Experimental Evaluation of AODV in a Hybrid Wireless Mesh Network

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***Abstract*— Wireless Mesh Networks (WMNs) are a variant of ad-hoc networks that have recently received increasing attention. They are a promising technology for a wide range of applications for the reason of their cost-effectiveness, self-configuring and self-healing nature. Routing protocols are a key component of WMNs, as they are responsible for discovering and establishing end-to-end, often multi-hop, paths between nodes in dynamic environments. In this paper, we evaluate the performance of the Ad-hoc On-demand Distance Vector (AODV) protocol for hybrid WMNs, which are a special type of wireless mesh network that are comprised of both static infrastructure nodes as well as mobile client devices. The results obtained from our test-bed network indicate that AODV performs effectively in hybrid WMNs and is able to handle a high volume of traffic with minimal latency. While existing works on performance evaluation of ad-hoc and WMN routing protocols are typically performed either via simulations or via experiments on test-beds. Comparisons of results from both methods are rarely provided. One of the key contributions of this paper is the validation of our simulation results by performing experiments on a real WMN test-bed using the same scenario and mobility pattern. Our results show a reasonably good correlation between the simulation results and our test-bed measurements and we are able to explain the observed variations. Our work serves as a base line result for the exploration of larger and more complex network topologies.**

Keywords: Hybrid, mesh, wireless, network, routing.

I. Introduction

Wireless Mesh Networks (WMNs) can be considered as a variant of Mobile Ad-hoc Networks (MANET). In contrast to MANETs where the network consists exclusively of mobile client devices, WMNs are comprised of two types of nodes[1], Mesh Routers and Mesh Clients. Mesh Routers are typically static nodes connected to a permanent source of power. Mesh Clients are mobile devices such as PDAs or laptops, with relatively strict power constraints due to the fact that they run on batteries with limited capacity. WMNs are typically implemented using IEEE 802.11 technology.

Depending upon the deployment configuration, WMNs can be categorised into the following three types [1]: Infrastructure, client and hybrid WMNs. In infrastructure WMNs, the Mesh Routers form a high bandwidth wireless multi-hop backbone, which provides end-to-end connectivity to Mesh Clients. In these networks, Mesh Clients communicate with each other via the Mesh Routers, however, they never have to perform the routing or forwarding functions. This essentially requires Mesh Clients to have a single-hop path to at least one Mesh Router at all times.

Client WMN is simply another name for a mobile ad-hoc network [2]. A significant characteristic of these networks is that the network consists exclusively of mobile client devices without a wireless backbone. The Mesh Clients in a client WMN assume the role of Mesh Routers and route and forward packets for one another, extending the overall range of the network beyond the physical single-hop range of individual nodes.

As the name suggests, a hybrid WMN is the combination of an infrastructure and a client WMN, where both Mesh Routers and Mesh Clients participate in the routing and forwarding of packets. A typical scenario where a hybrid WMN might be employed is in emergency response and disaster recovery situations, where traditional communications infrastructure might not be available. In such a case, a hybrid WMN can provide a so-called incident area network, as illustrated in Fig. 1.

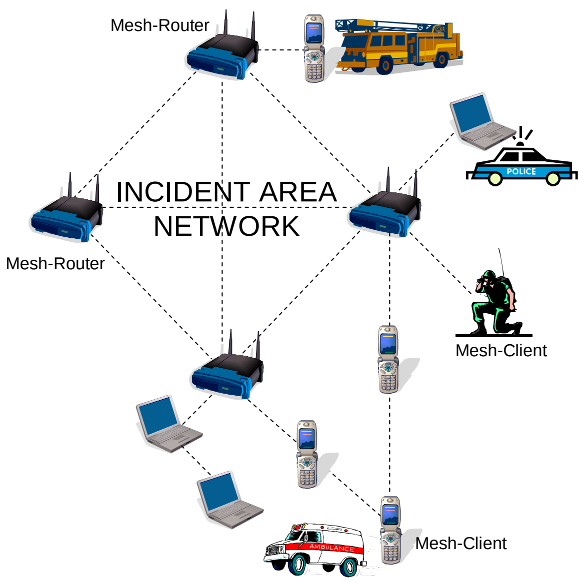

Fig. 1. Example Hybrid Wireless Mesh Network

[1]In this paper, we will use the term node interchangeably for Mesh Routers and Mesh Clients.

In a hybrid WMN, a number of communication scenarios can occur. Clients can directly talk to each other in a peer-to-peer manner or they can communicate with other clients via Mesh Routers. In either case, a routing protocol is needed to dynamically discover routes between nodes. Due to their ability to handle node mobility and the dynamic nature of wireless networks in general, a range of ad-hoc routing protocols have been developed for WMNs. These protocols can be categorized into reactive and proactive [3] types. Reactive protocols establish routes only when required whereas proactive protocols establish and maintain routes at all instants of time.

The use of ad-hoc routing protocols provides WMNs with a number of positive features, such as the ability to self-configure, self-heal and self-optimise. Further advantages of WMNs are ease and low cost of installation primarily due to the fact that no wired backbone infrastructure is required. These features make WMN technology an attractive candidate for a wide range of applications such as public safety and emergency response communication, intelligent transportation systems, home automation, wireless Internet access and community networks. Therefore, it does not come as a surprise that quite a few commercial WMN products have recently been introduced in the market [4], [5], [6]. These products make use of either proprietary or standards-based implementations of existing routing protocols [7], [8], [9], [10].

Ad-hoc On-demand Distance Vector (AODV) [10] is one such routing protocol with excellent potential for application to hybrid WMNs. AODV can support both static and mobile network configurations and has good scalability properties. The protocol's performance in ad-hoc network scenarios has been evaluated with the help of simulations in numerous prior works [11], [12]. However, it has become increasingly apparent that simulations alone are not sufficient to evaluate protocols used in wireless networks. Owing to model inaccuracies and other limitations, simulation results can vary drastically from the measurements obtained from real networks. In this paper, we evaluate the performance of AODV in a small hybrid WMN by means of simulation as well as via measurements on an actual WMN test-bed. A key contribution of this paper is the validation of our simulation results via comparison to the experimental results.

The remainder of the paper is organized as follows. Section II discusses related work. The AODV protocol is explained in Section III. The test-bed and simulation environment used to evaluate the performance of the AODV protocol is then explained in Section IV. The results and their analysis are presented in Section V. Section VI concludes the paper.

II. Related Work

Recently, there has been a lot of research activity in the area of routing protocols for WMNs. However, most work is based either on simulations or test-bed measurements, and only a very few works combine the two.

In [13], the OLSR [14] routing protocol is evaluated through both simulation and emulation. The authors use five wireless nodes to simulate a mobile ad-hoc network. The network simulator NS2 [15] is used for the simulation while the Mobile Network Emulator (MNE) [16] is used to emulate mobility on the test-bed by means of MAC address filtering. The results presented in the paper show a good match between the results obtained through the simulation and measurements.

In [17], the authors evaluate the effect of the hidden node problem in IEEE 802.11 wireless networks. A seven hops test-bed is established in a chain topology, using AODV as the routing protocol. All nodes are considered to be static and within radio range of the previous and next hop nodes. The authors compare the test-bed results with the results obtained from NS2 simulations. For this static scenario, the simulation results were very similar to the test-bed results.

In contrast to our work, none of these related works considers the special case of hybrid WMNs. The work presented in [13] considers a Client Mesh network whereas [17] considers a static topology, i.e. an Infrastructure Mesh network. The main difference between our work and the work presented in [17] is that we measure the network layer performance of the AODV protocol in a hybrid mesh network rather than in a static chain topology. In our case, the Mesh Routers are static while the Mesh Clients are mobile. Furthermore, in [17] the authors focus exclusively on the MAC layer. To the best of our knowledge, our work is the first evaluation of AODV for hybrid WMNs by means of simulation that includes validation of the results via measurements on a real test-bed.

III. AODV Protocol

The AODV routing protocol is 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 [7] and hop to hop routing vectors from the Destination-Sequenced Distance-Vector (DSDV) routing protocol [18]. Multi-path support has also been added to AODV through a number of extensions [19], [20], [21], 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 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 RREQ ID pair or does not maintain a fresher (with larger sequence number) route to the destination rebroadcasts the same packet after incrementing the hop-count. Such 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 node or any node that has a fresher route to the destination, a Route Reply packet is generated and is unicast back to the source of the Route Request packet. Each Route Reply packet contains the destination sequence number, the source and the destination IP addresses, route lifetime together with a 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.

IV. Test Environment

For the purpose of performance evaluation of AODV for hybrid WMNs, we create a simple and small network of 8 nodes, of which 4 are static Mesh Routers (M1, M2, M3 and M4) and 4 are mobile Mesh Clients (C1, C2, C3 and C4). The nodes are placed in an area of 500 x 500 metres, as shown in Fig. 2.

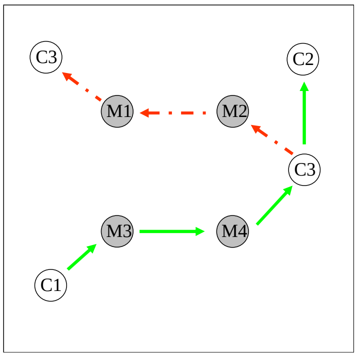

Fig. 2. Hybrid Mesh Network Layout

The Mesh Routers are placed in a 2x2 grid configuration with a horizontal and vertical distance of 162 metres between nodes. This distance was chosen so that the diagonal distance between Mesh Routers (M1-M4 and M3-M2), is within the transmission range of 250 metres that we chose for our simulation. At the start of the simulation, the Mesh Clients are arbitrarily placed in the area and subsequently move according to the random way-point mobility model. As the Mesh Routers are static, they assist the Mesh Clients in establishing relatively stable connections in the network. It has been shown that the presence of static Mesh Routers in the network significantly improves the packet delivery rate and lowers the routing overhead in comparison to a pure client mesh architecture, consisting of mobile clients only [22].

Two concurrent unidirectional CBR (UDP) sessions are established from C1 to C2 and from C3 to C4 respectively. This scenario serves as the basis for our evaluation via simulation as well as measurements. We use this scenario to evaluate the performance of the AODV protocol on our test-bed as well as using the NS2 simulator, for varying levels of offered traffic loads and client speeds.

Fig. 3. Mesh Router with RB532a SBC and CM9 Wireless Card

A. Test-bed

The WMN test-bed consists of four Mesh Routers. Each Mesh Router is made up of a Routerboard[2] RB532a Single Board Computer (SBC), as depicted in Fig. 3.

The boards are equipped with a MIPS 32 4Kc processor running at 266MHz and have 64MB of RAM. As Mesh Clients, we use four standard PCs with AMD Sempron 2800+ CPU and 512MB RAM. All nodes are equipped with a CM9 AR5212 mini-PCI wireless network cards operating in IEEE 802.11b auto-rate mode, using the Madwifi[3] driver SVN version r1639. We further use external 5dBi omni-directional antennas on each node. Mesh Routers run Linux with kernel version 2.4.31, while the Mesh Clients run kernel 2.6.8.

We ran our experiments with AODV-UU[4] version 0.9.1 as the routing protocol on all nodes. Since the Mesh Clients in our test-bed are physically static, we emulate virtual client mobility with the Mobile Network Emulator (MNE) [16], which has been developed by the Naval research laboratory.

MNE has been designed as a flexible, low-cost mobile wireless testing toolkit to emulate a variety of motion patterns with support for internal motion models, live experiment motion traces, and motion input from other tools such as network simulators.

We use the mobility scenario file from NS2 as input to MNE. This guarantees that we utilise the same mobility pattern in both our simulation and test-bed. The network topology and mobility pattern is implemented via MAC filtering using iptables[5]. MNE dynamically adds and deletes MAC entries from the filter tables of all nodes to emulate mobility.

In order to minimise the impact of RF interference from nearby wireless networks, all tests were carried out overnight when network traffic and therefore interference was minimal. Our results were averaged over 10 individual experiments.

[2] http://wwww.routerboard.com
[3] http://madwifi.org/
[4] http://core.it.uu.se/AdHoc/AodvUUImpl
[5] http://www.netfilter.org

B. Simulation

The NS2 network simulator is a discrete event simulator, which is used extensively by the research community to simulate wired and wireless networks. We used NS2 version 2.1b9a along with the CMU ad-hoc networking extensions [23]. The AODV_LINK_LAYER_DETECTION flag is enabled, which allows link layer feedback to be used for the detection of link breakages. We disable AODVs HELLO packets on both AODV-UU as well as in the simulator. The mobility scenario files have been generated using the setdest utility and are exported to MNE.

C. Test Parameters

The test parameters are listed in Table I.

TABLE I
TEST PARAMETERS

Test time	900 seconds
Test area	500 x 500 m
Mobility model for Mesh Clients	Random way-point
Maximum speed of Mesh Clients	0, 5, 10, 15 & 20 m/s
Transmission range	250 m
Number of CBR sessions	2
Traffic type	CBR (UDP)
Packet size	512 bytes
Transmission rate	0.256, 0.512, 1, 2 & 4 Mbps

D. Assumptions

The following assumptions have been made:

- All Mesh Clients and Mesh Routers have a single wireless transceiver
- All Mesh Clients and Mesh Routers operate on one common channel
- The transmission and reception ranges of the wireless transceivers are comparable
- The wireless antennas are omni-directional

E. Mobility Model

We implement the random way point mobility model for the simulation, in which a Mesh Client first waits for the pause interval and then moves to a randomly chosen position with a velocity randomly chosen between 0 m/s and the maximum speed. The Mesh Client waits at this location for the pause time, and then moves on to another random position. A maximum speed of 0 m/s correlates to a static network.

F. Communications Model

The IEEE standard 802.11 Distributed Coordination Function (DCF) [24] is used as the MAC layer. All packets are transmitted using the un-slotted Carrier Sense Multiple Access protocol with Collision Avoidance (CSMA/CA). In CSMA/CA each broadcasting node waits for a vacant channel by sensing the medium. If the channel is vacant, it makes the transmission. In case of a collision, the colliding stations wait using the Ethernet binary exponential back off algorithm [25]. Virtual Carrier Sensing (RTS/CTS) is disabled during the simulations by setting a large value for the RTS Threshold variable.

G. Performance Metrics

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 [26].

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

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

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

V. RESULTS AND ANALYSIS

A pair of tests was conducted to evaluate the performance of the AODV protocol under varying mobility and traffic loads. In the first test we vary the Mesh Client mobility from 0 to 20 m/s and keep the transmission rate fixed at 512 kbps. In the second test we increase the transmission rate from 256 kbps to 4 Mbps while keeping the maximum Mesh Client speeds at 5 m/s.

The results for the first test are shown in Fig. 4. The results obtained using NS2 are labelled with AODV-NS2 and those obtained from the test-bed using MNE are labelled with AODV-MNE. The results indicate that the packet loss of the AODV-MNE is significantly higher than that of the AODV-NS2. This higher loss can be attributed to the fact that all nodes engaged in the MNE test are physically within the transmission range of each other but virtually isolated using MAC layer filtering. These nodes are also influenced by the co-channel interference present in the local neighbourhood. This essentially causes contention for the physical medium by all participating nodes causing blockades, which in turn saturate the network interface queues resulting in packet losses. On the other hand, the NS-2 simulator does not confront these problems and so we observe lower packet losses compared to AODV-MNE.

The packet loss rate also influences the aggregate goodput and packet delivery rate of the network. We observe that the packet delivery of AODV-MNE drops from almost 99% at zero mobility to less than 90% at a speed of 20 m/s. On the other hand, AODV-NS2 is not affected by the increased packet losses and thus we only observe minimal decrease in the packet delivery rate at high speeds. The 2% drop in the packet delivery rate of AODV-NS2 is attributable to the high frequency of route breakages and route creations occurring at high speeds.

The latency of the network increases with the increase in the Mesh Client speeds. At higher speeds the routes are significantly more unstable, which causes routes to break frequently. The AODV protocol endeavours to fix these broken routes using gratuitous route replies. In doing so, it elongates the routes in comparison to the optimal possible routes. This implies that the packets now have to traverse longer routes and thus depict higher latency. The latency observed with AODV-NS2 varies from 2 ms to 10 ms when the speed varies from 0

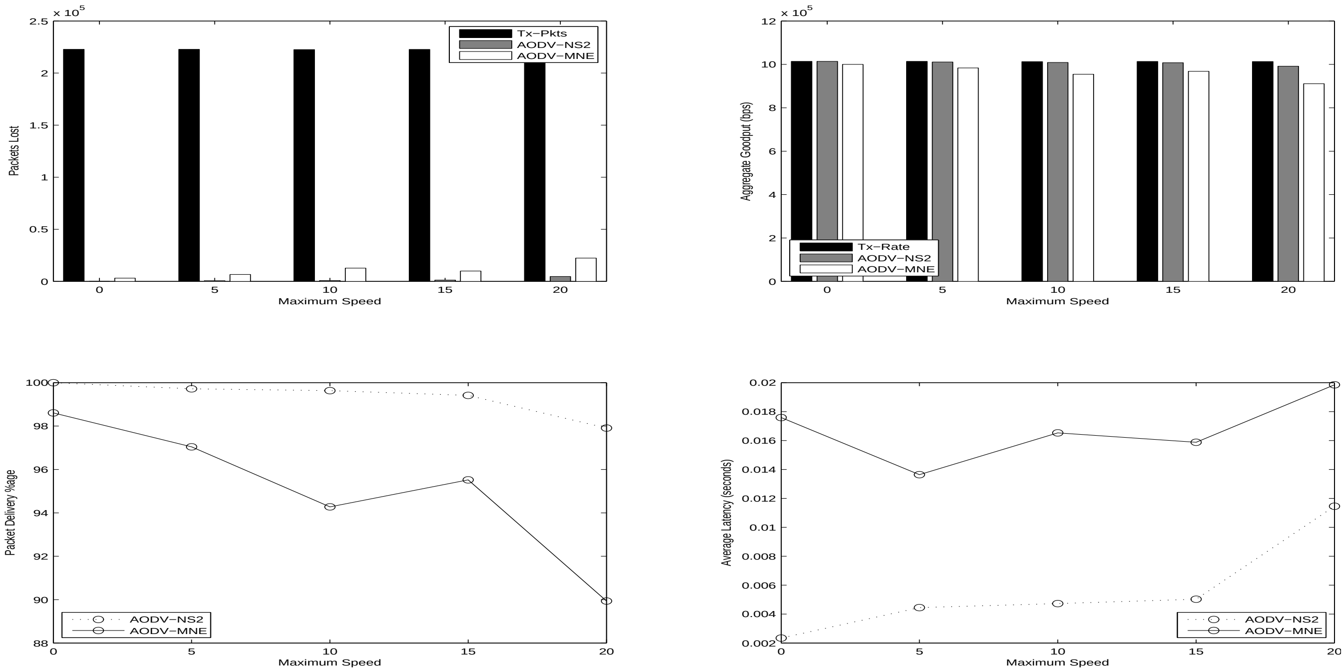

Fig. 4. Test Results with varying Mesh Client Speeds

to 20 m/s. The latency of AODV-MNE varies from 18 ms to almost 20 ms for a similar increase in Mesh Client speeds. The additional latency observed is attributable to the extraneous interference generated by the test-bed.

The results obtained from the second test are shown in Fig. 5. The packet loss of the AODV protocol increases with the transmission rate (Tx-Rate). The results indicate that the packet loss rapidly increases when the Tx-Rate is increased beyond 1Mbps. At 2Mbps, the number of packets dropped using AODV-MNE are more than 60% of the number of data packets transmitted (Tx-Pkts). AODV-NS2 also suffers from the packet losses at higher Tx-Rates but the losses are comparatively lower than the AODV-MNE. However, when the Tx-rate is increased to 4Mbps, the packet loss in AODV-NS2 becomes higher than that of AODV-MNE. This is caused due to the peculiar manner in which the IEEE 802.11b physical layer is represented in NS2. The physical layer in NS2 has no option for Auto Rate Fall-back (ARF), and hence we observe higher packet losses at 4Mbps when the physical layer is no longer able to sustain the higher layer transmission rate. On the other hand, AODV-MNE takes advantage of the ARF control algorithm, which helps in lowering the physical transmission rate in high interference environments. Thus we observe better performance by AODV-MNE as compared to AODV-NS2 under high traffic loads.

AODV-NS2 achieves almost 100% packet delivery rate for a Tx-Rate of 256 kbps. While AODV-MNE depicts up to 5% degradation in the packet delivery rate as compared to AODV-NS2. This degradation is contributed to the higher packet losses observed by AODV-MNE and due to the elevated level of test-bed interference. The packet delivery rate of AODV-NS2 drops to almost 30% when the Tx-Rate is increased to 4 Mbps. An equivalent drop in the goodput is also observed, where for a combined Tx-Rate of almost 8 Mbps the aggregate goodput is almost Mbps. However, the goodput for the AODV-MNE remains higher than that of the AODV-NS2 due to its adaptation of the physical layer using the ARF. A higher injection rate of packets causes additional contention for the medium resulting in increased delays. During packet traversal, these delays are accumulated across each hop, which augments the overall latency. AODV-MNE takes advantage of the ARF mechanism and is able to lower its latency at higher transmission rates as compared to that of the AODV-NS2.

VI. Conclusions

A Hybrid Mesh Network essentially represents a combination between a mobile ad-hoc wireless network and an infrastructure mesh network. Hybrid WMNs support a multitude of communication modes, where routes can be established using either or both Mesh Routers and Clients. The Ad-hoc On-demand Distance Vector routing protocol is a well known routing protocol currently being used for mobile ad-hoc wireless networks. However, the protocol's potential has not been fully exploited and by far and large its application has been restricted to ad-hoc networks. In this paper, we apply the AODV protocol to a hybrid wireless mesh network and evaluate its performance under varying speeds and traffic loads. In order to obtain a realistic perspective of the protocol's performance we carry out tests both on an actual mesh test-bed and on a network simulator. The results obtained from the test-bed and simulation are comparable and only show deviation that is caused due to an artefact of the emulation environment. The results indicate that the AODV protocol can successfully

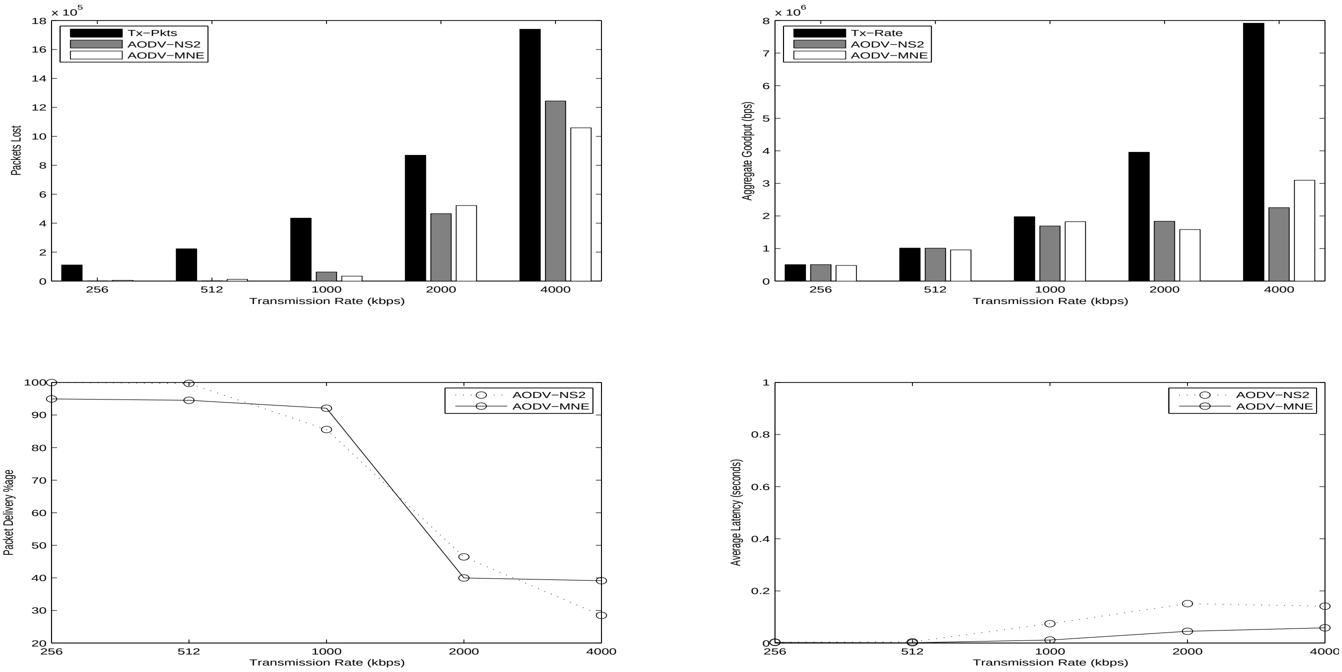

Fig. 5. Test Results with varying Transmission Rates

achieve a packet delivery rate exceeding 90% with a latency of almost 10ms when the packet injection rate is 1Mbps in an actual Hybrid Wireless Mesh Network.

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