Evaluation of Multi-Radio Extensions to AODV for Wireless Mesh Networks

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ABSTRACT

Due to their self-configuring and self-healing capabilities, as well as their low equipment and deployment cost, Wireless Mesh Networks (WMNs) based on commodity hardware present a promising technology for a wide range of applications. Currently, one of key challenges that WMN technology faces is the limited capacity and scalability due to high levels of interference, which is typical for multi-hop wireless networks. A simple and relatively low-cost approach to address this problem that has recently been proposed is the use of multiple wireless network interfaces (radios) per node. Operating the radios on each node on different, non-overlapping channels allows making more efficient use of the radio spectrum and thereby reducing interference and contention. In this paper, we evaluate the performance of the Ad-hoc On-demand Distance Vector (AODV) routing protocol in a Multi-Radio Wireless Mesh Network. Our simulation results show that under high traffic load conditions, Multi-Radio AODV (AODV-MR) is able to efficiently utilize the increased spectrum, and proves to be far superior to single radio AODV. We therefore believe that AODV-MR is a promising candidate for multi-radio WMNs.

Categories and Subject Descriptors

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

General Terms

Experimentation, Performance

Keywords

Multi-radio, routing, mesh, wireless, network

1. INTRODUCTION

Wireless Mesh Networks (WMNs) have recently gained considerable popularity due to their their low cost, and self-configuring and rapid deployment capabilities. Application scenarios from WMNs that have been proposed include building automation, intelligent transportation systems, metropolitan area networks and public safety applications. In their most generic form, WMNs can be comprised of a combination of static `MESH_ROUTER`s and mobile `MESH_CLIENT`s [1]. `MESH_ROUTER`s form the backbone infrastructure and provide connectivity between the `MESH_CLIENT`s. They may also provide access to a wired network. Due to their mobility, `MESH_CLIENT`s are typically more resource constrained than `MESH_ROUTER`s.

Depending upon their architecture and deployment configuration, WMNs can be broadly categorised into three main types [1]: Infrastructure mesh, client mesh and hybrid mesh networks. In the infrastructure mesh scenario, the `MESH_ ROUTER`s collectively provide a wireless backbone infrastructure. This is similar to a traditional WLAN, with the key difference that the wired backbone is replaced with a wireless multi-hop network. `MESH_CLIENT`s simply access the network directly via a `MESH_ROUTER`. In this architecture, clients have a passive role and do not contribute to the mesh network infrastructure. In a client mesh architecture, the network is made up of mobile `MESH_CLIENT`s only, and no dedicated network infrastructure is involved. `MESH_CLIENT`s, therefore, need to perform network functions such as routing and packet forwarding. A client mesh WMN is essentially identical to a traditional pure ad-hoc network [14].

A hybrid mesh architecture, such as illustrated in Fig. 1, is the most generic type of WMN, combining the concepts of infrastructure and client mesh networks. A hybrid WMN consists of relatively static `MESH_ROUTER`s which form the backbone of the network. In addition, mobile clients can act as a dynamic extension of the static infrastructure part of the network, by implementing routing and packet forwarding functionality. The hybrid mesh architecture is very flexible and allows combining the benefits of both infrastructure and client meshes. In this paper, we primarily focus our evaluation on hybrid mesh networks, however, in future we intend extending our evaluations to infrastructure and client mesh networks.

Ad-hoc routing protocols are promising candidates for hybrid and client WMNs, due to their capability to deal with highly dynamic environments. DSR [6] and AODV [12] are two well-known ad-hoc routing protocols, which are currently undergoing extensive research in regards to their

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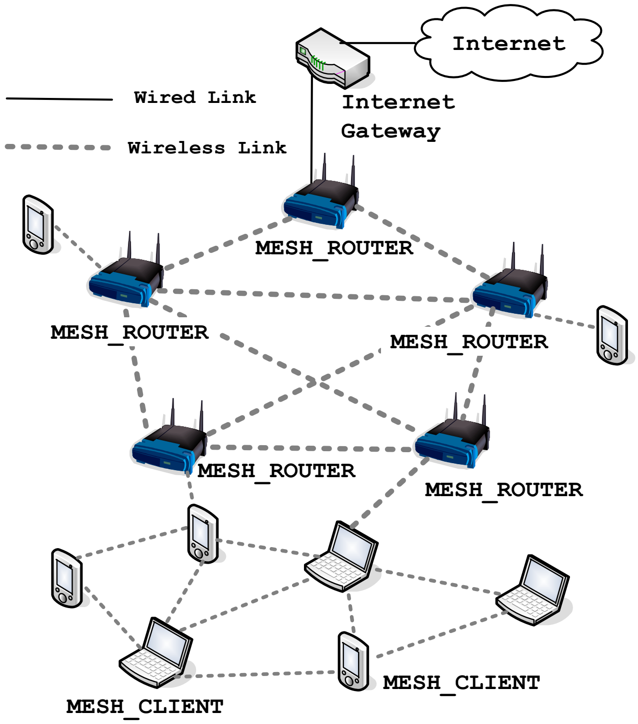

Figure 1: Hybrid Wireless Mesh Network

suitability for mesh networks [4][16]. So far, these protocols have been studied exclusively in single-radio mode. To the best of our knowledge, this paper presents a first evaluation of AODV in a multi-radio WMN scenario. We show that in contrast to single-radio AODV, the multi-radio variant of AODV (AODV-MR) can effectively support high traffic loads and `MESH_CLIENT` mobility. We performed extensive simulations to gather various performance metrics for networks with one, two and three wireless network interfaces per node.

The remainder of the paper is organized as follows: Section 2 provides an overview of the most relevant related work. The multi-radio extensions to AODV are explained in Section 3. Our simulation environment is described in Section 4 and simulation results are presented and discussed in Section 5. Section 6 concludes the paper.

2. RELATED WORK

2.1 Hyacinth

Hyacinth [18] is a static wireless mesh network that uses multiple radios and channels to improve 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 [5] to load balance the network as well as to rectify route failures. The `MESH_ROUTER`s that have access to the wired network are considered as the root nodes of the spanning tree. The authors prove that even with complete knowledge of the network topology, the channel assignment problem is NP-hard. Hyacinth's channel assignment heuristic breaks a single-channel collision domain into multiple domains, one per distinct channel. 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 upstream interfaces (UP-NICs) and downstream interfaces (DOWN-NICs). Each node has control over the channel assignment on its DOWN-NICs only. During the second phase, each node exchanges periodic channel usage status messages with its immediate neighbours. Using the per-channel total load information, a node can issue a change channel message to its downstream neighbours in order to switch to a less 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 that has a valid path to the root node advertises this information to its one-hop neighbours. This advertisement also contains the cost metric, which is made up of hop-count and uplink capacity. Each node that receives this advertisement makes a decision whether to join the advertising node based on the cost metric. If the node decides to join, it sends an acceptance message to the advertising node and a departing message to the parent node it was previously attached to. New nodes entering the network broadcast `HELLO` packets in order to initiate the joining process.

2.2 Single-Radio Multi-Channel Routing

The Multi-Channel Routing Protocol (MCRP) [19] is a routing protocol specifically designed for wireless nodes with a single-radio, but with the ability to switch channels with a delay of less than 80 μs [7]. The protocol assigns channels to data flows rather than to nodes. This implies that all nodes that are involved in a flow need to be on a 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 a flow. The protocol considers all nodes in the network to be in one of the four states, i.e. free, locked, switching or hard-locked. The free nodes are nodes that are not supporting any flow at the moment. Locked nodes are nodes that are currently supporting a single flow. A switching node supports two or more flows on different channels. A hard-locked node is one that, due to certain constraints, cannot become a switching node. The MCRP protocol benefits from multiple channels without modifying the MAC layer. The routing scheme is similar to that of AODV. However, each `ROUTE_REQUEST` is broadcast on each channel in a round robin manner. Each receiving node rebroadcasts the `ROUTE_REQUEST` in a round robin manner. The 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 `ROUTE_REQUEST` contains the operating channel[1] number of the hop sending the `ROUTE_REQUEST`. The `ROUTE_REQUEST` also contains a channel table and flow table to be propagated along with each `ROUTE_REQUEST`. The channel table contains a list of channels that are used on a single flow path. The flow tables maintain a list of simultaneous flows being carried out on a single channel. These tables are used by the destination to make a decision regarding the selection of the optimal route from multiple received `ROUTE_REQUEST`s. The `ROUTE_REPLY` is unicast from the des-

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

tination to the source via the optimal path. All nodes forwarding the `ROUTE_REPLY` 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) protocol [4] has been developed for static community wireless networks. The protocol works in conjunction with the Mesh Connectivity Layer (MCL), which permits higher layer applications to connect to the wireless mesh network using Wi-Fi or WiMAX technology. The MCL implements an intermediary layer between the link and network layer. It is implemented as a loadable driver, which acts as a virtual network adapter with the ability to multiplex between several physical adapters. The MCL emulates a virtual network adapter and routes packets using MR-LQSR, which is an optimized version of the DSR protocol. The MR-LQSR protocol assumes that the number of wireless interfaces per node 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, 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) metric on each link is computed using the Expected Transmission Count (ETX), bandwidth and packet loss [3]. The ETT metric is then used to compute the Weighted Cumulative Expected Transmission Time (WCETT), which is a path metric that represents a trade off between high throughput and low delay paths. In contrast to native DSR which uses hop-count as the routing metric, MR-LQSR uses WCETT as the path metric.

2.4 Mult-Radio Multi-Channel Routing

The Multi-Channel Routing (MCR) Protocol [8] has been developed for dynamic wireless mesh networks, where nodes have multiple wireless interfaces. The protocol makes use of an interface switching mechanism to assign interfaces to channels. Two types of interfaces are defined: Fixed and switchable. With fixed interfaces, K out of a total of M interfaces are assumed to be operating on K fixed channels. With switchable interfaces, the remaining M-K interfaces are dynamically assigned to any of the remaining M-K channels. The switching is carried out depending on the maximum number of data packets which are queued for a single channel. Multiple queues are maintained for all switchable interfaces and each node maintains a neighbour table and a channel usage list. The neighbour table contains information regarding the fixed channels that are being used by the node's neighbours. The channel usage list contains the nodes and their corresponding fixed channels. Each node periodically transmits a `HELLO` packet on all channels, containing the node's fixed channel number. Each node that receives a `HELLO` packet updates its neighbour table and a channel usage list. The information in this table and list is used to manage the channel and interface switching mechanism. The switching mechanism assists the MCR protocol in establishing routes over multiple channels. MCR uses a new routing metric which is computed as a function of the channel diversity cost, interface switching cost and hop-count. Diversity cost is determined by the number of distinct channels used in a route. A route composed of a large number of distinct channels is considered as having a lower diversity cost. The switching cost represents the cost involved in switching interfaces from one channel to another. The route discovery mechanism of MCR is similar to that of the DSR. However, each `ROUTE_REQUEST` also contains the channel number and switching cost. When the destination receives the `ROUTE_REQUEST`, it computes the channel diversity cost and the total switching cost (sum of all link switching costs). The selection of the path is based on minimizing the sum of all these costs.

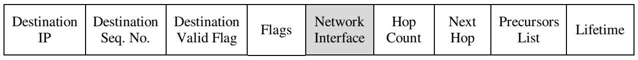
The related work indicates that two types of switching mechanisms can be used to improve the routing performance of a network i.e. interface switching and channel switching. In the former mechanism network interfaces are generally switched in order to connect to other network nodes, while in the latter channels are switched on a single interface to connect to nodes operating on the same channel. Both mechanisms permit optimal utilization of the frequency spectrum. However the accurate execution of these mechanisms in a mobile network entails the availability of a virtual switching protocol and incurs switching delays [2, 4]. The switching protocol may be integrated with the MAC layer or may run as a higher layer independent protocol. However, in either case, it requires precise synchronization between the nodes negotiating an interface or channel switch. In order to avoid the requirement of a separate switching protocol, in the following sections, we explain and evaluate the AODV-MR protocol, which makes use of the diversity in interfaces and operates each interface on precisely one channel at a time. The protocol's simultaneous operation over multiple channels not only offers a lower contention medium to the participating nodes but also significantly improves the performance of the network.

3. MULTI-RADIO AD-HOC ON-DEMAND DISTANCE VECTOR ROUTING

The Multi-Radio Ad-hoc On-Demand Distance Vector Routing (AODV-MR) protocol is a multi-homing extension to the AODV protocol. 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 since it sets up routes only when required. 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 [13]. Multi-path support has also been added to AODV through a number of extensions [9, 10], which permit 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. Each `ROUTE_REQUEST` packet contains an ID, source and destination IP addresses, sequence numbers, hop-count and control flags. The ID field uniquely identifies the `ROUTE_REQUEST` packet and the sequence numbers indicate the freshness of control packets. The hop-count represents the path length between the source and destination. Each recipient of a `ROUTE_REQUEST` packet that has not seen a request with the same source IP and 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 also create and preserve a reverse route to the source node for a certain interval of time. When the `ROUTE_REQUEST` packet reaches the destination or any node that has a fresher route to the destination, a `ROUTE_REPLY` packet is generated and unicast back to the source of the `ROUTE_REQUEST`. Each `ROUTE_REPLY` packet also contains a destination sequence number, source and the destination IP address, a route lifetime parameter, hop-count and 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 transmits the packet on 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 its active neighbours that were using that particular route.

In our scenario, each node is equipped with multiple radios and each radio can operate on one of multiple non-overlapping channels. When a route is required in AODV-MR, the `ROUTE_REQUEST` is broadcast simultaneously on all interfaces and neighbour nodes, which share at least one common channel with the sender node, receive the packet. If the `ROUTE_REQUEST` is not a duplicate (determined by source IP and destination ID), a reverse route pointing towards the source node is created.



Destination IP	Destination Seq. No.	Destination Valid Flag	Flags	Network Interface	Hop Count	Next Hop	Precursors List	Lifetime

Figure 2: AODV-MR Routing Table Fields

AODV-MR maintains an interface number in the routing table, as shown in Fig. 2. The interface number indicates the network interface via which a next hop node, for a particular path, can be reached. This information permits sending of the `ROUTE_REPLY` and future data packets on the correct interface. The intermediate nodes, after updating their routing tables, broadcast the `ROUTE_REQUEST` on all interfaces except the one on which the `ROUTE_REQUEST` was initially received. If the number of nodes in the network is n and the number of interfaces per node is i, the maximum number of `ROUTE_REQUEST`s propagated in the network is *(n-1).i*.

The propagation of `ROUTE_REQUEST` messages continues until the IP TTL expires. If the `ROUTE_REQUEST` is received by the destination itself or any node with a fresh route to the destination, a `ROUTE_REPLY` packet is sent to the source node using a loop free path. When the `ROUTE_REPLY` packet is received by intermediate nodes, a forward route to the destination is established by creating the corresponding routing table entries, including the interface number.

We can model a multi-radio WMN with two graphs G_1 and G_2. $G_1 = (N, E)$ represents the set of all nodes N in the network and the set of edges E. An edge $e_{i,j}$ exists between nodes n_i and n_j ($e_{i,j} \in E$) if the two nodes are within transmission range of each other.[2] In single-radio WMNs, where all nodes operate on a single shared channel, being within transmission range of another node directly implies network connectivity. This is not necessarily the case for multi-radio WMNs, where it is possible that two nodes that are in close proximity do not have network connectivity due to the fact that none of their interfaces operates on a shared channel. To make this distinction, we use L as the set of actual network links between nodes. The graph $G_2 = (N, L)$ represents the network connectivity graph of a WMN. A link $l_{i,j}$ between nodes n_i and n_j exists ($l_{i,j} \in L$) if the following two conditions are met. First, n_i and n_j need to be within transmission range of each other, i.e. $e_{i,j} \in E$. Secondly, the two nodes need to share at least one common channel.

Given that C_i and C_j represent the sets of channels on which the interfaces of node n_i and n_j are operating on, this condition can be expressed as $C_i \cap C_j \neq \emptyset$. We make the assumption that no two interfaces on the same node are tuned to the same channel. In single-radio WMNs, where all nodes operate on a single channel that is shared by all nodes, E and L and thus also G_1 and G_2 are equivalent. In our simulations of AODV-MR, we make the simplifying assumption that all nodes have the same number of interfaces, with identical channel allocation. This guarantees optimal connectivity of the network. We use hop-count as the routing metric for our simulations.

4. SIMULATION ENVIRONMENT

4.1 Set-up

We evaluated the efficiency of the AODV-MR protocol via simulations in NS-2 [11] using the Extended Network Simulator (ENS) extensions [17]. A mesh network covering an area of 1 sq. km is established using 16 equally distributed static `MESH_ROUTER`s, as shown in Fig. 3. These routers assist in establishing 30 simultaneous connections between randomly selected `MESH_CLIENT`s. On each connection we are sending CBR traffic with a rate of 10 packets/s, with varying packet sizes. The performance metrics are obtained by averaging results from over 50 simulation runs. AODV-MR with i number of interfaces is represented by AODV-MR-i. The simulation parameters are listed in Table 1.

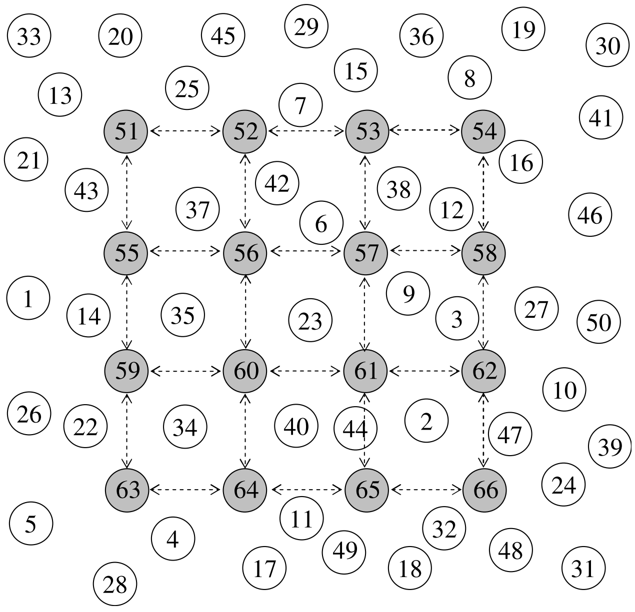


Figure 3: Structure of the Mesh Network

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[2] We assume bi-directional links and a constant transmission range for all radios.

Table 1: Simulation Parameters

Examined Protocol	AODV and AODV-MR
Channel Numbers	1, 6 and 11
Simulation time	900 seconds
Simulation area	1000 x 1000 m
Mobility 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)
Number of Connections	30
Payload size	128, 256, 512, 1024, 1440 bytes
Packet rate	10 pkt/sec
Interface Queue	50 pkts

4.2 Metrics

Our simulations provide the following performance metrics:

1. **Packet Loss:** The number of packets that were lost due to unavailable or incorrect routes, MAC layer collisions or through the saturation of interface queues [15].
2. **Aggregate Goodput:** The total number of application layer data bits successfully transmitted in the network per second.
3. **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.
4. **Routing Overhead:** The ratio of the total number of control packets generated to the total number of data packets that are successfully received.
5. **Average Latency:** The mean time (in seconds) taken by packets to reach their respective destinations.
6. **Path Optimality:** The ratio between the length (number of hops) of the shortest possible path and the actual path taken by the packets.

5. RESULT AND ANALYSIS

In our simulations, a relatively high offered load was injected into the network. The results, shown in Fig. 4, indicate that the standard AODV protocol is barely able to cope with the 250 thousand data packets (Tx-Pkts) transmitted in the network during a simulation run. A high level of interference, a large number of collisions and overflowing interface queues result in severe packet loss. In contrast, nodes executing AODV-MR-2 or AODV-MR-3 experience a lower degree of interference and contention since the traffic is distributed across multiple non-overlapping channels. We observe a significant decrease in packet loss with an increasing number of radios per node. As expected, packet loss for all variants of AODV increases with the offered load, i.e. packet size. Large packets seize the wireless medium for a long period of time and thus increase the contention for the medium, resulting in an increasing number of packets being dropped.

The packet loss rate also impacts on the aggregate goodput of the network. In our simulated scenario, standard AODV is clearly not able to handle the offered load and shows degraded performance with increased Tx-Rates. However, AODV-MR-2 and AODV-MR-3 cope better with high loads and achieve significantly higher goodput compared to standard AODV. The packet delivery ratio of standard AODV remains very low under high traffic load conditions, and drops to almost 23% when the input Tx-Rate is increased to 3 Mbps. In contrast, the AODV-MR-3 protocol is able to keep up with the increasing traffic volume. For an increase in the injected traffic load from 280 kbps to 3 Mbps, the packet delivery ratio of AODV-MR-3 decreases from 95% to 80%, while that of AODV-MR-2 decreases from 78% to 51%. It is interesting to note that for large packets and thus high traffic load, there seems to be a roughly linear relationship between the number of radios and the average goodput that can be achieved.

As mentioned earlier, the overall number of control packets generated by AODV-MR-i is i times higher than for standard AODV. However, since the routing overhead metric is computed as the ratio of routing packets to the number of successfully received data packets, AODV-MR outperforms AODV due to its improved packet delivery rate.

The lower packet loss and smaller number of collisions of AODV-MR also results in considerably lower packet delivery delay. For a packet size of 1440 bytes, the average delay for AODV-MR-3 is less than 0.3 seconds, compared to single-radio AODV with a packet delay of more than 1.2 seconds. The path optimality in terms of path-length of the AODV-MR protocol is only insignificantly lower than for the single-radio case.

In summary, it is clear the AODV-MR provides a great improvement in terms of quality of service over the standard AODV protocol. The key advantages of AODV-MR are as follows:

- Improved capacity and throughput
- Lower packet loss
- Reduced latency
- Simplicity and cost-effectiveness[3]

6. CONCLUSIONS

Wireless mesh networks have a great potential for a wide range of applications, due to a number of features such as robustness, self-configuration capability and low cost of deployment and equipment. One of the key shortcomings of WMNs challenges is the limited capacity and scalability, which is typical of multi-hop wireless networks. It has been shown previously that using multiple radio-interfaces per node, operating on orthogonal channels, can greatly increase the capacity of wireless mesh networks. In this paper we have presented, for the first time, a performance evaluation of the AODV routing protocol in a multi-radio wireless mesh network. Our simulation results are very encouraging and show a significant improvement in terms of throughput and delay of multi-radio AODV over its single-radio counterpart, especially under high load. AODV-MR makes ef-

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[3] AODV-MR can easily be implemented with currently available commodity hardware.

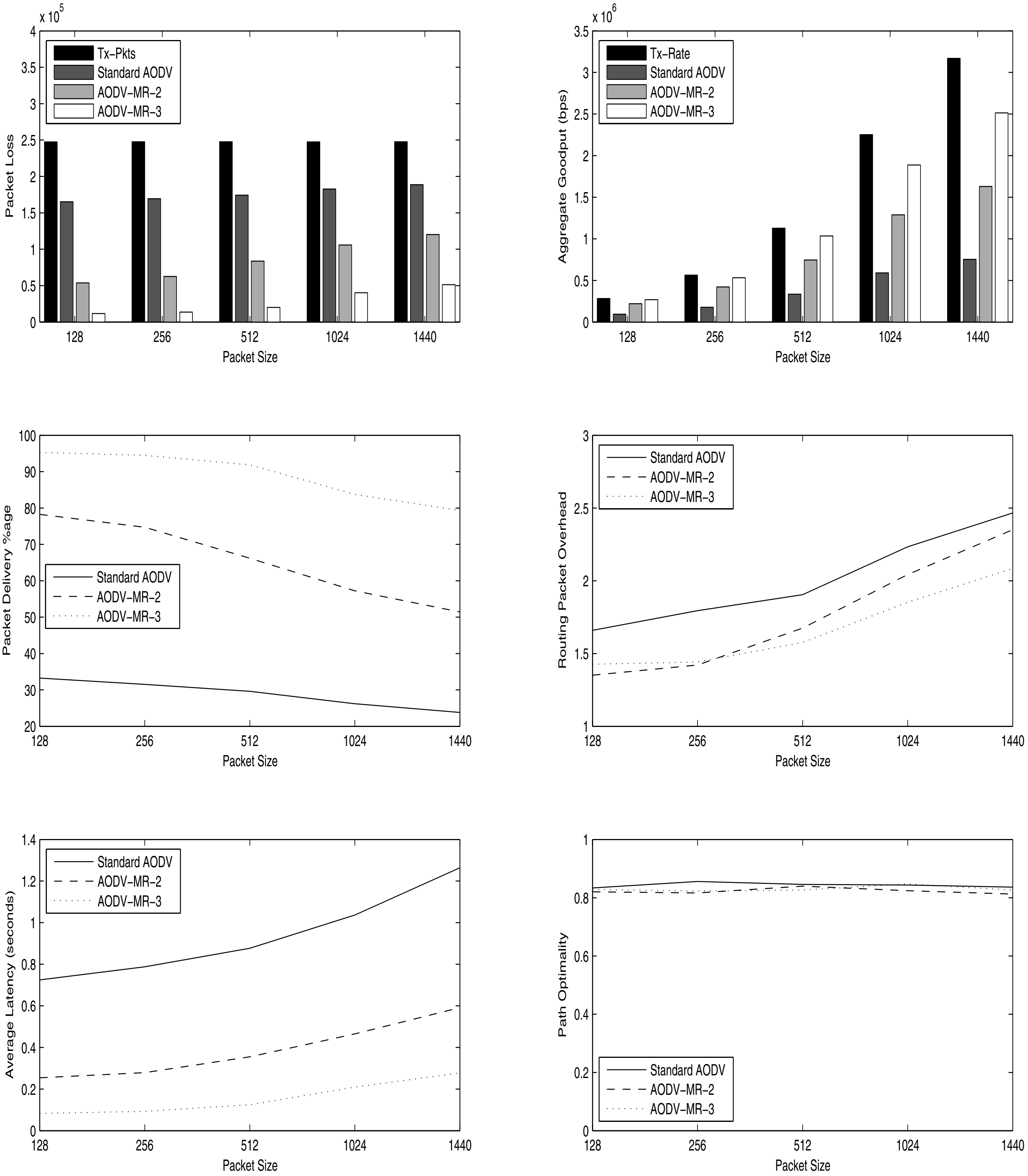

Figure 4: Simulation of Multi-Radio AODV Protocol

ficient use of the multiple interfaces and the increased radio spectrum to minimize interference and contention in the network. We believe there is a great potential to further improve the performance of AODV-MR, for example by using routing metrics that not only consider path length, but also the quality of the individual links [20]. Further improvements can be gained by making optimal use of channel diversity of the end-to-end path, thereby minimizing co-channel interference. These and similar ideas are currently being investigated in our ongoing work.

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