types to minimize user perceived latency.

*Routing Scheme 2:* In scenarios where a large amount of traffic is within the ad hoc network and the Internet applications are not sensitive to latency, scheme 2 can be used to reactively discover a route to the foreign agent and utilize it for Internet communication.

In this scheme, mobile nodes register with the foreign agent only when they have data to transmit to the wired network. Nodes do not rebroadcast the advertisement messages. Instead the foreign agent advertisement messages are unicast directly to each registered mobile node. In scenarios where the majority of traffic is inside the network, this reduces the Mobile IP control message flooding in the network.

When a mobile node originates data traffic, it performs route discovery to locate the destination. In AODV, nodes generate a Route Request (RREQ) message for the destination. If the correspondent node is within the ad hoc portion of the network, the source node receives a Route Reply (RREP) message indicating the route; otherwise, no RREP message is received from the other nodes within the ad hoc network.

The gateway node has a special operation upon receiving the RREQ messages. When it receives a RREQ, the foreign agent first checks whether the destination node is within the ad hoc network by determing whether that node is registered with it. If the node is registered with it, the gateway only replies to the source if it has a fresh routing entry to the destination. Otherwise, if the node is not registered with the foreign agent, the foreign agent may assume the destination is on the wired network and is reachable through its wired interface. In this case, the foreign agent replies to the source node with a special foreign agent (FA-RREP), indicating the route to the destination through itself.

There can be cases where the correspondent node is within the ad hoc network and is not registered with the foreign agent. In this case, the source node may receive an FA-RREP before the RREP from the actual destination. To eliminate this erroneous route, the source node may retain the route indicated by FA-RREP until the time interval to receive a normal RREP has expired. Alternatively, before sending out the FA-RREP, the foreign agent can attempt to ping the correspondent node on its wired interface and ensure the destination is reachable in the wired network.

Because of the special processing by the foreign agent, this scheme can adapt to different traffic by using different RREPs. If the destination is within the ad hoc network, the source will use the route indicated in the RREP from the mobile nodes in the network; otherwise, the source will use the route indicated by the gateway.

## IV. Performance Evaluation

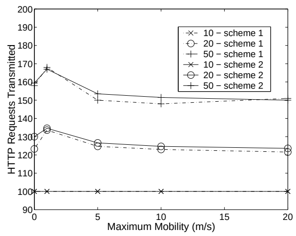
To evaluate the proposed schemes, simulations are performed in a wide range of scenarios. The schemes were implemented in the NS-2 simulator. Unless otherwise noted, the parameter values for Mobile IP and AODV are the same as those suggested in [4] and [6], respectively.

### A. Experimental Setup

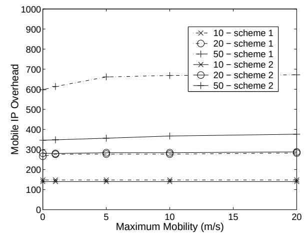
The simulations are evaluated in networks of 10, 20 and 50 nodes. As the number of nodes in the ad hoc network is increased, the size of the simulation area is also increased so that a consistent node density is maintained. The simulation areas are 330m$\times$330m, 670m$\times$670m and 1000m$\times$1000m, respectively.

All mobile nodes move according to the random waypoint mobility model. Node speeds are randomly distributed between zero and some maximum, where the maximum speed varies between 0 and 20 m/s. The pause time is consistently 10 seconds. Each data point represents an average of 10 runs with the same traffic models, but different randomly generated mobility scenarios.

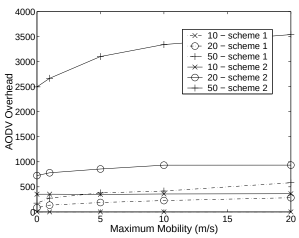
In all simulations there is a single foreign agent in the network that is connected through its wired interface to the wired



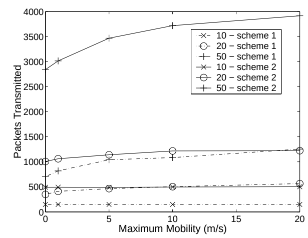

(a) Average Number of Session Requests.




(b) Mobile IP Overhead.




(c) AODV Overhead.




(d) Total Control Overhead.

Fig. 2. Performance Based on Web Traffic Applications.

network. Though the routing schemes apply when there are multiple foreign agents, we include only results from a single foreign agent for simplicity. In the first set of simulations, web traffic with HTTP sessions is used to evaluate the performance of the two routing schemes in the first application scenario described in section I. The scenario models a large percent of traffic as Internet traffic with numerous short TCP sessions. All the source nodes are within the ad hoc network and they randomly request web pages from the correspondent nodes on the wired network.

The second set of simulations examines the performance of the two routing schemes with different percentages of Internet (wired) traffic. All traffic is CBR traffic with 512 byte data packets at the sending rate of 10 packets per second. All the sources are within the ad hoc network; the correspondent nodes are either within the ad hoc network or reachable through the wired network.

### B. Simulation Results

*Web Traffic:* In this set of simulations, web traffic is used to evaluate the performance of the two routing schemes. 100 HTTP sessions are initiated by 10 random mobile nodes in the ad hoc network within 100 seconds.

Figure 2(a) shows the average number of HTTP requests (including retransmissions) of the two schemes with different network sizes. The number of transmissions in larger networks is higher because of the retransmission of requests caused by link breaks and network partitions. In figure 2(b), the Mobile IP overhead is generally higher with scheme 1 than scheme 2, due to the Agent Advertisements flooding the network. With scheme 2, only the 10 source nodes register

| Network Size | 10 nodes | 20 nodes | 50 nodes |
|---|---|---|---|
| MIP Registration (ms) | 15.8 | 26.3 | 36.2 |
| Route Discovery (ms) | 13 | 20.5 | 29.8 |
| Web Page Retrieval Scheme 1 (ms) | 29 | 37 | 54 |
| Web Page Retrieval Scheme 2 (ms) | 43 | 64 | 89 |

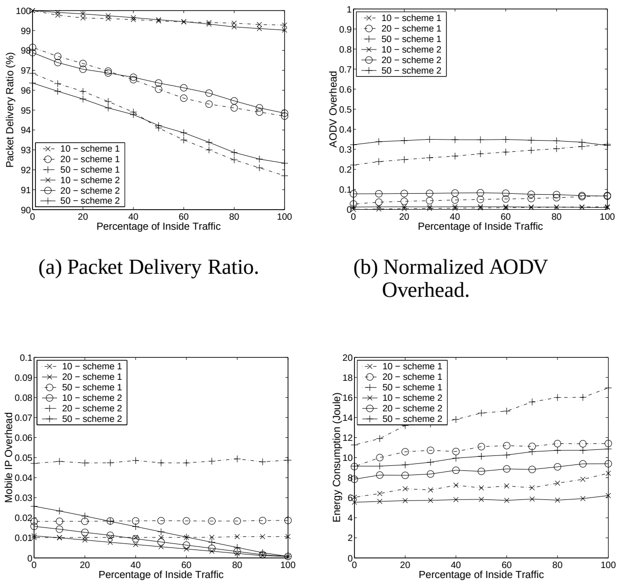
TABLE I
WEB ACCESS LATENCY.

with the foreign agent; the beacons are unicast only to these nodes. The difference is most significant with the largest network size. Figure 2(c) shows the AODV overhead of the two schemes. Scheme 2 has higher AODV overhead than scheme 1 because a source node always issues a RREQ when it initiates a data transmission. In scheme 1, only when the link between the node and the gateway breaks, is a RREQ issued. Figure 2(d) shows the total overhead of two schemes.

In addition to these results, we also investigated the web page retrieval latency and the average routing table size during the simulation for the two routing schemes. In table I, the MIP registration time includes the time for the node to receive the agent advertisement, send out the Registration Request and receive the Registration Reply. Route discovery includes the broadcasting of the RREQ and the latency to receive RREP. These two latencies are identical in the two schemes. However, in routing scheme 2, nodes only register with a foreign agent when they want to send Internet data traffic. Hence, they have the initial Mobile IP registration latency during the web page retrieval, as well as the route discovery latency. In routing scheme 1, on the other hand, nodes proactively register with the foreign agent before they originate data traffic; hence there is no Mobile IP latency during the retrieval, nor is there a route discovery latency. As a result, the web page retrieval time for scheme 2 is higher than that of scheme 1. Further, the MIP registration latency and the route discovery latency occupy a large percentage of the retrieval time. This latency may not be tolerable when users require real-time interaction. While not shown, the simulation results also show that the routing table size of scheme 2 is nearly double of that of scheme 1, because a route discovery and route table entry is needed for each destination.

*Mixed Traffic:* The second set of simulations examines the performance of the two routing schemes with different percentages of Internet traffic. The percentages vary from 0% to 100%. There are 10 CBR traffic sources in the ad hoc network. The destinations are either in the wired network or in the ad hoc network, as dictated by the percentage of Internet traffic. Other parameters in these simulations include maximum node mobility of 20m/s, agent advertisement interval of 15 seconds and simulation time of 900 seconds.

Figure 3(a) illustrates the packet delivery ratio with varying traffic locality. Traffic locality indicates the percentage of traffic with destinations within the ad hoc network. When the




(a) Packet Delivery Ratio.

(b) Normalized AODV Overhead.

(c) Normalized Mobile IP Overhead.

(d) Energy Consumption of the Network.

Fig. 3. Effects of Different Traffic Locality.

traffic locality is low, most of the traffic is Internet traffic going through the gateway; the packet delivery ratio of routing scheme 1 is slightly higher than scheme 2 because the periodic foreign agent advertisement messages help to update the route for the mobile nodes to the foreign agent. Thus fewer link breaks occur and packet loss is reduced. When the traffic locality is higher, the packet delivery ratio of scheme 2 decreases because the initial packets are sent directly to the gateway. These packets are transmitted on the erroneous route until the source receives the ICMP redirect message and discovers the route within the ad hoc network.

In figure 3(b), when the traffic locality increases, the normalized AODV overhead for scheme 1 increases, while it is fairly stable for scheme 2. Normalized overhead is a ratio of the number of control packets transmitted to the number of data packets received at the destination. Normalized Mobile IP overhead remains stable for scheme 1 while it decreases linearly for scheme 2 as the locality increases, as shown in figure 3(c). In scheme 2, as the traffic locality decreases, more nodes register with the foreign agent, resulting in increased MIP overhead.

Figure 3(d) shows the total power consumed by all the mobile nodes. Our energy consumption model is based on [7]; energy costs are 1.6W for transmissions and 1.2W for receptions. 1.0W is consumed when idle. The network energy consumption should be proportional to the total packet transmission in the network. Because the data packet transmissions are the same for the two approaches, the approach with the higher control overhead should have higher power consumption. However, in most of the experiments, scheme 1 experienced higher power consumption although it does not always have higher total control overhead. The reason is that periodic rebroadcast of Advertisement messages contributes much to this consumption. Although nodes do not retransmit duplicate packets, thereby reducing the control overhead, energy is still consumed by nodes to receive the packets.

## V. Conclusions

To combat the limitations of infrastructured wireless networks and provide Internet connectivity to ad hoc networks, hybrid networks can be deployed to support different types of applications. As wireless communication becomes increasingly prevalent, we envision hybrid ad hoc/infrastructured wireless networks becoming a viable networking solution. The Mobile IP and AODV routing protocols can work together to create a hybrid ad hoc/infrastructured network in which mobile nodes can discover multi-hop paths to foreign agents, thereby gaining Internet connectivity.

Different applications in this hybrid network may have varying requirements in terms of latency, scalability, etc. These different requirements affect the underlying routing schemes. This paper proposes two routing schemes for hybrid networks that meet different application requirements and traffic patterns. Simulation results show that with a large percentage of short web-based traffic sessions, using a gateway as a default router results in better performance with lower latency, fewer routing table entries, and manageable control overhead. When traffic locality is high and Internet traffic is only an occasional occurrence, the reactive routing scheme results in better performance with low control overhead and higher throughput.

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