Performance Comparison of Multi-Path AODV and DSR Protocols in Hybrid Mesh Networks

Asad Amir Pirzada
†Queensland Research Laboratory,
National ICT Australia Limited,
Brisbane, QLD 4000, Australia.
Email: Asad.Pirzada@nicta.com.au

Marius Portmann† and Jadwiga Indulska†
School of Information Technology and Electrical Engineering,
The University of Queensland, Australia,
Brisbane, QLD 4072, Australia.
Email: {marius, jaga}@itee.uq.edu.au

***Abstract*— Wireless Mesh Networks (WMNs) have gained a lot of attention recently. Features such as self-configuration, self-healing and the low cost of equipment and deployment make WMN technology a promising platform for a wide range of applications. Traditional ad-hoc routing protocols are typically used to deal with the dynamic nature of these networks, which is mainly due to mobility. However, these protocols typically suffer from a number of shortcomings, such as high routing overhead and limited scalability. More recently, it has been shown that multi-path ad-hoc routing protocols have a number of advantages over their single-path counterparts, including reduced overhead and increased reliability. This motivates the work presented in this paper, which provides a comparison of AOMDV and DSR-MP, the multi-path variants of AODV and DSR. We specifically study the performance of these protocols in a hybrid wireless mesh network, where static mesh routers and mobile clients collaborate to implement network functionality such as routing and packet forwarding. Based on extensive simulations, we present a comparative analysis covering performance metrics such as packet loss, latency and path optimality.**

Keywords: Multi-path, routing, mesh, wireless, network.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) can be broadly categorised into three main types according to their architecture [1]: Infrastructure mesh, client mesh and hybrid mesh.

An infrastructure mesh consists of relatively static mesh routers operating in ad-hoc mode. Typically, one or more of these mesh routers act as gateways to the WIRED_NETWORK and provide WAN connectivity for the entire WMN. The key difference to traditional wireless LANs is that the wired backhaul is replaced with a wireless multi-hop network infrastructure provided collectively by the MESH_ROUTERs. An infrastructure WMN can be thought of as a normal WLAN, formed with the help of Access Points (MESH_ROUTERs) connected wirelessly in ad-hoc mode [2], preferably on a different radio or channel [3] and providing connectivity to the WIRED_NETWORK.

A client mesh is essentially a pure mobile ad-hoc wireless network with each MESH_CLIENT acting as an independent router with no centralized routing control [4]. In a client mesh architecture, the network is made up of mobile client devices only, without any dedicated network infrastructure. Consequently, client devices are responsible for implementing network functionality such as routing and forwarding of packets.

A Hybrid mesh architecture is the most generic and interesting version of a WMN. Hybrid WMNs are formed through the amalgamation of infrastructure and client mesh networks. In this scenario, MESH_ROUTERs provide the basic backbone infrastructure and MESH_CLIENTs actively participate in the operation of the network, as shown in Fig. 1. Mobile clients can, therefore, provide a dynamic extension of the more static infrastructure part of the network. Communication in a Hybrid WMN can take place in the following four modes:

- MESH_CLIENT-to-MESH_CLIENT
- MESH_CLIENT-to-MESH_ROUTER
- MESH_ROUTER-to-MESH_ROUTER
- MESH_ROUTER-to-WIRED_NETWORK

In the MESH_CLIENT-to-MESH_CLIENT communication mode, the wireless nodes talk with each other in a peer-to-peer manner. Since MESH_CLIENTs are typically mobile, special ad-hoc routing protocols perform the critical task of discovering valid routes in this highly dynamic network environment. Based upon their mode of execution, these protocols can be categorized into two basic types: Reactive or Proactive [5]. Since MESH_CLIENTs generally have limited battery power, reactive routing protocols endeavour to limit communication

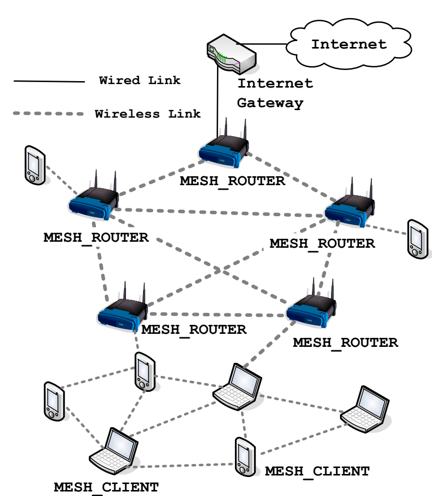

Fig. 1. Hybrid Wireless Mesh Network

overhead by discovering routes only when this is absolutely necessary. In contrast, proactive routing protocols continually establish and maintain routes in order to avoid the latency incurred due to new route discoveries.

MESH_CLIENT-to-MESH_ROUTER communication is similar to the MESH_CLIENT-to-MESH_CLIENT communication mode. MESH_CLIENTs need to discover the optimal (e.g. nearest) MESH_ROUTERs to gain access to the infrastructure part of the network. This type of communication is also highly dynamic due to client-mobility and therefore traditional ad-hoc routing protocols can be employed.

If we can assume that MESH_ROUTERs are reasonably static, any traditional routing protocol such as OSPF [6] or RIP [7] may be employed to provide routing in the MESH_ROUTER-to-MESH_ROUTER mode. However, in case the MESH_ROUTERs exhibit a significant level of mobility, ad-hoc routing protocols would also be required for MESH_CLIENT-to-MESH_ROUTER communication.

The MESH_ROUTER-to-WIRED_NETWORK configuration is similar to the previous configuration where, depending upon the mobility of the MESH_ROUTERs, either traditional or ad-hoc routing protocols can be used.

Wireless Mesh Networks have gained tremendous interest in recent years. One of the key characteristics of WMNs is the ability to self-organize and self-configure, which allows rapid and easy deployment. Since no back-haul wiring infrastructure is required, deployment of WMNs is significantly more cost-effective than traditional wireless network deployments. This allows WMNs to be deployed temporarily as well as on a permanent basis. The fact that WMNs can be built with widely available low-cost commodity hardware based on IEEE 802.11 standards further adds to their appeal. These features make WMNs an attractive technology for a wide range of applications such as public safety, intelligent transportation systems and building automation.

Most traditional ad-hoc routing protocols establish a single path from a source to a destination. It has been shown that multi-path ad-hoc routing protocols, which establish multiple disjoint paths during a single route discovery phase, have a number of benefits. Multi-path protocols typically have a lower overhead, lower packet loss rate and increased reliability compared to their single-path counterparts [8].

DSR and AODV are probably the two most prominent ad-hoc routing protocols and research is currently underway to study their suitability for Wireless Mesh Network environments [9] [10]. These protocols are inherently single-path, i.e. they establish and maintain a single path from a source to a destination. A number of multi-path routing protocols are available for ad-hoc wireless networks, but to the best of our knowledge, no study has been done to compare their performance in the context of wireless mesh networks, and specifically for hybrid wireless mesh networks. In this paper, we provide a comparison of the performance of AOMDV and DSR-MP, the multi-path variants of AODV and DSR. We use simulations to evaluate various performance metrics for a range of client mobility conditions.

The remainder of the paper is organized as follows. In Section II, we give an overview of the two multi-path routing protocols that we are considering. Section III describes our simulation environment and the relevant parameters and metrics. Simulation results and a corresponding analysis are presented in Section IV. Finally, Section V concludes the paper.

II. Multi-Path Routing Protocols

A. Ad-hoc On-Demand Multi-path Distance Vector Routing Protocol (AOMDV)

AODV [11], the single-path variant of AOMDV [8], is inherently a distance vector routing protocol that has been optimised for ad-hoc wireless networks. It is an on demand protocol as it finds the routes only when required and is hence also reactive in nature. AODV borrows basic route establishment and maintenance mechanisms from the Dynamic Source Routing (DSR) protocol and hop-to-hop routing vectors from the Destination-Sequenced Distance-Vector (DSDV) routing protocol [12]. To avoid the problem of routing loops, AODV makes extensive use of sequence numbers in control packets.

When a source node intends to communicate with a destination node whose route is not known, it broadcasts a ROUTE_REQUEST packet. Each ROUTE_REQUEST packet contains an ID, source and the destination node IP addresses and sequence numbers, together with a hop count and control flags. The ID field uniquely identifies the ROUTE_REQUEST packet. The sequence numbers indicate the freshness of control packets and the hop-count maintains the number of nodes between the source and the destination. Each recipient of the ROUTE_REQUEST packet that has not seen the source IP and ID pair, or does not maintain a fresher (with larger sequence number) route to the destination, rebroadcasts the packet after incrementing the hop-count. Such intermediate nodes also create and preserve a reverse route to the source node for a certain period of time. When the ROUTE REQUEST packet reaches the destination node or any node that has a fresher route to the destination, a ROUTE_REPLY packet is generated and unicast back to the originator of the ROUTE_REQUEST packet. Each ROUTE_REPLY packet contains the destination sequence number, the source and the destination IP addresses, a route lifetime, a hop count, as well as control flags. Each intermediate node that receives the ROUTE_REPLY packet increments the hop-count, establishes a forward route to the source of the packet and sends the packet via the reverse route.

To preserve connectivity information, each node executing AODV can use link-layer feedback or periodic HELLO messages to detect link breakages to nodes that it considers as its immediate neighbours. In case a link break is detected for a next hop of an active route, a ROUTE_ERROR message is sent to the active neighbours that were using that particular route.

In order to facilitate multi-path support in AODV, a number of extensions have been proposed [13] [14]. AOMDV is one such extension that provides loop-free and disjoint alternate paths. During route discovery, the source node broadcasts a

ROUTE_REQUEST packet that is flooded throughout the network. In contrast to AODV, each recipient node creates multiple reverse routes while processing the ROUTE_REQUEST packets that are received from multiple neighbours. However, care is taken to verify loop freedom and path disjointness while creating these reverse routes. Similarly, one or more ROUTE_REPLY packets are generated in response to each received ROUTE_REQUEST packet, either by the destination node itself or any node having a route to the destination.

These ROUTE_REPLY packets, when received by the source or intermediate nodes, result in the creation of multiple forward routes leading to the same destination. To ensure loop freedom and path disjointness, AOMDV requires a minor modification to the AODV ROUTE_REQUEST and ROUTE_REPLY packet headers, to include the last hop information that acts as a unique path identifer. AOMDV uses this information to ensure loop freedom while creating multiple paths to a single destination. The AOMDV protocol guarantees path or link disjointness if any two paths to a single destination have unique next hops as well as unique last hops. Similarly, AOMDV assures loop freedom by not preserving multiple paths with identical sequence numbers to a single destination.

B. Dynamic Source Routing (DSR-MP)

As the name suggests, the Dynamic Source Routing (DSR) [15] protocol uses IP source routing. All data packets that are sent using the DSR protocol contain the complete list of nodes that the packet has to traverse. DSR uses three different types of control packets for route discovery and maintenance, i.e. ROUTE_REQUEST, ROUTE_REPLY and ROUTE_ERROR. During route discovery, the source node broadcasts a ROUTE_REQUEST packet with a unique identification number. The ROUTE_REQUEST packet contains the address of the target node to which a route is desired. All nodes that have no information regarding the target node or have not seen the same ROUTE_REQUEST packet append their IP addresses to the ROUTE_REQUEST packet and rebroadcast it. In order to control the spread of the ROUTE_REQUEST packets, the broadcast is done in a non-propagating manner with the IP Time-To-Live (TTL) field being incremented in each route discovery. The ROUTE_REQUEST packets keep on spreading until they reach the target node or any other node that has a route to the target node.

The recipient node creates a ROUTE_REPLY packet, which contains the complete list of nodes that the ROUTE_REQUEST packet has traversed. Depending on the implementation, the target node may respond to one or more incoming ROUTE_REQUEST packets. Similarly, the source node may accept one or more ROUTE_REPLY packets for a single target node. The selection of the ROUTE_REPLY can be made based on minimal hop count or latency.

In the multi-path version (DSR-MP) [16] of the DSR protocol, each ROUTE_REQUEST packet that is received by the destination is responded to with an independent ROUTE_REPLY packet. However, only those ROUTE_REQUESTs are replied to which are link-wise disjoint from the primary source route. Upon receipt of these ROUTE_REPLY packets, the source node caches the redundant routing information contained in these packets. This routing information is subsequently used to form alternate routes when the primary or secondary routes fail. The source node uses this information to create routes until the cached information becomes invalid, upon which a new route discovery is initiated [17].

For optimisation reasons, nodes maintain a Path Cache or a Link Cache [18]. The former stores complete paths to a particular destination, while the latter only caches information related to individual links. The advantage of the Link Cache scheme is that it allows alternate paths to a destination even when some of the intermediate links have failed. Nodes that either forward or overhear data and control packets add all useful information to their respective cache. This information is used to limit the spread of control packets for subsequent route discoveries.

III. Simulation Environment

A. Set-up

To evaluate and compare the effectiveness of these two multi-path routing protocols in a hybrid wireless mesh network, we performed extensive simulations in NS-2 [19]. Each simulation is carried out under a different mobility and traffic pattern and the performance metrics are obtained by ensemble averaging [20] over 50 simulation runs. AOMDV and DSR-MP protocols assisted by the MESH_ROUTERs are represented as AOMDV-Mesh and DSR-MP-Mesh respectively. The simulation parameters are listed in Table I.

TABLE I
TABLE 1: SIMULATION PARAMETERS

Examined Protocol	AOMDV and DSR-MP
Simulation time	900 seconds
Simulation area	1000 x 1000 m
Number of MESH_CLIENTs	50
Number of MESH_ROUTERs	16
Movement model	Random way-point
Propagation Model	Two-ray Ground Reflection
Transmission range	250 m
Maximum speed	20 m/s
Pause time	10 seconds
Traffic type	CBR (UDP)
Maximum Connections	20
Payload size	512 bytes
Packet rate	4 pkts/sec

B. Mesh Structure

A mesh network covering an area of 1 square km is established using 16 static MESH_ROUTERs (numbered 51 to 66) distributed according to a regular grid topology, as shown in Fig. 2. These routers assist in establishing 20 simultaneous connections between the mobile MESH_CLIENTs (numbered 1-50). Source and destination of these connections are randomly chosen among the MESH_CLIENTs.

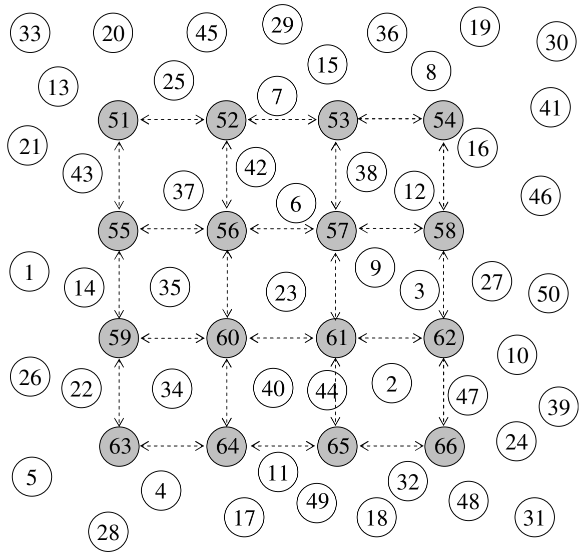

Fig. 2. Structure of the Mesh Network

C. Mobility Model

We use the random way-point mobility model, in which a MESH_CLIENT first waits for the pause interval and then moves to a randomly chosen position with a velocity chosen randomly between 0 m/s and 20 m/s, waits there for the pause time, and then moves on to another random position.

D. Communication Model

The IEEE 802.11 Distributed Coordination Function (DCF) is used as the MAC layer. All ROUTE_REQUEST packets are broadcasted using the un-slotted Carrier Sense Multiple Access protocol with Collision Avoidance (CSMA/CA). In CSMA/CA each sending node waits for a vacant channel by sensing the medium. If the channel is clear, the node seizes the channel and transmits the data. In case of a collision, the colliding stations abort transmission and wait using a binary exponential back-off algorithm. To unicast packets, a node first reserves the channel by transmitting a short Ready-to-Send (RTS) frame. The intended recipient node sends a Clear-to-Send (CTS) frame to the RTS sender in response. All nodes overhearing the RTS or CTS frames desist from transmitting for the Network Allocation Vector (NAV) interval. Upon receipt of the CTS, the packet is transmitted and acknowledged by the recipient [21].

E. Metrics

Our simulation provides the following performance metrics:

1) **Packet Loss.** This is the number of packets that were lost due to unavailable or incorrect routes, MAC layer collisions or through the saturation of Interface Queues [22].
2) **Aggregate Goodput.** It is the total amount of application layer data in bps that is successfully transmitted in the network.
3) **Packet Delivery Percentage.** It is the ratio between the number of packets received by the application layer of destination nodes to the number of packets sent by the application layer of source nodes.
4) **Routing Packet Overhead.** This is the ratio between the total number of control packets generated to the total number of data packets received during the simulation time.
5) **Average Latency.** The mean time (in seconds) taken by the data packets to reach their destinations.
6) **Path Optimality.** The ratio between the number of hops of the shortest path to the number of hops in the actual path taken by the packets.

IV. Results and Analysis

The simulation results shown in Fig. 3 indicate that the presence of static MESH_ROUTERs in the network significantly improves the packet delivery rate of the multi-path routing protocols and lowers the routing overhead in comparison to a pure client mesh architecture, consisting of mobile clients only. The number of data packets dropped by AOMDV-Mesh and AOMDV are significantly lower than for the DSR-MP-Mesh and DSR-MP protocols. AOMDV utilizes its multi-path functionality at each hop, while DSR-MP provides its multi-path facility only at the source node, with minimal support for en-route re-direction. This enables AOMDV to use alternate routes to support the ongoing connections and thus lowers the packet drop rate. In cases where no alternate paths are available at an intermediary node and no routes can be discovered in the maximum route discovery interval, packets are simply dropped.

DSR-MP makes use of its aggressive caching strategy by preferring routes present in the cache over newer route discoveries. Thus, if a source finds a neighbouring link suddenly unavailable, it constructs an alternate path to the destination using the cached information and does not initiate a new route discovery. However, under high mobility, these paths frequently contain inaccurate information, therefore, we observe a significant increase of packet loss.

AOMDV-Mesh and DSR-MP-Mesh are assisted by the static MESH_ROUTERs, which essentially provide semi-static gratuitous routes to the MESH_CLIENTs. These semi-static routes consist of a static route portion, containing the MESH_ROUTERs, and a dynamic route portion, comprised of the MESH_CLIENTs. Thus, the addition of the MESH_ROUTERs decreases the probability of link failure and therefore reduces the overall packet loss.

The lower packet loss of the AOMDV-Mesh and DSR-MP-Mesh protocols contributes to their higher forwarding rate, where intermediary nodes successfully forward packets in accordance with the routing protocol. The aggregate goodput of the multi-path protocols, which are assisted by the MESH_ROUTERs, is significantly higher than their unassisted counterparts. However, as the packet loss increases with mobility, the goodput of all protocols drops with the increase

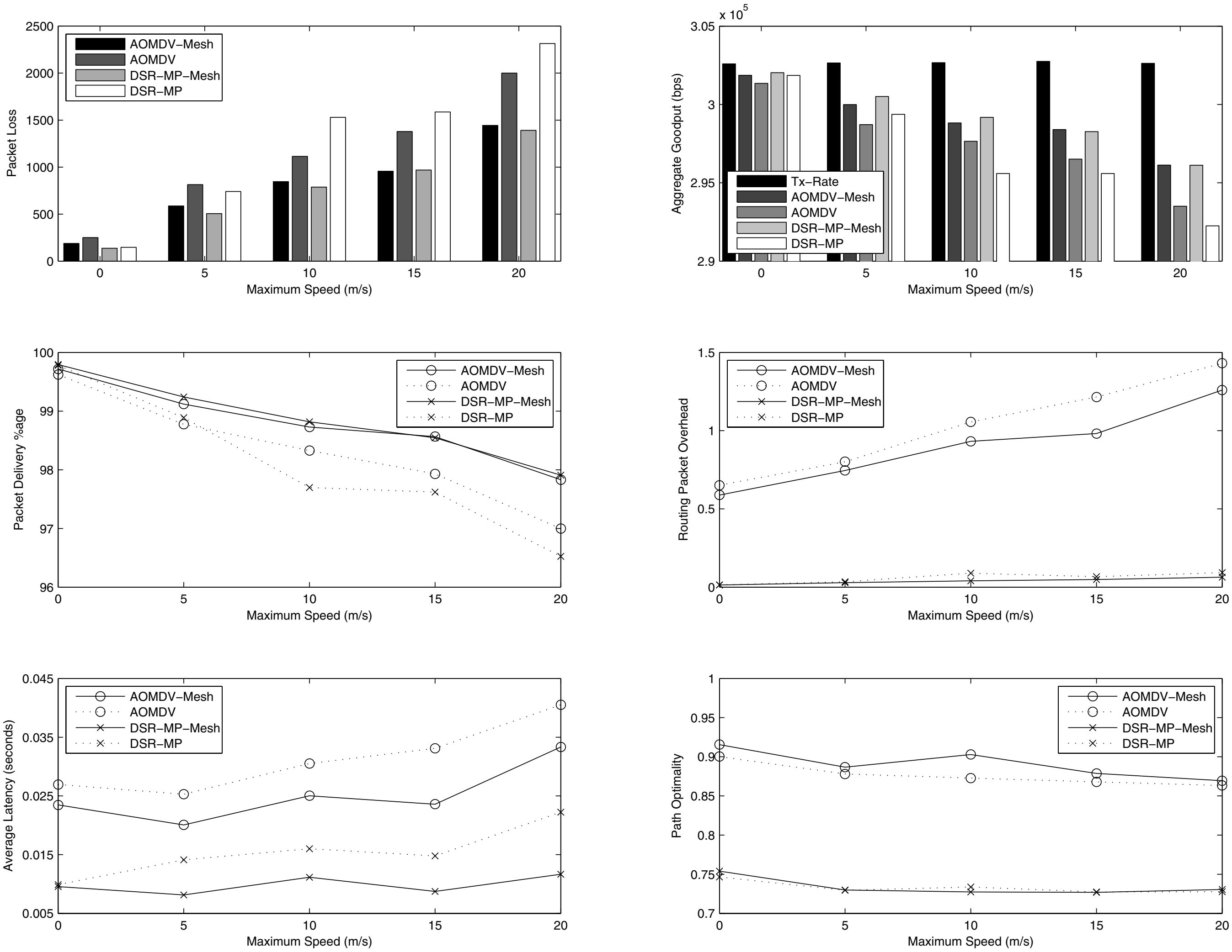

Fig. 3. Simulation of Multi-Path Routing Protocols

in speed, even when the transmission rate (Tx-Rate) is kept constant.

Both AOMDV-Mesh and DSR-Mesh are able to achieve a high packet delivery ratio under both static and dynamic environments, compared to the standard AOMDV and DSR-MP. At zero mobility, AOMDV-Mesh achieves a 99.76% packet delivery rate, which gradually drops to 97.83% when the speed of the `MESH_CLIENT`s reaches 20 m/s. DSR-MP has a 99.78% packet delivery rate when the network is totally static. This delivery rate then gradually drops to 97.92% at speeds of 20 m/s.

The routing overhead of the AOMDV protocol gradually increases with the increase in the network mobility due to frequent link breakages. AOMDV endeavours to establish and maintain multiple paths simultaneously and in doing so generates more routing packets. AOMDV's preference for fresher routes over stale ones requires extra `ROUTE_REQUEST` packets to be frequently propagated in the network. However, the presence of static `MESH_ROUTER`s helps in lowering the routing overhead. On average, AOMDV-Mesh generates one routing packet for every two data packets in comparison to AOMDV, which generates almost one routing packet for every single data packet.

In contrast to AOMDV, DSR-MP makes effective use of its inherent caching strategy to limit the control packet overhead. The protocol populates its cache using a variety of mechanisms, including promiscuous mode overhearing, learning while forwarding etc. This information is then rigourously used to suppress subsequent route discoveries. The routes containing `MESH_ROUTER`s, which are present in a `MESH_CLIENT`'s cache, remain relatively stable over a period of time. This helps DSR-MP-Mesh to lower its routing overhead to almost one control packet for every ten data packets.

The latency of the network is primarily determined by the route establishment time. A source node executing DSR-MP makes use of the cached routing information and is therefore able to quickly find routes. However, with the increase in node mobility the cached routes tend to become stale. This causes more route discoveries to be initiated, which increases the latency in the network. In AOMDV, path selection has to be made at the destination as well as at each forwarding node. This in turn increases the latency of the network. However, the generation of gratuitous replies by the nearest available MESH_ROUTER helps in lowering the latency of the network for AOMDV-Mesh or DSR-MP-Mesh.

The path optimality of both AOMDV protocols remains higher than for the DSR-MP protocols. The route maintenance mechanism of AOMDV requires known routes to be frequently purged. This results in a new route discovery for every new data connection. The routes returned from these route discoveries are relatively close to the optimal routes. In contrast, the DSR-MP protocol variants maintain routes in the cache for a significant amount of time and use this information to create alternates routes in the network, without initiating new route discoveries. Thus the routes, formed using the cached information, elongate over time and deviate from the shortest possible routes.

V. Conclusions

Hybrid Wireless Mesh networks employ ad-hoc routing protocols, which can satisfy both their static and mobile requirements. These routing protocols facilitate on-the-fly establishment of routes in a highly dynamic environment. This comes at a cost of relatively high routing overhead due to their flooding-based route discovery mechanism. Multi-path ad-hoc routing protocols have reduced overhead and provide a number of other advantages over their single-path counterparts. In this paper, we provide a comparison of AOMDV and DSR-MP, two well known multi-path ad-hoc routing protocols. We specifically studied their performance in a wireless hybrid mesh network comprising of static MESH_ROUTERs and dynamic MESH_CLIENTs. Our results indicate that both protocols, when assisted by MESH_ROUTERs, have a high packet delivery rate even under excessive MESH_CLIENT mobility. Compared to DSR-MP, AOMDV is able to establish more optimal paths at the cost of a higher routing overhead. On the other hand, DSR-MP has lower packet latency due to its effective utilisation of available routing cache. The performance of both multi-path routing protocols is greatly influenced by the number of MESH_ROUTERs along with their placement in the network. These MESH_ROUTERs aid the routing protocols in provisioning of reliable gratuitous routes, which in turn reduce the packet losses, improve the packet delivery ratio and lower the latency of the network.

Acknowledgements

National ICT Australia is funded by the Australian Government's Department of Communications, Information Technology, and the Arts and the Australian Research Council through Backing Australia's Ability and the ICT Research Centre of Excellence programs and the Queensland Government.

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