Adaptive Multi-mode Routing in Mobile Ad Hoc Networks

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Abstract. Mobile ad hoc networks are wireless multi-hop networks with a completely distributed organization. The dynamic nature of these networks imposes many challenges on mobile ad hoc routing protocols. Current routing protocols do not take into the account the network context and therefore their performance is only optimal under certain network conditions. This paper proposes a novel concept for routing in mobile ad hoc networks, adaptive multi-mode routing, and demonstrates its feasibility and effectiveness.

1 Introduction

A mobile ad hoc network (MANET) is an autonomous system consisting of mobile nodes that communicate with each other over wireless links [1]. The network does not rely on any fixed infrastructure for its operation. Therefore nodes need to cooperate in a distributed manner in order to provide the necessary network functionality. One of the primary functions each node has to perform is routing in order to enable connections between nodes that are not directly within each others send range. Developing efficient routing protocols is a non trivial task because of the specific characteristics of a MANET environment [2]: the network topology may change rapidly and unpredictably because of node movements, the available bandwidth is limited and can vary due to fading or noise, nodes can suddenly join or leave the network… All this must be handled by the routing protocol in a distributed manner without central coordination. Consequently, routing in ad hoc networks is a challenging task and much research has already been done in this field, resulting in various routing protocols [3]. However, most current routing protocols are general purpose routing protocols that do not take into account the specific network conditions they operate under. As a consequence and as shown by various performance evaluation studies, their performance is only optimal under certain network conditions and no overall winner can be designated. In section 2, we discuss two commonly known routing techniques, proactive and reactive routing, and show that their performance strongly depends on the network conditions. This justifies the need to use different routing techniques depending

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on the network conditions. Therefore, in section 3 we propose a solution to this problem through the development of an adaptive multi-mode routing protocol and discuss the advantages and implementation issues of this new approach. In section 4, the feasibility and possible performance gain of our approach is demonstrated. Finally, conclusions are made in section 5.

2 Performance of Existing Routing Protocols

2.1 Classification of Routing Protocols for Mobile Ad Hoc Networks

Over the last few years, numerous routing protocols have been developed for ad hoc networks. Basically, these protocols can be categorized in the following two classes depending on the way they find routes: *proactive* routing protocols and *reactive* routing protocols.

Proactive routing protocols or table-driven routing protocols attempt to have at all times an up-to-date route from each node to every possible destination. This requires the continuous propagation of control information throughout the entire network in order to keep the routing tables up-to-date and to maintain a consistent view of the network topology. These protocols are typically modified versions of traditional link state or distance vector routing protocols encountered in wired networks, adapted to the specific requirements of the dynamic mobile ad hoc network environment.

Reactive protocols or on-demand routing protocols only set up routes when needed. When a node needs a route to a destination, a route discovery procedure is started. This procedure involves the broadcasting of a route request within the network. Once a route is established by the route discovery phase, a route maintenance procedure is responsible for keeping the route up-to-date as long as it is used.

Most other types of routing protocols [4] can be seen as variants of proactive and reactive techniques. Hybrid routing protocols try to combine proactive and reactive techniques in order to reduce protocol overhead. Nearby routes are kept up-to-date proactively, while far away routes are set up reactively. Position-based routing protocols use geographical information to optimize the routing process. Finally, hierarchical protocols, such as clustering protocols, introduce a hierarchy in the network in order to reduce the overhead and to improve the scalability. In the remainder of the paper we focus on the fundamental proactive and reactive techniques.

2.2 Performance Evaluation of Proactive and Reactive Routing Protocols

In the literature, many simulation studies have been performed in order to evaluate the performance of proactive and reactive routing protocols [5]. They all come to the conclusion that each technique has its advantages and disadvantages and can outperform the other depending on the network conditions. To illustrate this observation, we extensively simulated the performance of WRP (Wireless Routing Protocol) and

AODV (Ad Hoc On-Demand Distance Vector Routing) in the network simulator Glomosim [6].

WRP [7] is a proactive distance vector protocol in which nodes communicate the distance and the second-to-last hop for each destination through update messages sent at periodic times and on link changes. On receiving an update message, the node modifies its distance table and looks for better paths using this new information. The extra second-to-last hop information helps remove the counting-to-infinity problem most distance vector routing algorithms suffer from. Also, route convergence is speeded up when a link failure occurs.

AODV [8] builds routes using a route request - route reply query cycle. A source node that needs a new route, broadcasts a route request packet across the network. Nodes receiving this packet set up backwards pointers to the source node. If a node is either the destination or has a valid route to the destination, it unicasts a route reply back to the source, otherwise the request is rebroadcasted. As the reply propagates back to the source, nodes set up forward pointers to the destination. Once the source node receives the reply, data can be forwarded to the destination. On a link break in an active route, the node upstream of the link break propagates a route error message to the source node after which it can reinitiate route discovery.

In order to illustrate the dependence of protocol performance on the network conditions, we present the simulation results for both protocols in a 50 node static network, with nodes randomly distributed in a rectangular region of size 600m by 600m. Packets of size 512 bytes are sent at a rate of 10 packets per second by 5 and 20 sources respectively. The transmission range of all nodes is approximately 200 meter and the MAC layer model used is 802.11b direct sequence spread spectrum at 2Mbit/s. The performance metrics considered are the packet delivery ratio, the end–to-end delay and the number of control packets per data packet delivered.

Figure 1 presents the simulation results. When there are few traffic sources present in the network, both protocols succeed in delivering almost all data packets. However, the number of control packets AODV needs in order to deliver the data is significantly lower than WRP. In a static network, AODV only uses control packets to set up routes when they are needed, whereas WRP periodically exchanges routing update messages in order to keep all routes up to date. The end-to-end delay of both protocols is comparable. In these network conditions, the deployment of a reactive protocol is preferred.

When the number of sources increases to 20, WRP does not need additional control messages for keeping its routing tables up to date, which results in a lower number of control packets per data packet delivered and is opposite to the behavior of AODV. For these high network loads, the results become completely different. Both protocols suffer from a lower packet delivery ratio, because more transmitting nodes contend for the wireless medium causing congestion and packet loss. However, the effect of high network loads is more distinct for AODV. When packets are dropped due to congestion, the MAC layer protocol notifies AODV of the loss. AODV will assume a link break has occurred and reacts by sending a route error message back to the source and reinitiating a new route discovery, during which additional packets in the saturated buffers are dropped. This effect, together with the higher number of control packets results in a significant increase in number of control packets per data packet delivered and in end-to-end delay. This means that for high network loads, the use of proactive routing is advised.

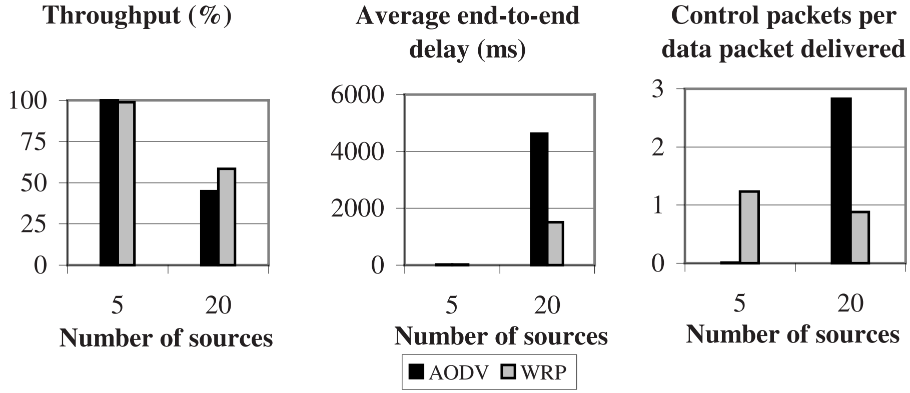

Fig. 1. Performance evaluation of WRP (proactive) and AODV (reactive) in a 50 node static network with nodes randomly distributed in a rectangular region of size 600m by 600m. Traffic is sent at a rate of 10 packets per second by 5 and 20 nodes respectively

This simulation result proves that the performance is strongly dependent on the network conditions. Apart from the number of traffic sources, also the network size, node density, send rate and mobility have influence on the performance.

So, basically both approaches rely on the propagation of control messages throughout the entire network in order to establish routes, but the way in which the broadcasting of control messages is applied differs completely. As a consequence, their performance will be different, with one technique outperforming the other depending on the network conditions.

3 Adaptive Multi-mode Ad Hoc Routing Framework

3.1 The Need for Adaptive Routing

The example presented in section 2.2 clearly shows the strong dependency of protocol performance on the network conditions. Existing routing protocols are unable to adapt to the networking context, which can result in a severe performance degradation. Ideally, devices should choose the optimal routing technique depending on the type of ad hoc network they participate in and the current network conditions in this network. For overhead and compatibility reasons it is currently not feasible having devices implementing different protocols and switching protocol according to the network conditions. Hybrid routing protocols such as the Zone Routing Protocol, Fisheye State Routing and SHARP [9] are already a first step into the development of routing protocols that combine multiple routing techniques, but they do not obtain the degree of adaptation we envision.

Therefore, we propose the development of an adaptive multi-mode routing protocol that has multiple compatible modes of operation (e.g. proactive, reactive, flooding or variants), where each mode is designed to operate as efficiently as possible in a given networking context. Simulation studies or analytical studies can be used to determine the optimal network conditions of the different modes. The main issue in the development of such a framework is that nodes need to be capable of monitoring and estimating the network conditions in their environment with as little overhead as possible. Based on these predictions nodes can adapt their mode of operation to the networking context and perform the best possible routing. In the following sections we present the framework of our novel adaptive multi-mode routing protocol.

3.2 The Adaptive Multi-mode Ad Hoc Routing Framework

Our framework (see figure 2) consists of two main components, a monitoring agent and the actual routing protocol, which we will now discuss in more detail.

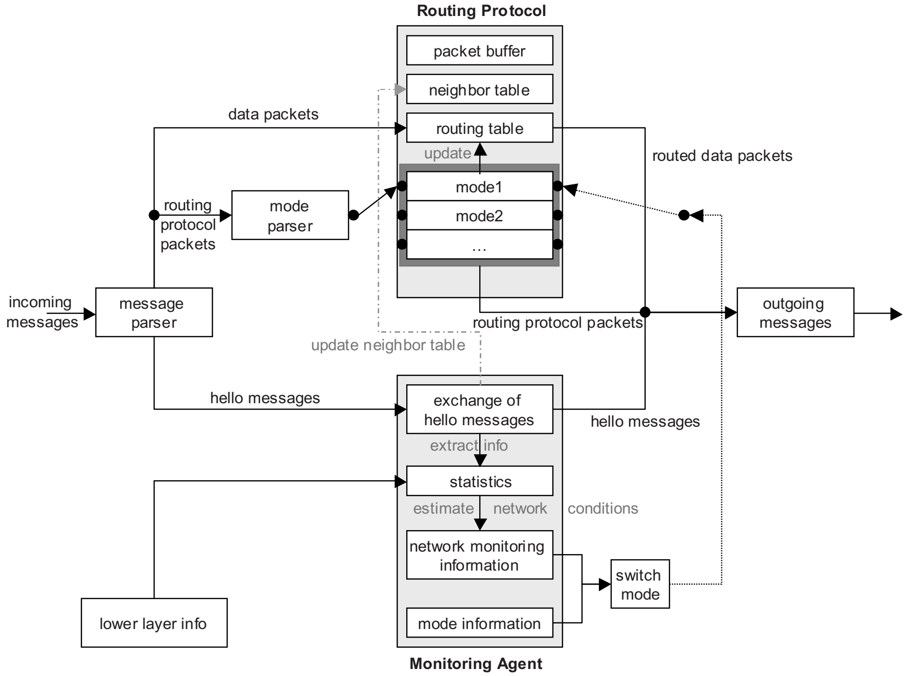

Fig. 2. Framework of the proposed adaptive multi-mode routing protocol

The monitoring agent is responsible for collecting information about the network conditions in the environment of the node. This is done in two ways. First of all, *local* *statistics* from the network layer or other layers are collected in the *statistics* component of the monitoring agent. These statistics can include, but are not limited to: the number of data packets routed, signal strength of the received packets, number of packets dropped due to congestion… Secondly, *non-local statistics* are collected through the periodic broadcasting of hello messages to the neighboring nodes. These hello messages provide two types of information. By receiving or not receiving hello messages the connectivity to other nodes is determined and link breaks are detected. In addition, the hello messages contain statistics and network monitoring information collected by the sender of the hello message, such as the observed network load and the mode of operation the node is currently in. In this way, by receiving hello messages, nodes are provided with information from their immediate environment.

When a node receives a hello message, the information in the message is extracted and stored in the statistics component. In addition, the connectivity and mode information is used to update the *neighbor table* in the routing protocol.

Periodically, the network monitoring information component processes the collected statistics. This component is responsible for extracting useful information about the networking context such as the network load or mobility. Based on simulation studies or analytical models, the *mode information* component has knowledge under which network conditions each of the available modes their performance is optimal. This information, together with the information provided by the *network monitoring information* component, is used by the *switch mode* component to decide whether or not the node should switch to a more efficient mode of operation. If the node has to switch to another mode of operation the routing protocol is informed.

When a message arrives, a *message parser* determines the message type. Hello messages are delivered to the monitoring agent; data and routing protocol packets are delivered to the routing protocol. The routing protocol has multiple modes of operation. When a routing protocol packet arrives, the *mode parser* determines the mode of the protocol packet and the packet is relayed to the appropriate mode component. According to the content of the protocol packet, the mode component takes the appropriate action (e.g. a reactive mode will relay a route request or answer with a route reply) and, if necessary, updates the main routing table. This table contains all valid route entries, possible coming from different modes. The different modes can use the information in the neighbor table in order to improve their efficiency. Packets that cannot be routed immediately can be stored in the packet buffer. At each moment only one mode is chosen as the active mode (as determined by the *switch mode* component), but protocol packets from nodes in another mode can also be received.

3.3 Compatibility Issues

As already stated, we want the different modes of operation of the adaptive protocol to be compatible. In this way, different modes in different parts of the network can coexist and each node can decide in a distributed manner when to switch to another mode. For instance, consider a large ad hoc network with a number of heavily loaded clusters of nodes. In these clusters it will be more efficient to proactively set up routes, whereas in the other parts of the network reactive routing is advised (assuming we only have a proactive and reactive mode). Another example is a static ad hoc network with a lot of traffic and a few highly mobile nodes. In this case, it would be more efficient that the highly mobile nodes set up their routes reactively and do not take part in the proactive routing process in the remainder of the network.

The development of compatible modes requires some compatibility issues to be resolved, which we will now illustrate for two cases, assuming the protocol has a proactive and reactive mode.

Case 1: Node *n* does not have a route entry for a data packet with destination *d* that has to be routed

- and *n* is currently in a reactive mode: if the route request was broadcasted throughout the entire network and no reply was received, node *d* is unreachable and the data packet is dropped
- and *n* is currently in a proactive mode: destination *d* can be located outside a proactive part of the network. Therefore, node *n* can use the functionality of the reactive mode to find a route by broadcasting a route request.

Case 2: Node *n* its mode is proactive

- and a neighbor *m* changes its mode from reactive to proactive: node *n* should send its current proactive tables to node *m*
- and a neighbor *m* changes its mode from proactive to reactive: node *n* removes all information related to node *m* from its proactive tables, as node *m* does not participate anymore in the proactive routing process. However, by simply removing this information, active connections that use node *m* as relay will now have a sub-optimal route or no route at all. Therefore, before cleaning up the proactive tables, this information will be used to create reactive entries for the active connections that use node *m* as relay node. As a consequence, running connections will not be influenced by the change in protocol mode. Finally, node *n* will send an update packet to inform neighboring nodes in proactive mode of this change.

The above examples illustrate that during the implementation of new modes care should be taken to sustain compatibility with the existing modes. Also, when writing modes, generic functions need to be provided, in order to easily integrate new modes.

3.4 Advantages of Adaptive Multi-mode Routing

Adaptive multi-mode routing has numerous advantages:

- Improved efficiency by adaptation: by its capability to adapt to the network, the routing protocol can provide better routing in networks with varying conditions. As mobile ad hoc networks are intrinsically characterized by a very dynamic nature, this is certainly a big advantage opposed to existing routing protocols that are not aware of the network context.
- Compatibility: when the modes are developed with built-in compatibility in mind, different modes in different parts of the network can coexist.

- User friendliness: devices can participate seamlessly in different types of ad hoc networks without the need to manually switch to another protocol, because the protocol will adapt itself to the current network conditions. This user friendliness can certainly be an advantage.
- Future proof: the use of different modes eases the future development of the protocol. Existing modes can be extended or enhanced or new modes can be added without the need to completely change or rethink the protocol design.

4 Performance Evaluation

Based on the framework described in section 3, we developed a proof of concept version of the proposed adaptive multi-mode ad hoc routing protocol with two compatible modes of operation, one proactive mode and one reactive mode. These modes are based on WRP and AODV respectively. The functionality of the network monitoring agent is currently limited to determining the network load based on the number of packets to route and the number of neighbors, which are affected by the packet transmissions. This information is exchanged with the neighboring nodes by broadcasting hello messages. When the observed network load exceeds a certain threshold, which was now manually determined, nodes change their mode of operation from reactive to proactive. Once the load falls below this threshold, the mode is set back to reactive.

We simulated the performance of the initial implementation of our adaptive multimode ad hoc routing protocol (AMAHR) in a 50 node static network, with nodes randomly distributed in a rectangular region of size 600m by 600m. Packets of size 512 bytes are sent at a rate of 10 packets per second. The number of sources is initially set to 5. After 1300 seconds the number of sources is increased to 20 and after 2500 seconds the number of sources is set back to 5. The transmission range of all nodes is approximately 200 meter and the MAC layer model used is 802.11b direct sequence spread spectrum at 2Mbit/s. The hello interval is 1 second in the proactive mode and 5 seconds in the reactive mode. Again, the performance metrics considered are the packet delivery ratio, the end–to-end delay and the number of control packets per data packet delivered. Figure 3 shows the evolution of these three performance metrics over time.

The results clearly show that AMAHR combines the advantages of both proactive and reactive routing by its capability to adapt to the network context. Initially, the observed traffic load is low and nodes set up routes reactively. Once the number of traffic sources increases to 20, the network monitoring component detects the increase in network load. The observed network load then exceeds the defined threshold and nodes switch to proactive routing.

As a consequence, under low network loads our adaptive protocol has the high packet delivery ratio and low control overhead of AODV. The number of control packets per data packet delivered is slightly higher than the reactive routing protocol, due to the periodic exchange of hello messages needed for monitoring the network environment. However, this is not necessarily a drawback, as the neighborhood information provided by the hello messages could be used for implementing a more efficient broadcasting scheme, thereby reducing the control overhead.

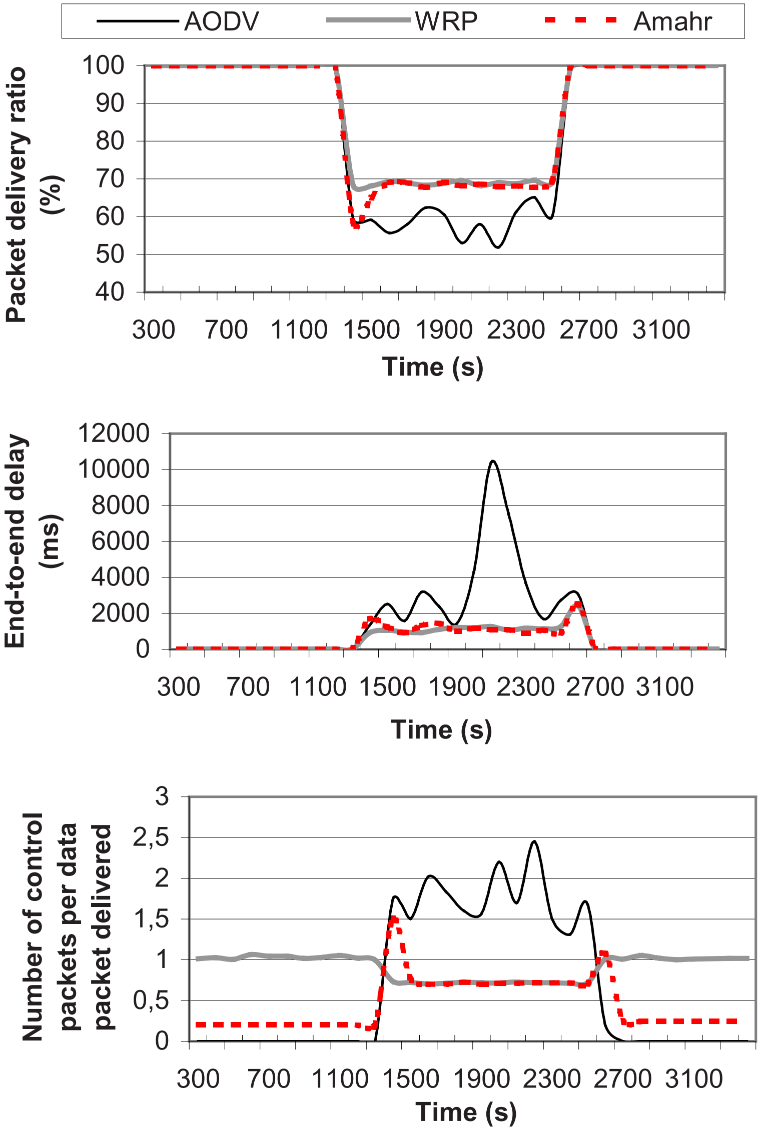

Fig. 3. Performance evaluation of WRP (proactive), AODV (reactive) and AMAHR in a 50 node static network with nodes randomly distributed in a rectangular region of size 600m by 600m. Traffic is sent at a rate of 10 packets per second and the number of sources is increased from 5 to 20 after 1300 seconds and back decreased to 5 sources after 2500 seconds

By changing its mode from reactive to proactive when the traffic load increases, AMAHR achieves the high packet delivery ratio and low control overhead and end-to-end delay of WRP. Only at the time nodes switch to another mode, the performance is less than the optimum, as nodes need time to detect the change in network conditions.

Our simulation results clearly show the advantages of being able to adapt the routing protocol to the network context. Currently, only a proof of concept version of the protocol has been developed in order to proof the feasibility of this novel approach. Further research is needed to include other network context information such as mobility and to define the thresholds that determine when to switch to another mode. Also, attention should be given to the stability of the protocol (e.g. continuous alternating between modes should be avoided) and the performance of the protocol in networks where network conditions differ from place to place.

5 Conclusions

In this paper, we have shown the need to adapt the deployed routing technique to the network conditions in order to obtain an overall optimal performance. To this end, we presented the concept of an adaptive multi-mode routing protocol that can offer an optimal performance in terms of packet delivery ratio, control overhead and/or delay under varying network conditions by its capability to adapt to the network context. The details of the framework and its advantages were discussed. Finally, by means of a proof of concept implementation the feasibility and effectiveness of the proposed approach has been demonstrated.

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