

Establishing High Capacity Routes in Wireless Mesh Networks

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Abstract—A Wireless Network consists of two types of nodes, Mesh Routers and Mesh Clients. Mesh Routers are static multi-radio nodes that form the wireless back-haul. Mesh Clients are mobile single-radio nodes that communicate using the wireless back-haul. Routing protocols act as the binding force in these networks by forming a ubiquitous network environment. However, routing across heterogeneous devices encompasses a number of hurdles. One common problem is the lack of capability-aware routing in a highly contented wireless medium. In this paper, we present a variant of the Ad-hoc On-demand Distance Vector (AODV) routing protocol with the aim to exploit node heterogeneity in wireless mesh networks. The protocol endeavours to discover and establish multiple parallel links between adjacent Mesh Routers. These links are then bundled to create a high capacity virtual link. As demonstrated via extensive simulations, our protocol achieves a more than 100% improvement over standard AODV in terms of key performance metrics such as packet delivery ratio, routing overhead and latency.

Keywords: Wireless, mesh, network, routing, channel.

I. INTRODUCTION

Wireless Mesh Networks (WMN) have recently gained considerable popularity owing to their self-configuring, self-optimising and self-healing capabilities. These networks offer an attractive platform for a wide range of applications, such as public safety and emergency response communications, intelligent transportation systems, and community networks.

There are two major challenges associated with multi-hop communication in a WMN. The first problem is due to the shared wireless medium (Physical/MAC layer), while the second problem is associated with the discovery of optimal routes in a highly dynamic network (Network layer) [1].

WMNs commonly adopt the IEEE 802.11 standard [2] at the Physical and MAC layers. For single-hop communication the CSMA/CA scheme is considered adequate and offers efficient use of the frequency spectrum. However, for multi-hop communication the performance of the CSMA/CA scheme degrades significantly with increasing number of hops [3]. One of the problems is that CSMA/CA based communication is half-duplex and cannot sustain simultaneous sending and receiving of data. Another performance limiting factor in WMNs is co-channel interference, where nodes within interference range are transmitting simultaneously on the same channel, resulting in collisions, reduced throughput and increased communication delays.

Routing in a multi-hop wireless mobile network is a challenging task. In contrast to the relatively static Mesh Routers, Mesh Clients can be highly mobile, resulting in frequent route severing. In addition, as Mesh Clients are relatively resource constrained devices, the routes should preferably be established via the static Mesh Routers. Consequently, the type of node, i.e. Mesh Client versus Mesh Router, should be taken into consideration during the route establishment process.

The Ad-hoc On-demand Distance Vector (AODV) protocol is one of the most commonly used reactive routing protocols. AODV was originally developed for homogenous mobile ad-hoc networks, where nodes have comparable computational and communication resources. Thus, WMNs that employ standard AODV, including commercially supported products [4], are unable to exploit the heterogeneity in the network, especially in WMNs. The protocol does not perform preferential routing through the multi-radio Mesh Routers rather than the single radio Mesh Clients, hence, poor network performance is observed when the standard AODV is engaged. In addition, the discovery of multi-radio nodes can also facilitate in striping of data across parallel links and load balancing. However, AODV only discovers a single link between each Mesh Router pair and, hence, no link optimisations can be performed.

In this paper, we present a variant of the AODV protocol that effectively mitigates the problems and limitations associated with the Physical, MAC and Network layers in WMNs. One of the key contributions is the discovery of parallel wireless links between adjacent multi-radio Mesh Routers during the route establishment phase. We further show how the multiple links can be used to stripe data to create high-capacity wireless trunks. With the help of extensive simulations, we show that our variant of AODV outperforms standard AODV by a considerable margin.

The remainder of the paper is organised as follows. We first discuss some relevant work in Section II. The proposed routing protocol is then explained in Section III. Simulation results and the corresponding analysis is presented in Section IV, with concluding remarks in Section V.

II. RELATED WORK

Hyacinth [5] is a well known multi-channel protocol that uses multiple radios and channels to improve the network

performance in a static community WMN. Hyacinth’s channel assignment algorithm breaks a single-channel collision domain into multiple collision domains, each operating on a different frequency. Nodes control and coordinate allocation of channels to interfaces via periodic exchange of messages containing channel usage status. Another protocol also developed for static community wireless networks is the Multi-Radio Link Quality Source Routing (MR-LQSR) [6] protocol. The protocol identifies all nodes in the wireless mesh network and assigns weights to all possible links. The link information including channel assignment, bandwidth and loss rates are propagated to all nodes in the network. The Multi-Channel Routing (MCR) protocol [7] has been developed for dynamic, multi-radio WMNs. The protocol makes use of an interface switching mechanism to assign interfaces to channels. Switching is carried out depending upon the maximum number of data packets queued for a single channel. 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-count.

Hyacinth, MR-LQSR and MCR use interface switching to improve upon the routing performance in the network. However, the accurate execution of these mechanisms in a mobile network entails the availability of a virtual switching protocol. Inaccurate execution of such protocols can cause partitioning and jitter in the network. Another problem with these routing protocols is their inability to exploit the wide frequency spectrum offered by the Mesh Routers. This results in poor or uneven utilisation of the channels, which causes higher contention for the wireless medium, thereby, inducing severe packet losses and increased latency.

Striping is the mechanism in which data can be sent between two nodes using multiple parallel links. Striping can be performed at the link, network and higher layers. In [8] the authors present the Surplus Round Robin mechanism for striping of data across parallel links at the network layer using a Load Sharing Algorithm at the sender stage and a Fair Queuing Algorithm at the receiver stage. The mechanism is similar to the Round Robin mechanism but adds a quantum of service (counter) to each queue to limit the maximum amount of data sent through each queue. Similarly, the receiver uses an inverse version of the striping algorithm to select the appropriate receiver queue that receives the incoming striped data. The scheme uses special marker packets, which are sent periodically, to maintain synchronisation between the sender and receivers. In [9] the authors discuss striping of data across multiple 802.11b links at the transport layer. The work essentially adds modifications to the Surplus Round Robin mechanism to improve the performance of TCP.

In the next section, we present a reactive routing protocol that integrates the discovery of parallel links between multi-radio nodes with the route discovery mechanism. A further contribution of this paper is the subsequent use of the discovered parallel links for creating a high bandwidth wireless trunk through striping.

III. STRIPED AD-HOC ON-DEMAND DISTANCE VECTOR ROUTING PROTOCOL

The Striped Ad-hoc On-demand Distance Vector (AODV-S) Routing Protocol is a variant of the standard AODV protocol with improved routing support for multi-radio nodes. In order to explain the working of AODV-S, we first briefly explain the standard AODV protocol in this section.

The AODV routing protocol is a reactive routing protocol that has been optimised for mobile ad-hoc wireless networks [10]. When a source node intends to communicate with a destination node whose route is not known, it broadcasts a Route Request packet (RREQ). Each recipient of the RREQ that has not seen an earlier copy of the RREQ, or does not maintain a fresher route to the destination, rebroadcasts the RREQ after incrementing the hop-count. Such intermediate nodes also create 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 fresher route to the destination, a Route Reply packet (RREP) is generated and unicast back to the source of the RREQ. Each intermediate node that receives the RREP, increments the hop-count, establishes a forward route to the source of the packet and transmits the packet on the reverse route. In case a link break is detected for a next hop of an active route, a Route Error (RERR) packet is sent to its active neighbours that were using that particular route.

The standard AODV protocol was originally developed for single-radio nodes in a wireless ad-hoc network. However, later on the protocol was modified to support nodes having multiple radios. We refer to the standard AODV protocol with support for multiple radios as AODV-MR in this paper.

When using AODV-MR, each RREQ is broadcast on all the node’s interfaces. Intermediate nodes with one or more interfaces operating on a common channel, receive the RREQ and create a reverse route that points towards the source node. The first RREQ received by the destination, or any intermediary node, is selected and all subsequent RREQs are discarded. As shown in Fig. 1, the RREQs received by Mesh Router **C** from Mesh Router **B** on channels C_{i+1} and C_{i+2} are discarded and the route is only formed on C_i .

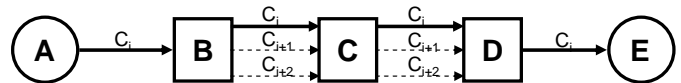


Fig. 1. Route Establishment using AODV-MR

The RREP is generated in response to the selected RREQ, and is sent back to the source node via the existing reverse route. Thus, in the worst case scenario, the same channel C_i may be selected across all hops between the source Client **A** and the destination Client **E** via Mesh Routers **B**, **C** and **D** respectively. This causes extensive interference in the shared wireless medium causing packet losses and higher latency.

AODV-S places prime focus on the discovery of Mesh Routers and the multiple links between them. Similar to

AODV-MR, the RREQ in AODV-S is sent on all available wireless channels. The recipient Mesh Router, instead of receiving the first copy only and discarding the rest, receives and processes all incoming copies of the RREQ on all interfaces. As each RREQ carries the immediate sender's IP address, a reverse route entry is made to the source node with the sender as its next hop, which is accessible via one or more wireless interfaces. It is important to note that the RREQ is not delayed at any node, rather the first received RREQ is broadcasted immediately after creating the reverse route. The Mesh Routers only update the interface information in the reverse routes upon receipt of duplicate copies of the RREQ from the next hop. For example as shown in Fig. 2, multiple copies of the RREQ sent by Mesh Router **B**, enable Mesh Router **C** to create a reverse route to Mesh Client **A** with Mesh Router **B** as the next hop, which is accessible via interfaces operating channels C_i , C_{i+1} and C_{i+2} respectively.

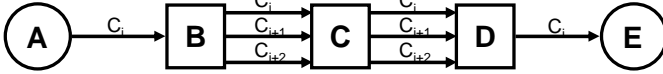


Fig. 2. Route Establishment using AODV-S

This process continues until the time the RREQ is received by the destination or any other node that has an active route to the destination. That node responds with a RREP, which contains information about the channels through which the next hop is accessible. For example Client **E** sends a RREP to Mesh Router **D**. The packet contains channel number C_i indicating that **D** can communicate with **E** via channel C_i . Similarly, when Mesh Router **D** is forwarding the RREP to Mesh Router **C** on its default interface¹, it appends channel numbers C_i , C_{i+1} and C_{i+2} indicating to Mesh Router **C** that it can communicate with Mesh Router **D** via channels C_i , C_{i+1} and C_{i+2} . Similarly Mesh Router **C** informs Mesh Router **B** regarding the channels with which it can communicate with Mesh Router **C**. Thus at the culmination of the route discovery process, all nodes forming the route know the precise channel numbers that can be used to directly communicate with their adjacent nodes.

To stripe the data across multiple parallel links, we use a round-robin mechanism similar to [9]. The link selection is carried out based upon two criteria. The first criterion is to achieve a two-hop channel diversification i.e. $C_i \neq C_{i-1}$. This diversification ensures that there is no additional intra-flow interference caused by the striping mechanism.

The second criterion seeks least congested links, indicated by the minimal interface queue (IFQ) length. To differentiate queues with comparable lengths but different link rates we use the Queue Discharge Interval (QDI). If we assume that the current IFQ length of a channel C_i is represented by Q_i , then for a link bandwidth of BW_i , the QDI of C_i is given by:

$$QDI = \frac{Q_i}{BW_i}$$

The QDI represents the time a packet has to remain in the IFQ before being transmitted on to the physical medium. By normalising Q_i , we ensure that the QDI of different links with varying bandwidths are comparable.

The link with the least QDI is selected as a potential candidate for striping. The link selected in this manner thus not only guarantees channel diversification but also ensures that traffic is distributed evenly across all available wireless links. Thus for the scenario in Fig. 2, Mesh Router **B** stripes the data on to channels C_{i+1} and C_{i+2} depending upon their current QDIs. In case the QDI of one of the channels is significantly lower than the other, the channel with the lower QDI may only be utilised for striping. However, when the QDI of this channel increases due to traffic load of flows, interference or noise, the striping function would resume on the other channel.

In order to avoid the problem with reordering of packets, we employ a marker synchronisation scheme. In this scheme, special marker packets containing the stripe round number are sent periodically on each stripe. These packets, which are distinguishable from data packets, enable the stripe receiver to remain in synchronisation with the stripe sender. For additional details we refer the reader to [8].

IV. SIMULATION RESULTS AND ANALYSIS

We have evaluated the efficiency of the AODV-S protocol through extensive simulations in NS-2 [11], using the Extended Network Simulator (ENS) extensions [12]. A WMN covering an area of 1 square km is established using 25 static Mesh Routers. The Mesh Routers are distributed in a uniform 5x5 grid and each is equipped with six 802.11b radios². The network further consists of 50 mobile Mesh Clients, each equipped with a single-radio and placed randomly in the simulation area. Thirty simultaneous 128 kbps CBR flows are established between randomly selected source and destination Mesh Client pairs.

The simulation results are shown in Fig. 3. The results indicate that AODV-S is able to significantly reduce the packet loss compared to standard AODV-MR. During route establishment, AODV-S focuses on engaging minimally loaded channels for striping of data traffic. This helps to sustain the 30 simultaneous 128 kbps connections. However, standard AODV-MR forms routes over multiple hops by randomly selecting the available channels. Thus, a route may be comprised of a large number of overlapping and saturated channels, resulting in severe packet losses. The lower packet losses incurred by AODV-S enable it to achieve a higher packet delivery ratio. The packet delivery ratio of AODV-S drops from 100% to almost 93% when the maximum client speed is increased from

¹The default interface is the interface on which the first copy of the RREQ is received.

²Although, 802.11b can only support three orthogonal channels, we have configured the NS-2 802.11b physical layer to consider all channels to be orthogonal. This allows us to simulate the behaviour of radios that support a high number of orthogonal channels such as 802.11a.

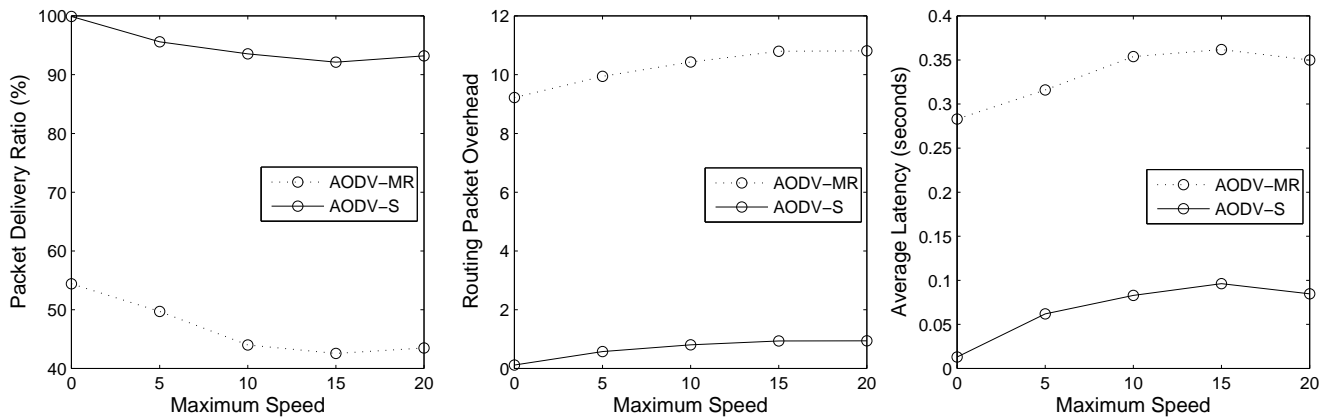


Fig. 3. Simulation results with varying Maximum Client Speeds

0 to 20 m/s. The packet delivery of standard AODV-MR drops from 55% to 43% for a similar increase in client speed.

As mentioned earlier, the standard AODV-MR protocol forms routes using random channels rather than selecting optimal channels available in the network. As a result, links frequently get saturated and suffer from interference. This essentially causes the routes to sever, thereby causing new route discoveries. These route discoveries increase the routing overhead of AODV-MR to more than ten control packets for each received data packet. On the other hand, AODV-S stripes data packets over diverse and least loaded channels. This enables the route to be effective for longer durations, which minimises the need for extraneous route discoveries, keeping the routing overhead to less than one control packet per received data packet.

As the striping has been optimised for minimal interference in AODV-S, packets are sent promptly without incurring excessive contention for the physical medium. This has the effect of less than 100 ms of latency for data packets traversing an average of four hops. In contrast, the packets flowing on routes established using AODV-MR face severe contention for the physical medium, and are significantly delayed at each hop, causing a latency of more than 300 ms.

V. CONCLUSIONS

In this paper, we have presented a routing protocol for Wireless Mesh Networks that discovers multiple parallel links between multi-radio nodes. This is in contrast to traditional ad-hoc and mesh routing protocols, which only discover a single link between node pairs in a particular route. The multi-link discovery has been integrated with the route establishment process of the AODV reactive routing protocol. Our proposed scheme further uses striping to make effective use of the discovered parallel links. The key idea of the striping algorithm is to transmit data in parallel on least congested links, while minimising co-channel interference. The simulation results indicate that the proposed protocol performs extremely well in Wireless Mesh Networks and is able to achieve a significantly high packet delivery ratio with low latency and routing overhead.

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