AODV-HM: A Hybrid Mesh Ad-hoc On-demand Distance Vector Routing Protocol

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Wireless Mesh Networks (WMNs) have recently gained increasing attention and have emerged as a technology with great potential for a wide range of applications. WMNs can be considered as a superset of traditional mobile ad-hoc networks (MANETs), where the network is comprised of mobile client devices MESH_CLIENTs. In addition to MESH_CLIENTs, a WMN can also contain relatively static devices called mesh routers (MESH_ROUTERs). Such hybrid WMN *are characterized by a high level of heterogeneity, since static MESH_ROUTERs are typically much less resource constrained than mobile MESH_CLIENTs, and are also often equipped with multiple radio interfaces. Traditional ad-hoc routing protocols do not differentiate between these types of nodes and therefore cannot achieve optimal performance in hybrid WMNs. In this paper, we propose simple extensions to the Ad-hoc On-demand Distance Vector (AODV) routing protocol, which aim to take advantage of the heterogeneity in hybrid WMNs by preferentially routing packets via paths consisting of high capacity MESH_ROUTERs. In addition, we implement a simple channel selection scheme that reduces interference and maximizes channel diversity in multi-radio WMNs. Our simulation results show that in hybrid WMNs, our extensions result in significant performance gains over the standard AODV protocol*[1].

Classification: C2.2 [Computer-Communication Networks]: Network Protocols — Routing protocols

General Terms: Mesh, Routing, Performance

Additional Key Words and Phrases: Wireless Mesh Networks, Routing, Hybrid Mesh Networks, Channel Diversity

1. INTRODUCTION

Wireless Mesh Networks (WMNs) are self-organizing and self-configuring wireless networks, typically implemented with IEEE 802.11 hardware. In conventional wireless LANs, clients communicate with access points via a single-hop wireless link and access points are interconnected via a wired backbone infrastructure. WMNs do not rely on such a wired backhaul and implement connectivity via a wireless multi-hop network. Their robustness, self-organizing and self-

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[1] This paper extends upon our previous research paper titled "Hybrid Mesh Ad-hoc On-demand Distance Vector Routing Protocol", published in the proceeding of the Thirtieth Australasian Computer Science Conference (ACSC'07), Ballarat, Australia, Vol 29(1), pages 49-58.

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configuring nature, and the low cost of wide area deployment make WMNs an attractive platform for a wide range of applications, such as public safety and emergency response communications, intelligent transportation systems, or community networks.

We can differentiate between two types of nodes in a WMN: MESH_ROUTERs and MESH_CLIENTs. MESH_ROUTERs are relatively powerful and static nodes, which have either access to mains power or are equipped with high capacity batteries. In addition, MESH_ROUTERs typically have multiple radio interfaces, which significantly increases the transmission capacity if the radios are operated on orthogonal channels. In contrast to MESH_ROUTERs, MESH_CLIENTs are relatively resource constrained mobile client devices, such as WiFi-enabled PDAs. These devices usually have only a single radio interface and their key constraint is limited battery power.

A WMN that is entirely comprised of MESH_ROUTERs is referred to as an infrastructure WMN, whereas a client WMN is a network made up of client devices only (Akyildiz and Wang, 2005). A client WMN is essentially identical to a pure mobile ad-hoc network (MANET) (Pirzada *et al*, 2006), and we can therefore consider WMNs a superset of MANETs. A hybrid WMN, such as illustrated in Figure 1, consists of both MESH_ROUTERs and MESH_CLIENTs, with both types of nodes performing routing and forwarding functionality. In this case, MESH_ROUTERs form the (wireless) backbone of a hybrid WMN, whereas MESH_CLIENTs can be seen as a dynamic extension.

Current routing protocols for WMNs can be roughly grouped into two categories. The first category consists of protocols that are based on traditional routing protocols for wired networks such as RIP (Routing Information Protocol) (Malkin, 1998) or OSPF (Open Shortest Path First) (Moy, 1998). Since these protocols are not able to handle node mobility or highly dynamic networks in general, their application is restricted to relatively static infrastructure WMNs.

The second category consists of protocols that are based on MANET routing protocols. Tremendous research efforts have been made in this area over the last few years and an impressive number of mobile ad-hoc routing protocols has been proposed (Royer and Toh, 1999). These

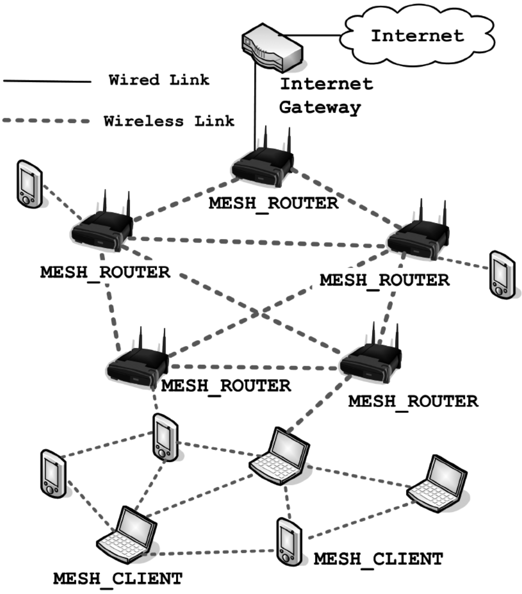

Figure 1: Hybrid Wireless Mesh Network

protocols were designed for networks with highly mobile and typically power constrained devices. As a consequence, they are able to handle node mobility and the generally dynamic nature of client WMNs and hybrid WMNs, which is why they form the basis of most current WMN routing protocols.

However, since these routing protocols have been designed for relatively homogeneous MANETs, consisting entirely of resource constrained mobile devices, they do not perform optimally in highly heterogeneous hybrid WMNs. Current WMN routing protocols do not differentiate between different types of nodes MESH_CLIENTs and MESH_ROUTERs) in the network and are therefore unable to take full advantage of high capacity MESH_ROUTERs in hybrid WMNs.

A fundamental problem of multi-hop wireless networks in general and WMNs in particular is the limited scalability and the degradation of performance with increasing path length. One approach to overcome this problem is to use multiple radio interfaces per node, operating on orthogonal channels. Multi-radio nodes have significantly increased capacity, due to reduced interference and the ability of full-duplex communication, which is not supported by single radio nodes. In order to achieve optimal performance in a multi-radio WMN, an efficient channel allocation and selection scheme is required. Even with complete knowledge of the network topology, optimal channel assignment is very difficult to achieve and is considered an NP-hard problem (Raniwala and Chiueh, 2005).

The routing protocol presented in this paper aims to achieve two goals. First, it tries to make optimal use of high capacity MESH_ROUTERs in a hybrid WMN by routing packets along paths consisting of MESH_ROUTERs whenever possible. This not only increases the overall throughput and reduces latency, it also helps to conserve the battery power of client devices. Secondly, we present a very simple yet effective scheme that tries to maximize per-path channel diversity. For example, the scheme aims to prevent the use of the same channel on neighbouring links of an end-to-end path, which would lead to significant interference and performance degradation.

The Ad-hoc On-demand Distance Vector (AODV) routing protocol (Perkins *et al*, 2003) forms the basis of our work. AODV is a popular reactive MANET routing protocol with excellent scalability properties. Even though AODV has inherent support for multi-radio nodes, it lacks built-in support for optimal channel or interface selection and is therefore unable to maximize channel diversity. AODV has been designed for homogeneous MANETs where nodes have similar computational communication resources and are also similar in terms of their level and pattern of mobility. Thus, AODV will not be able to perform optimally if deployed on a hybrid WMN with high capacity MESH_ROUTERs that are static and are equipped with multiple radios.

In this paper, we present an extended version of AODV, called AODV-HM (AODV-Hybrid Mesh). The key contributions of our work are:

- We propose a simple modification of AODV's route discovery mechanism to allow selection of paths which maximize the use of MESH_ROUTERs and minimize the involvement of MESH_CLIENTs. These routes are more stable due to the lower mobility of MESH_ROUTERs and provide lower latency, improved packet delivery rates and a lower control packet overhead.
- We integrate a channel selection scheme into AODV's route discovery mechanism which increases channel diversity of end-to-end paths. This reduces interference and contention and further increases the packet delivery rate and reduces latency.

The remainder of the paper is organized as follows: Section 2 discusses relevant related work. The AODV-HM protocol is explained in Section 3. In Section 4 we provide details of our simulation environment. Simulation results and their analysis are presented in Section 5 with concluding remarks in Section 6.

2. RELATED WORK

2.1 Hyacinth

Hyacinth (Raniwala and Chiueh, 2005) is a multi-channel static wireless mesh network protocol that uses multiple radios and channels to improve the network performance. It supports a fully distributed channel assignment algorithm, which can dynamically adapt to varying traffic loads. It uses a spanning-tree based routing algorithm (IEEE, 2003) to load balance the network as well as to rectify route failures. The MESH_ROUTERs having access to the wired network are considered as the root nodes of the spanning tree. Hyacinth's channel assignment algorithm breaks a single-channel collision domain into multiple collision domains, each operating on a different frequency. The channel assignment algorithm operates in two phases: Neighbour-Interface Binding and Interface-Channel Assignment.

In the first phase each node separates its interfaces into UP-NICs and DOWN-NICs. Each node has control to change the channel on its DOWN-NICs only. During the second phase each node exchanges a periodic message, which contains the channel usage status, with its neighbours in the interference range. Using the per-channel total load information a node can issue a change channel message to its neighbour in order to switch to a least used channel. The advantage of this channel assignment scheme is that a fat-tree architecture is obtained in which links close to the root of the spanning tree are given higher bandwidth. The channel assignment is further integrated with the routing process. Each node having routing information to the root advertises this information to one-hop neighbours. This advertisement also contains the cost metric, which comprises of the hop-count and the residual uplink capacity. Each node receiving this advertisement makes a decision, based upon the cost, as regards to joining the advertising node. If the node decides to join, it sends an acceptance message to the advertising node and a departing message to the parent node with which it was previously attached. New nodes joining the network broadcast HELLO packets, such as to initiate the joining process by the neighbouring nodes.

2.2 Single-Radio Multi-Channel Routing Protocol

The Multi-Channel Routing Protocol (MCRP) (So and Vaidya, 2004) is a routing protocol specifically designed for networks with single-radio nodes, which can support a channel switching delay of 80 μs or less (Kyasanur and Vaidya 2005). The protocol assigns channels to data flows rather than assigning channels to nodes. This implies that all nodes supporting a flow have to be on one common channel. The advantage of this mechanism is that once the route is established, nodes are not required to switch channels for the duration of the flow. The protocol considers all nodes in the network to be in essentially one of four states: free, locked, switching or hard-locked. The free nodes are nodes that are not supporting any flow at the moment. Locked nodes are those that are currently supporting one flow. A switching node is one that is supporting two or more flows on different channels. A hard-locked node is one, which due to certain constraints, cannot become a switching node. MCRP benefits from multiple channels without modifying the MAC protocol.

The routing scheme is similar to that of AODV. However, each Route Request packet (RREQ) is broadcast on each channel in a round robin manner and each receiving node also rebroadcasts the RREQ. Intermediate nodes also create a Reverse Route to the source and maintain a channel number for the next hop with each Reverse Route table entry. To convey the channel information of the next hop, each RREQ contains the operating channel[2] number of the hop sending the RREQ. The RREQ also contains the channel table and flow table to be propagated along with each RREQ.

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[2] The operating channel of a node is the default channel on which it is generally listening on.

The channel table contains the count of similar channels being consecutively used on a single flow path. The flow tables maintain a count of simultaneous flows being carried out on a single channel. These tables are used by the destination node to make a decision regarding the selection of the optimal route from multiple received RREQs. The Route Reply packet (RREP) is unicast from the destination to the source on the optimal path. All nodes forwarding the RREQ change their operating channels to the channel selected by the destination.

2.3 Multi-Radio Link Quality Source Routing

The Multi-Radio Link Quality Source Routing (MR-LQSR) (Draves *et al*, 2004) protocol has been developed by Microsoft for static community wireless networks. The protocol works in conjunction with the Mesh Connectivity Layer (MCL). The MCL permits higher layer applications to connect to the wireless mesh network using WiFi or WiMAX. The MCL implements an interposition layer between the link and network layers. It essentially consists of a loadable driver, which acts as a virtual network adapter with the ability to multiplex several physical adapters. Routing of packets is carried out by MR-LQSR, which is an optimized version of the Dynamic Source Routing (DSR) protocol (Johnson *et al*, 2003).

The MR-LQSR protocol assumes that the number of wireless interfaces is equal to the number of channels being used in the network. The protocol identifies all nodes in the wireless mesh network and assigns weights to all possible links. To do so, the link information including channel assignment, bandwidth and loss rates are propagated to all nodes in the network. This propagation is combined with the delivery of DSR control packets. The Expected Transmission Time (ETT) on each link is computed using the Expected Transmission Count (ETX), bandwidth and packet loss. The ETT metric is further used to compute the Weighted Cumulative Expected Transmission Time (WCETT), which defines the path metric designed for multi-radio WMNs. The WCETT is then applied to the Link Cache scheme of the DSR protocol. In native DSR, the default cost of links is set to one. Hence, when the Dijkstra algorithm is executed over the link cache by a source node, the shortest path in terms of number of hops is always returned. However, when the WCETT is used as the link cost, the protocol aims to return the path in terms of link bandwidth, loss rate and channel diversity.

2.4 Multi-Channel Routing Protocol

The Multi-Channel Routing (MCR) protocol (Kyasanur and Vaidya, 2006) has been developed for dynamic WMNs, where nodes have multiple wireless interfaces, each supporting multiple channels. The protocol makes use of an interface switching mechanism to assign interfaces to channels. Two types of interfaces are assumed: fixed and switchable. In fixed interfaces, K number of interfaces out of a total M interfaces are assumed to be operating on K fixed channels. In the switchable interfaces, the remaining interfaces are dynamically assigned to any of the remaining channels. Switching is carried out depending upon the maximum number of data packets queued for a single channel. Multiple queues are maintained for all switchable interfaces. Each node maintains a neighbour table and a channel usage list. The neighbour table contains information regarding the fixed channels used by the node's neighbours. The channel usage list contains the count of nodes that are using each channel as their fixed channel. Each node periodically transmits a HELLO packet on all channels, containing the node's fixed channel number. Each node receiving the HELLO packet updates its neighbour table and channel usage list. The information from the table and list is used to control the channel and interface switching mechanism. The switching mechanism assists the MCR protocol in finding routes over multiple channels.

MCR uses a new routing metric, which is computed as a function of channel diversity, interface switching cost and hop-counts. The diversity cost is assigned according to the least number of channels used in a route. Thus, a route with a larger number of distinct channels in a route is considered to be having a lower diversity cost. The switching cost is used to minimize the frequent switching of wireless interfaces. The route discovery mechanism of MCR is similar to that of DSR. In addition, each RREQ also contains the channel number and switching cost. When the destination receives the RREQ, it computes the diversity cost (number of channels in the RREQ) and the switching cost (sum of all link switching costs). These costs help the destination in determining and selecting the optimal path available between the source and the destination.

Table 1 presents a comparison of the discussed protocols. All protocols assume homogeneous node configurations i.e. equal number of interfaces and do not differentiate between different node types. Hyacinth and MR-LQSR have been specifically designed for infrastructure WMNs and have no support for client mobility. Hyacinth, MR-LQSR and MCR use interface switching to improve upon the routing performance in the network, where the interfaces are switched dynamically to different channels. MCRP makes use of channel switching on a single interface to connect to nodes operating on the same channel, to improve upon the network performance. Both interface and channel switching achieve efficient use of the available spectrum. However, the virtual switching protocol and the constant switching incurs significant delays causing excessive jitter (Chandra and Bahl, 2004; Draves *et al*, 2004). In the remainder of this paper, we will present and discuss AODV-HM, which can achieve efficient spectrum usage without the need for a complex and expensive channel switching mechanism.

3. MESH-AWARE AODV PROTOCOL

3.1 Standard AODV

The AODV is inherently a distance vector routing protocol that has been optimised for ad-hoc wireless networks. It is an on demand or reactive protocol, as it finds the routes only when required.

Protocols	**Research**	**Year Group**	**Interface**	**Mobility**	**Derivative**	**Routing**	**Remarks Metric**
Hyacinth	Stony Brook University	2005	Multi-Radio	No	Spanning Tree	Hop Count, link/path loads	• Independent channel switching protocol required
MCRP	University of Illinois, Urbana-Champaign	2004	Single-Radio	Yes	AODV	Hop Count	• High speed interface switching required • Complex to handle multiple flows
MR-LQSR	Microsoft Research	2004	Multi-Radio	No	DSR	WCETT	• Proprietary Mesh Connectivity Layer • Bandwidth computed using packet probes • Requires propagation of intermediary node ETT's to source node
MCR	University of Illinois, Urbana-Champaign	2006	Multi-Radio	Yes	DSR	Channel diversity and switching cost	• Hybrid of fixed and switchable channels • Periodic distribution of channel usage lists

Table 1: Comparison of Recent WMN Protocols

AODV borrows basic route establishment and maintenance mechanisms from the DSR protocol, and hop-to-hop routing vectors from the Destination-Sequenced Distance-Vector (DSDV) routing protocol (Perkins and Bhagwat, 1994). Multi-path support has also been added to AODV through a number of extensions (Li and Cuthbert, 2004; Marina and Das, 2001), permitting discovery and establishment of loop-free and disjoint alternate paths. 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 (RREQ). Each RREQ contains an ID, source and destination node IP addresses, and sequence numbers together with a hop count and control flags. The ID field uniquely identifies the RREQ; 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 RREQ that has not seen the source IP and RREQ ID pair or does not have a fresher (with larger sequence number) route to the destination rebroadcasts the same packet after incrementing the hop-count.

Intermediate nodes create and preserve a Reverse Route to the source node for a certain interval of time. When the RREQ reaches the destination node or any node that has a fresh route to the destination, a Route Reply packet (RREP) is generated and unicast back to the source of the RREQ. Each RREP contains the destination sequence number, the source and the destination IP addresses, route lifetime, and a hop count and control flags. Each intermediary node that receives the RREP increments the hop-count, establishes a Forward Route to the source of the packet, and transmits the packet via the Reverse Route. To preserve connectivity information, each node executing AODV can use link-layer feedback or periodic HELLO packets 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 packet (RERR) is sent to its active neighbours that were using that particular route.

When using AODV in a network with multi-radio nodes, each RREQ is broadcast on all interfaces. In order to avoid broadcast storms, a random delay is added in the transmission of each RREQ. Intermediate nodes with one or more interfaces operating on a shared channel, receive the RREQ and create a Reverse Route that points towards the source node. If the RREQ is a duplicate, it is simply dropped. The first received RREQ received by the destination or any intermediary node is selected and all other RREQs are discarded. The RREP is generated in response to the selected RREQ, and is sent back to the source node on the existing Reverse Route.

3.2 AODV-HM

We have made the following assumptions for the design and evaluation of our AODV-HM protocol:

- All MESH_CLIENTs and MESH_ROUTERs should have at least one common operating channel.
- The transmission and reception ranges of the wireless transceivers are comparable.
- The wireless antennas are omni-directional.

The aim of AODV-HM is to maximize the involvement of MESH_ROUTERs into the routing process without significantly lengthening the paths. In addition, we want to maximize channel diversity in the selected paths. To implement these features we make two changes to the RREQ header. First, we add a 4-bit counter (MR-Count) indicating the number of MESH_ROUTERs encountered on the path taken by the RREQ. We further add a 7-bit field (Rec-Chan), which advertises the optimal channel to be used for the Reverse Route. We have used the existing 11 reserved bits in the RREQ header. The first four bits represent the MR-Count while the remaining seven represent the Rec-Chan as shown in Figure 2.

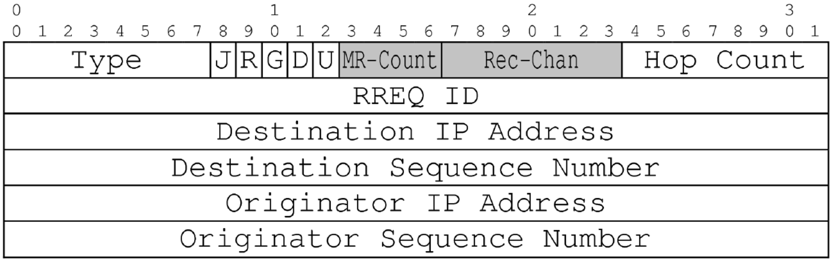

Figure 2: AODV-HM Route Request Packet Header

3.2.1 Discovery of MESH_ROUTERs

Whenever a MESH_CLIENT intends to communicate with another node whose route is not available in its routing table, it broadcasts a RREQ on all of its interfaces. Prior to the broadcast, it also sets the MR-Count in the RREQ to zero. Each MESH_ROUTER forwarding the RREQ increments the MR-Count field by one. When the RREQ is received by the destination or any intermediary node that can respond, the process shown in Figure 3 is initiated.

If the RREQ has not been received earlier[3], a RREQ-Timer is started and a RREQ-Counter is initialized. The RREQ-Timer determines the amount of time a node should wait after receipt of the first RREQ and before forwarding the optimal RREQ. The RREQ-Timer helps to evaluate alternate copies of the same RREQ arriving via different paths. The RREQ-Counter maintains a count of these copies. All copies of the RREQ are then buffered until the time when either the RREQ-Timer expires or the RREQ-Counter reaches a certain threshold.

The optimal values for the RREQ-Timer and Counter are primarily dependent upon the average node density. In case the density is high, the RREQ-Counter will reach its threshold value well within the RREQ-Timer. However, in case of a sparse network, the RREQ-Counter may never reach its threshold value before the RREQ-Timer expires. In the standard AODV protocol, the minimum Route Discovery Latency (RDL), i.e. time between transmission of the first RREQ and the receipt of its corresponding RREP, is

$$\text{RDL} = 2 \times n_p \times \text{NODE\_TRAVERSAL\_TIME}$$

where n_p is the number of nodes on the path (excluding the source node) taken by the RREP. NODE_TRAVERSAL_TIME is the approximate time taken by a packet to pass through one node.

For lower RREQ-Counter values in high density networks, AODV-HM incurs a RDL similar to that of the standard AODV. However, in sparse networks with large RREQ-Counter values, AODV-HM may incur a maximum RDL of:

$$\text{RDL} = n_p \times \text{NODE\_TRAVERSAL\_TIME} + n_p \times \text{RREQ-Timer}$$

In order to minimize the RDL, a low value of the RREQ-Counter is maintained or the RREQ-Timer is kept as close to the NODE_TRAVERSAL_TIME as possible.

When the RREQ-Timer expires or the RREQ-Counter threshold is reached, the RREQ, for which the routing metric (Hop-Count - MR-Count) is minimal, is selected. This selection is done from the set of n RREQs, stored in the RREQ Buffer (RREQ-BUFF), as indicated in Equation 1.

$$RREQ_s = RREQ_i \left| \underset{1 \le i \le n}{Min}(HopCount_i - MRCount_i) \right. \tag{1}$$

[3] Determinable through the Source IP and RREQ ID mapping

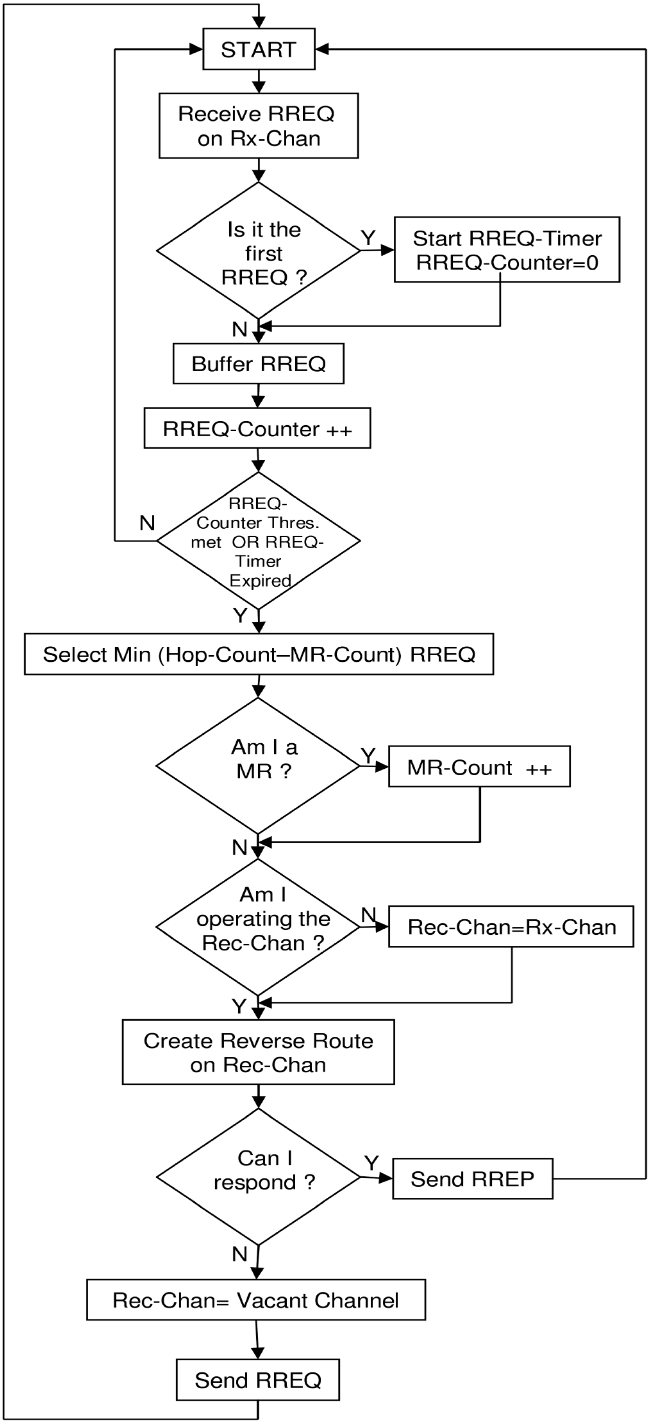

Figure 3: RREQ Processing in AODV-HM

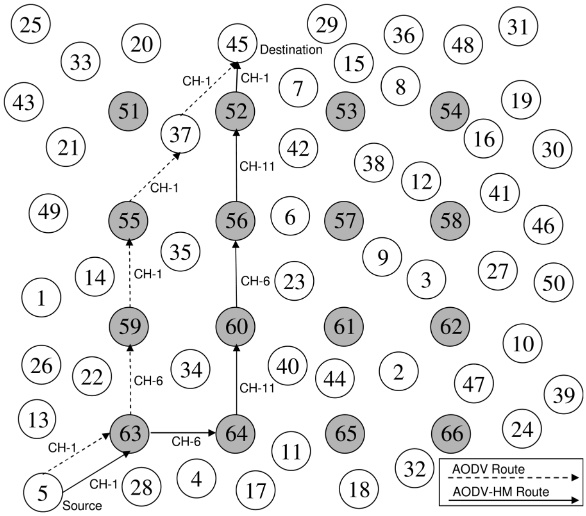

Figure 4: Route Development in AODV-HM

Let's consider the scenario shown in Figure 4, where MESH_CLIENT-5 (Source) wants to communicate with MESH_CLIENT-45 (Destination). The darker nodes represent the MESH_ROUTERs and the remaining nodes are MESH_CLIENTs. Standard AODV does not distinguish between MESH_ROUTERs and MESH_CLIENTs. Accordingly, when a route discovery is initiated from MESH_CLIENT-5 for MESH_CLIENT-45, the first arriving RREQ at MESH_CLIENT-45 establishes the route. The first route, between the source and destination, established using standard AODV is represented as follows:

$$R_{SD1} = \{ 5 \rightarrow 63 \rightarrow 59 \rightarrow 55 \rightarrow 37 \rightarrow 45 \}$$

Route R_{SD1} has a hop-count of five and contains three intermediary MESH_ROUTERs and one MESH_CLIENT. However, there may be occasions where the first RREQ arriving at the destination contains no MESH_ROUTERs, e.g. $R_{SD2} = \{ 5 \rightarrow 22 \rightarrow 14 \rightarrow 35 \rightarrow 37 \rightarrow 45 \}$. If MESH_CLIENTs operate on a single channel, as is typically the case, the above scenario would lead to a significant performance degradation over a route consisting only of MESH_CLIENTs (Li *et al*, 2001).

In contrast, AODV-HM is able to create Reverse Routes that traverse predominantly MESH_ROUTERs by delaying RREQs at intermediary nodes and selectively forwarding the one consisting mostly of MESH_ROUTERs, instead of the first one to arrive. For example, MESH_ROUTER-60 is likely to receive more than one RREQs originating from MESH_CLIENT-5. In case the first RREQ reaches MESH_ROUTER-60 via MESH_CLIENT-34 (with MR-Count=1), and the RREQ reaches MESH_ROUTER-60 via MESH_ROUTER-64 (with MR-Count=2), AODV-HM would select the latter which contains the smaller number of MESH_CLIENTs. In standard AODV, MESH_ROUTER-60 would simply forward the first RREQ received from MESH_CLIENT-34.

Similarly, more than one RREQs are received by the destination MESH_CLIENT-45. Let's assume five RREQs from MESH_CLIENT-5 have reached MESH_CLIENT-45 and stored in the RREQ-BUFF. The paths taken by the five RREQs are as follows:

R_{SD1} = { 5 → 63 → 34 → 35 → 37 → 45 }
R_{SD2} = { 5 → 63 → 59 → 55 → 51 → 45 }
R_{SD3} = { 5 → 63 → 59 → 55 → 51 → 20 → 45 }
R_{SD4} = { 5 → 63 → 64 → 60 → 56 → 52 → 45}
R_{SD5} = { 5 → 63 → 64 → 40 → 6 → 7 → 45}

Now using Eq. 1, we get the minimum difference between the Hop-Count and MR-Count for the above routes as follows: R_{SD1} : 5 - 1 = 4, R_{SD2} : 5 - 4 = 1, R_{SD3} : 6 - 4 = 2, R_{SD4} : 6 - 5 = 1 and R_{SD5} : 6 - 2 = 4 respectively. The minimum cost is achieved using the RREQ that arrived via routes R_{SD2} and R_{SD4}. In case two or more RREQs have the same cost, the first of these to arrive is responded to and the corresponding route is established.

3.2.2 Channel Diversity

In a wireless network, as the physical medium is shared, nodes have to constantly contend with each other to gain access to the network. All nodes before making a transmission execute the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to avoid future collisions (IEEE, 1997). The effectiveness of the CSMA/CA protocol is influenced by the density, mobility and traffic pattern of the network (Bianchi, 2000). In order to minimize packet collisions and contention, the physical medium is generally segregated using non-interfering channels. This in turn reduces the number of nodes contending per channel, which also lowers the number of packet collisions.

As mentioned earlier, the standard AODV protocol typically adds some random delay prior to the transmission of RREQs over multiple interfaces. Thus, the Reverse and Forward Routes may or may not have similar channel assignments[4]. For example, in Figure 4 the route between MESH_CLIENT-5 and MESH_CLIENT-45 indicated with dashed arrows includes three MESH_ROUTERs: 55, 59 and 63. Let's assume that the MESH_CLIENTs have one radio each operating on Channel 1 (CH-1) and that the MESH_ROUTERs have three radios each, operating on Channel 1 (CH-1), Channel 6 (CH-6) and Channel 11 (CH-11) respectively. During the route discovery process, MESH_ROUTER-63 introduces a small random delay before forwarding the RREQ on each of its three channels. If we assume the smallest delay is selected for CH-6, MESH_ROUTER-59 receives the first RREQ via this channel. In this case, the Reverse Route is created to MESH_CLIENT-5 via CH-6. When MESH_ROUTER-59 retransmits the RREQ, it employs a similar mechanism.

However, this time the first RREQ to reach MESH_ROUTER-55 is via CH-1. Thus, MESH_ROUTER-55 creates the Reverse Route to the source MESH_CLIENT-5 via CH-1. Similarly, the Reverse Route from MESH_CLIENT-37 is created via CH-1. This essentially introduces another collision domain between MESH_ROUTER-59 and MESH_CLIENT-37. Packets sent from MESH_ROUTER-59 to MESH_ROUTER-55, as well as packets sent from MESH_ROUTER-55 to MESH_CLIENT-37 have to contend for the same medium since they all share the same common channel (CH-1). Thus, the worst case channel selection strategy scenario for a route traversing through nodes with multiple radios may degrade to that of a path comprised of single-radio nodes.

In AODV-HM, we use a simple mechanism to achieve effective channel assignment during route discovery. Each node, before propagating a RREQ, appends the Recommended Channel (Rec-Chan) to the RREQ, as shown in Figure 2 and Figure 3. The Rec-Channel informs the RREQ

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[4] The first RREQ received on any interface determines the channel used for the Reverse Route to the source node.

IEEE Standard (3-bits)		Channel Number(4-bits)
802.11 a	000	1 ~ 16
802.11b	001	1 ~ 16
802.11g	010	1 ~ 16
...	...	1 ~ 16

Table 2: Assignment of Recommended Channels

recipient about the desired channel to be used for creating the Reverse Route. The Rec-Chan value is implemented as a 7 bit number, and its value is set according to Table 2. The first three bits define the IEEE physical layer standard the radio is operating on. The following 4 bits indicate the specific channel number. For example, in the network shown in Figure 4, all MESH_CLIENTs are operating a single radio and are tuned to CH-1 of 802.11b. In this case, Rec-Chan will have a value of 17 (0010001).

If a node operates only one radio, the Vacant Channel is the current operating channel. A node with multiple radios has the discretion to recommend any Vacant Channel. The Vacant Channel is selected based upon the following two criteria:

- he Rec-Chan is not interfering with the channel being used on the Reverse Route.
- The Rec-Chan is the least loaded channel.

A RREQ can be received by a multi-radio node on one of its Receive Channels (Rx-Chan). However, depending upon the current assignment of channels to the interfaces, the Rx-Chan may or may not be equal to the Rec-Chan. For example, a node could have all of its radios tuned to channels other than the Rec-Chan, which would make it impossible create a Reverse Route using the Rec-Chan. In case a node has an interface operating on Rec-Chan, it creates the Reverse Route to the previous hop using that interface, otherwise it creates the Reverse Route via the Rx-Chan.

Coming back to the example of Figure 4, before initiating the RREQ, MESH_CLIENT-5 sets the Rec-Chan to its current operating channel, i.e. CH-1. As MESH_CLIENT-5 is a single radio node, the RREQ is received by MESH_ROUTER-63 on CH-1 only. In this case Rx-Chan is equal to Rec-Chan, so MESH_ROUTER-63 creates the Reverse Route to MESH_CLIENT-5 using CH-1. MESH_ROUTER-63 is operating on three channels, i.e. CH-1, CH-6 and CH-11. Using the criteria mentioned above, it now selects the Vacant Channel to be equal to CH-6. The Rec-Chan is then set to the Vacant Channel and the RREQ is broadcast over all three interfaces. MESH_ROUTER-64, which is also operating the same three channels, now receives three RREQs from MESH_ROUTER-63. Since the Rec-Chan in all three RREQs is CH-6, MESH_ROUTER-64 creates the Reverse Route to MESH_ROUTER-63 using CH-6.

In our example, MESH_CLIENTs are operating on CH-1 and so this channel would experience a relatively high load. Thus, MESH_ROUTER-64 selects and recommends the Vacant Channel to be CH-11, which also does not interfere with the channel used on the Reverse Route. Similarly, MESH_ROUTER-60 creates the Reverse Route via CH-11 and recommends the Vacant Channel CH-6. In this manner, AODV-HM creates a route between MESH_CLIENT-5 and MESH_CLIENT-45 with less interference and contention compared to the route that is selected by standard AODV.

The routing metric used in AODV-HM aims to minimize the number of MESH_CLIENTs present in a particular route. This may seem analogous to shortest path routing, but this is not the case, since the metric attempts to route traffic through the MESH_ROUTERs, which in turn maximize the stability and channel diversity of the routes. A number of other routing metrics like ETX, ETT and WCETT also exist. Of these metrics, only WCETT takes advantage of the channel diversity, however, its direct application to AODV, which is a distance vector routing protocol, requires extensive modifications to the protocol's inherent working (Ramachandran *et al*, 2005).

4. SIMULATION ENVIRONMENT

We evaluated the efficiency of the AODV-HM protocol through extensive simulations in NS-2 (NS, 1989), using the Extended Network Simulator (ENS) extensions (Raman and Chebrolu, 2005). A WMN covering an area of 1 square km is established using uniformly distributed static MESH_ROUTERs and randomly distributed mobile MESH_CLIENTs. Concurrent UDP connections are established between randomly selected source and destination MESH_CLIENT pairs. A total of four simulations were conducted to evaluate the performance of the AODV-HM protocol under varying mobility, traffic load and node configurations. The parameters common to all four simulations are listed in Table 3.

The simulations provide the following performance metrics:

Packets Lost: The number of data packets that were lost due to unavailable or incorrect routes, MAC layer collisions or through the saturation of interface queues (Pirzada *et al*, 2006).

Examined Protocols	AODV and AODV-HM
Simulation time	900 seconds
Simulation area	1000 x 1000 m
Propagation model	Two-ray Ground Reflection
Mobility model for MESH_CLIENTs	Random waypoint
Maximum Speed of MESH CLIENTs[5]	1 m/s
Transmission range	250 m
Number of Connections[5]	30
Traffic type	CBR (UDP)
Packet Size	128 bytes
Packet Rate	25 pkts/sec
Number of MESH_ROUTERs[5]	25
Number of MESH_ROUTER Interfaces[5]	3
Number of MESH_CLIENTs	50
Number of MESH_CLIENT Interfaces	1
MESH_CLIENT RREQ-Counter	5 packets
MESH_ROUTER RREQ-Counter	25 packets
MESH_CLIENT RREQ-Timer	50 ms
MESH_ROUTER RREQ-Timer	250 ms

Table 3: Simulation Parameters

[5] The values of these parameters are varied in Simulations 1, 2, 3 and 4 respectively.

Aggregate Goodput: The number of data bits successfully transmitted in the network per second.

Packet Delivery Percentage: The ratio between the number of data packets successfully received by destination nodes and the total number of data packets sent by source nodes.

Routing Overhead: The ratio of the total number of control packets generated to the total number of received data packets.

Average Latency: The mean time in seconds taken by data packets to reach their respective destinations.

Path Optimality: The ratio between the length (number of hops) of the shortest possible path and the actual path taken by data packets.

5. RESULTS AND ANALYSIS

5.1 Simulation 1: Varying the MESH_CLIENT Speeds

In Simulation 1, we have varied the maximum speed of the MESH_CLIENTs from 0 m/s to 20m/s, with increments of 5 m/s. The results, shown in Figure 5, indicate that the packet loss is consistently lower for AODV-HM compared to standard AODV. This is primarily due to the selection of static MESH_ROUTERs in the routing process, which offer more stable routes with less contention. On the other hand, the standard AODV has no option for prioritizing the routing according to the node type. Thus both the MESH_ROUTERs and MESH_CLIENTs are randomly selected in establishing a route. Routes consisting mostly of single-radio MESH_CLIENTs have a higher packet loss due to the extended contention for the wireless medium, which can lead to saturated interface queues and packets being dropped. The routes formed by AODV-HM may also involve MESH_CLIENTs in its paths, but their number is relatively smaller. The lower number of MESH_CLIENTs in the path means improved utilization of the channel diversity and lower contention for the wireless medium. This in effect reduces the packet drop when the AODV-HM protocol is engaged. However, when the MESH_CLIENTs move at a higher speed, the routes are frequently broken and recreated. Thus we see an increase in the number of packets lost with the increase in the network mobility.

The number of packets lost in the network, due to collisions or saturation of interface queues, directly influences the aggregate goodput of the network. AODV-HM shows improved goodput over standard AODV for all speeds. Even though AODV-HM aims to route traffic through the MESH_ROUTERs, at higher speeds the routes become extremely unstable due to the movement of the source, destination and intermediary MESH_CLIENTs. The packet delivery rate of AODV-HM ranges from 83% at zero mobility to almost 57% at a speed of 20 m/s. Nevertheless, the packet delivery of AODV-HM is consistently higher than for standard AODV.

AODV-HM has the ability to create more stable routes by preferably involving static MESH_ROUTERs. This in turn reduces the number of route discoveries in the network, thereby lowering the control packet overhead. In addition, as AODV-HM is able to achieve a higher packet delivery rate, the control packet overhead per received data packet is significantly lower than for AODV. However, it should be noted that AODV-HM does not incur any additional byte overhead, since the MR-Count and Rec-Chan fields occupy existing fields of the AODV RREQ header.

The average latency of the network using AODV-HM is considerably lower than that of the standard AODV at varying speeds. The lower latency highlights the success of AODV-HM's route selection mechanism along with the dynamic channel assignment carried out during the route discoveries. As mentioned earlier, standard AODV selects the first incoming RREQ. However, the first RREQ to arrive does not necessarily arrive via the shortest path (in terms of the number of hops). Our simulations show that by delaying the RREQs in AODV-HM, the chance of discovering

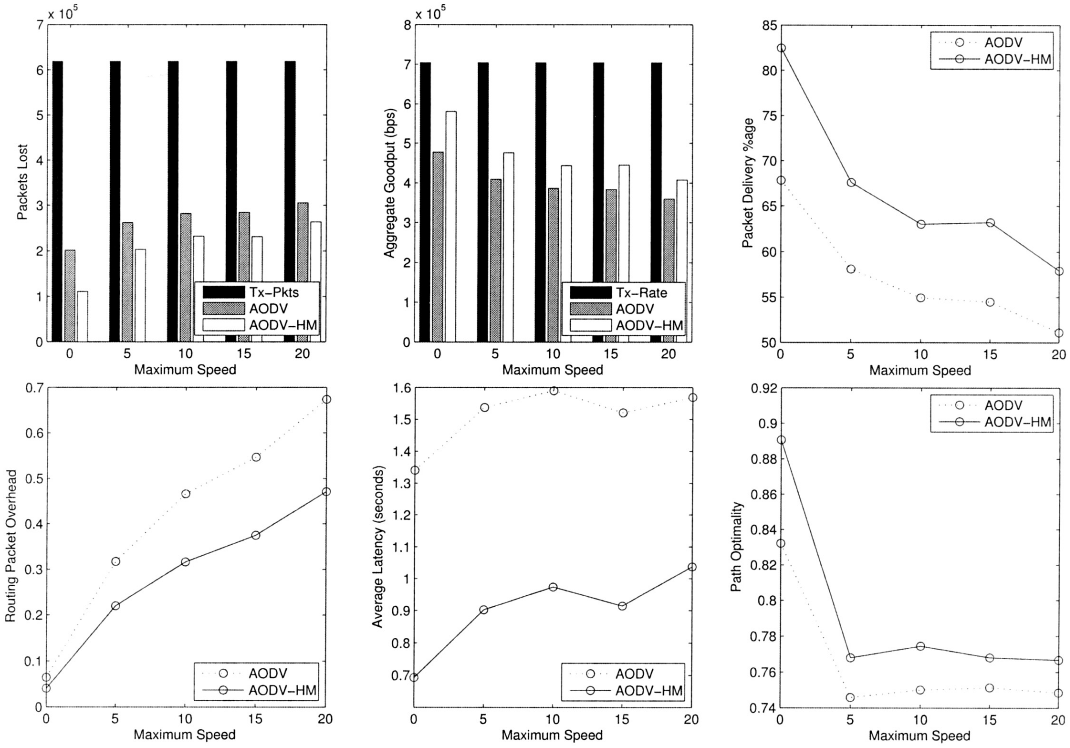

Figure 5: Results of Simulation 1

shorter paths is increased. This is shown in the path optimality metric, which shows that AODV-HM paths have higher path optimality, i.e. they are shorter.

5.2 Simulation 2 : Varying the Traffic Load

In Simulation 2, we varied the traffic load in the network by increasing the number of simultaneous connections between the MESH_CLIENTs from 10 to 50, with an increment of 10 connections. Our results (Figure 6) show that at lower traffic loads, the performance of AODV-HM is comparable to that of the standard AODV protocol. However, as the load is increased, the packet loss incurred by AODV increases significantly, thereby decreasing the goodput of the network. The packet delivery rate for both protocols stays close to 100% up to 20 concurrent connections. Beyond this point, the packet delivery rate of both protocols starts to degrade. Since the routes created by AODV-HM contain more MESH_ROUTERs than those created using AODV, we see an improved performance of the former under increasing traffic loads, relatively to AODV.

The routing packet overhead of AODV-HM also remains lower. The latency of the network increases with the increase in the traffic load due to increasing contention for the wireless medium by nodes operating on interfering channels. However, AODV-HM still manages to maintain a significant improvement over AODV.

5.3 Simulation 3: Varying the Number of MESH_ROUTERs

We have simulated hybrid WMNs with varying numbers of MESH_ROUTERs: 0, 4, 9, 16 and 25. Interestingly, the results (Figure 7) show that even when no MESH_ROUTER is present in the

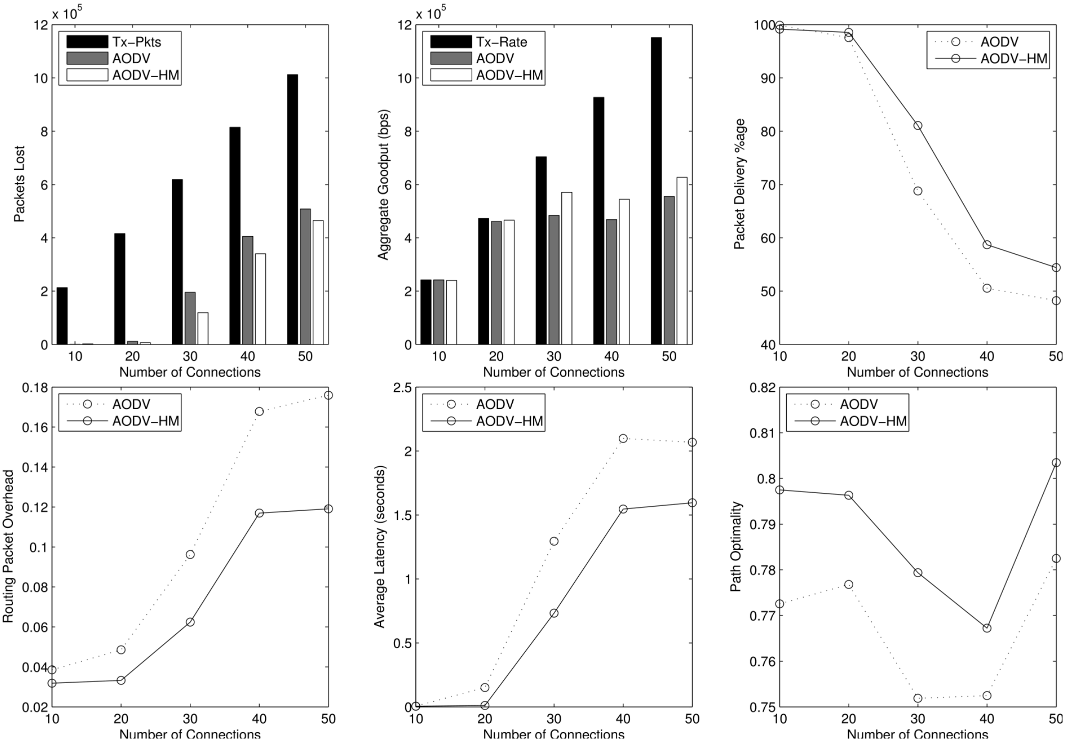

Figure 6: Results of Simulation 2

network, AODV-HM still has a lower packet loss than standard AODV. This is because AODV-HM delays the received RREQ and responds to the one with the lowest hop count, since in this case MR-Count=0. In contrast, standard AODV responds to the first RREQ that it received, which may not necessarily have arrived via the shortest path, due to interference or contention on one of the links. This use of non-shortest paths in AODV increases the total load in the network and increases contention and packet loss. This is also confirmed by looking at the path optimality of AODV-HM, which is much closer to the shortest possible path[6] than the paths created by AODV. The performance of both protocols improves with an increasing number of MESH_ROUTERs in the network. However, AODV-HM makes more efficient use of the MESH_ROUTERs and achieves an improved packet delivery rate, decreased packet overhead, and significantly lower latency.

5.4 Simulation 4: Varying the Number of Radios on each MESH_ROUTER

In Simulation 4, we varied the number of radio interfaces in each MESH_ROUTER from 1 to 9, with increments of 2 interfaces. All channels have been configured to be orthogonal and non-interfering with each other. The results of Simulation 4 (Figure 8) reveal that the only time standard AODV outperforms AODV-HM in terms of packet delivery rate is when all nodes are limited to a single radio operating on the same channel. This means that forcing packets to go via MESH_ROUTERs, when they do not have a higher capacity than MESH_CLIENTs, can have a

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[6] The shortest possible path is determined by an omniscient entity present in the NS-2 simulator known as the General Operations Director.

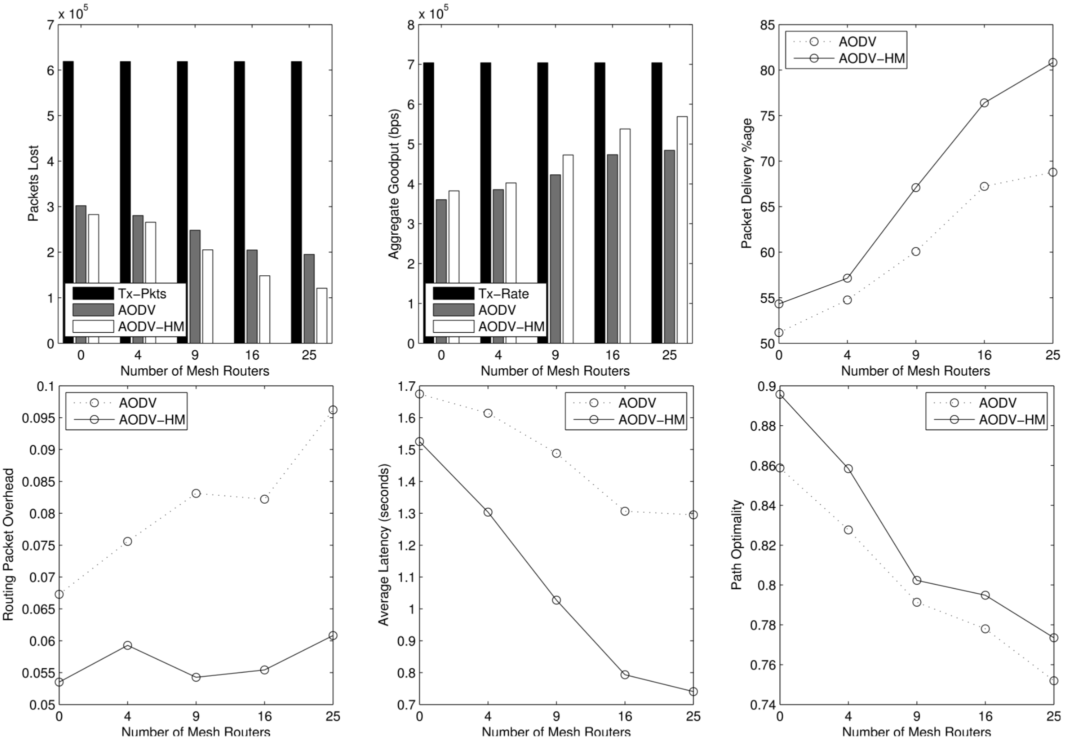

Figure 7: Results of Simulation 3

slightly negative impact. In this particular case, MESH_ROUTERs cannot take advantage of the channel diversity mechanisms of AODV-HM if they are equipped with only a single interface. Nevertheless, since the MESH_ROUTERs are static, they provide more stable routes than mobile MESH_CLIENTs, which results in a reduced packet overhead and lower latency in AODV-HM. The packet delivery rate rapidly improves when the number of interfaces in the MESH_ROUTERs is increased. AODV-HM significantly outperforms standard AODV in these scenarios. However, increasing the number of MESH_ROUTER interfaces to more than three does not show any further improvements. This is due to the fact that three interfaces operating on orthogonal channels are sufficient to provide the required capacity and channel diversity for the network and traffic pattern considered in our simulation. However, the ideal number of MESH_ROUTER interfaces will vary for different types of networks with different size, density and traffic load. AODV-HM maintains its superior performance over the standard AODV protocol with the increase in the number of interfaces. It shows significantly lower packet overhead and latency, and a considerably better packet delivery ratio.

6. CONCLUSIONS

Hybrid WMNs consist of a mix of mobile MESH_CLIENTs and static MESH_ROUTERs. These two types of node differ considerably in terms of their capacity to forward packets. MESH_ROUTERs are typically much less resource constrained than mobile MESH_CLIENTs, and can be assumed to be equipped with multiple radio interfaces. Current WMN routing protocols do

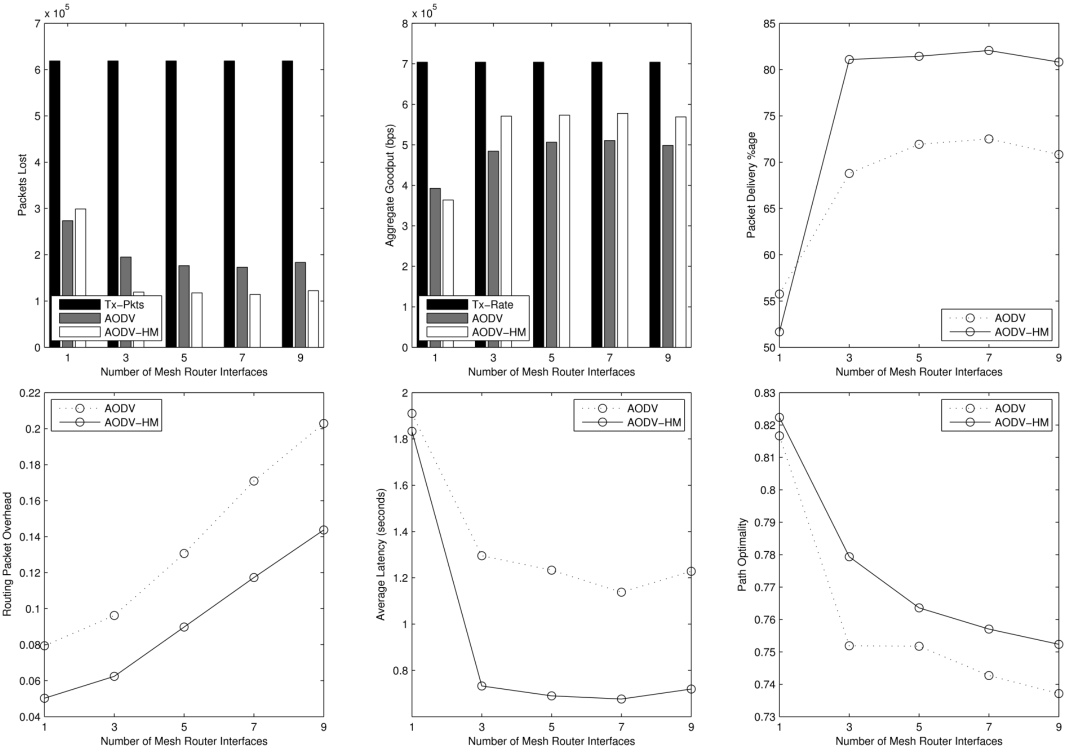

Figure 8: Results of Simulation 4

not differentiate between the types of node in a WMN, and are therefore not able to exploit the inherent heterogeneity in hybrid WMNs. In this paper, we presented simple extensions to the AODV routing protocol to increase its efficiency in hybrid WMNs. We defined a new routing metric that allows more efficient use of high capacity MESH_ROUTERs by preferential routing of packets via paths traversing the MESH_ROUTERs. In addition, we integrated a channel or interface selection scheme to maximize channel diversity and therefore minimize interference on end-to-end paths. We have performed extensive simulations to evaluate the performance of AODV-HM and compared it with standard AODV. The results show that AODV-HM consistently outperforms AODV in terms of all our performance metrics and for all simulation scenarios, except for the one special case discussed above. Compared to AODV, AODV-HM achieves an increase in the packet delivery rate of up to 15% in absolute terms, and achieves a reduction in latency by up to 50%. These are encouraging results, given that our proposed changes to the AODV protocol are very simple and incur only very minor additional overhead or complexity.

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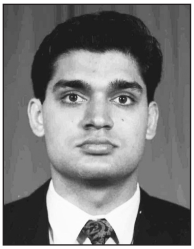
BIOGRAPHICAL NOTES

Asad Amir Pirzada is a researcher in the SAFE Networks work-package of the Safeguarding Australia program at NICTA's Queensland Research Laboratory. He is currently working on Wireless Mesh Networks that can be deployed in disaster scenarios for use by emergency services. He holds a masters degree in Computer Science and a masters degree in Information Security. He received his PhD from the University of Western Australia on Trust and Security issues in Ad-hoc Wireless Networks. Asad Pirzada's research interests include data communications and network security.



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