Performance Comparison of Reactive Routing Protocols for Hybrid Wireless Mesh Networks

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Abstract

Wireless mesh networks have recently gained a lot of popularity due to their rapid deployment and instant communication capabilities. These networks comprise of somewhat static multi-radio Mesh Routers, which essentially provide connectivity between the mobile single-radio Mesh Clients. Special routing protocols are employed, which facilitate routing between the Mesh Routers as well as between the Mesh Routers and the Mobile Clients. AODV is a well known routing protocol that can discover routes on-the-fly in a mobile environment. The protocol is highly scalable and can support thousands of nodes making it an ideal protocol for wireless mesh networks. However, as the protocol was actually developed for single-radio nodes, it frequently lacks the ability to exploit the potential offered by the Mesh Routers and, hence, sub-optimal routing takes place in a mesh environment. This paper gives an overview of four variants of the AODV routing protocol that can potentially be used for mesh formation. In order to determine their aptness for application to hybrid wireless mesh networks, this paper presents their characteristics and functionality, and then provides a comparison and discussion of their respective merits and drawbacks.

1. Introduction

Wireless Mesh Networks (WMNs) are ever increasingly finding their way into modern society. This appreciation is owed primarily to their self-organising, self-configuring and self-healing capabilities. A WMN consists of two major components, the Mesh Router and the Mesh Client [1]. Mesh Routers are static, high powered devices that form the structure of the WMN, often consisting of multiple radios. Mesh Clients are generally single radio communication devices that can either be mobile or stationary. Fig. 1 shows an amalgamation of a static WMN and a mobile WMN to form a hybrid WMN, which provides a holistic framework where both Mesh Routers and Mesh Clients are actively involved in the routing and forwarding of data packets.

In order to guarantee that the paths established in hybrid WMNs offer optimum performance, the design of routing protocols must take into account the particular characteristics unique to hybrid WMNs. Characteristics that require attention by routing protocols include;

1. Optimal use of multiple radios;
2. Intra-flow and inter-flow interference; and
3. Sudden changes in topology due to node mobility.

The standard protocols currently used in WMNs fall under two categories; Proactive and Reactive [10]. Proactive routing protocols maintain one or more node lists, which contain routing information to every other node in the network, by distributing routing tables in the network periodically. By refreshing these tables, all nodes obtain a consistent and up-to-date view of the network topology. Reactive

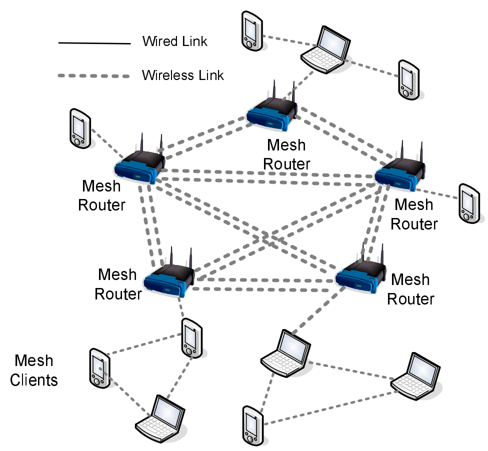

Figure 1. Hybrid Wireless Mesh Network

routing protocols, as the name suggests, only construct a route between a source and its destination when it is actually required.

One of the more popular and well analysed reactive routing protocols is the Ad-hoc On-Demand Distance Vector (AODV) routing protocol. AODV is also the core underlying protocol for the upcoming 802.11s Mesh standard. Several papers on WMN routing declare AODV as a high performance protocol for hybrid WMNs. Significant adaptations of differing routing metrics have been incorporated into the existing protocol in order to tackle its shortcomings.

In an effort to understand the effects on performance of AODV in WMNs using different routing metrics, our work makes the following contributions. First, we delineate the particular characteristics of a WMN and point out those which need to be taken into account during the design of a routing protocol. Second, we examine the standard AODV routing protocol outlining some of its deficiencies. Third, with a focus on routing metrics, we analyse four variants of the AODV routing protocol. Fourth, we produce a direct comparison between these AODV variants in order to understand the pro's and con's of the differing routing metrics and their performance against the standard AODV protocol.

The remainder of this paper is organised as follows. Section 2 examines the standard AODV protocol. Section 3 reviews and analyses four variants of the AODV routing protocol. Section 4 presents a comparison between the standard AODV protocol and its variants. Section 5 concludes the paper.

2. Ad-hoc On-demand Distance Vector Routing Protocol

The Ad-hoc On-demand Distance Vector (AODV) routing protocol employs an on-demand mechanism for route discovery and maintenance using a hop-count routing metric coupled with sequence numbers and periodic beacons [2]. The process occurs in two steps; Route Discovery and Route Maintenance.

Route Discovery involves request and reply packets. When a source node intends communicating with a destination node whose route is unknown, it broadcasts a Route Request (RREQ) packet. Each RREQ contains a unique ID, source and destination node IP addresses, as well as sequence numbers, hop-count and control flags. When the RREQ reaches the destination node a Route Reply (RREP) packet is generated and unicast back to the originator of the RREQ. Similar to the RREQ, the RREP contains the source and destination IP addresses, destination sequence number, hop-count, route lifetime and control flags. Each intermediate node that receives the RREP increments the hop-count and establishes a forward route to the source of the packet, and transmits the packet via the reverse route.

Route maintenance is relatively simple. Nodes can use either link layer feedback or periodic Hello messages. Failure to receive the link layer feedback or three consecutive Hello messages from a neighbour is taken as an indication that the link to the neighbour in question is down. In case a link break is detected for the next hop of an active route, a Route Error (RERR) packet is sent to its active neighbours that were using the particular route. This informs the neighbour nodes to re-acquire a new route to the destination using the route discovery process.

When using AODV in a network with multi-radio nodes, each RREQ is broadcast on all interfaces. 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.

Both the single and multi-radio variants of AODV utilise the hop-count routing metric which, although simple to implement, portrays a a number of shortcomings when applied directly to hybrid WMNs.

Firstly, being based on query and reply cycles and having route information being stored in all intermediate nodes on the route in the form of route table entries, the protocol does not have access to a great amount of routing information. Due to an absence of source routing and promiscuous mode learning [7], the perspective of each node is generally limited to its immediate nodes. This usually causes AODV to rely on frequent route discovery floods, which has a significant overhead, thus defeating the purpose of an on-demand routing protocol to reduce overhead.

Secondly, AODV does not make use of route caching intensely. The destination replies only once to the RREQ arriving first as duplicate RREQs are dropped and ignored. In this case, the routing table maintains at most, one entry per destination. This method not only means that AODV induces more route discovery floods, but it also implies that the source node does not have hands-on information for alternate routes, causing the route discovery process to trigger every time a link fails. Communicating in a relatively mobile part of a WMN, the route discovery latency would then be of significance, as route discovery may be induced often due to nodes coming in and out of range.

Thirdly, even though AODV accounts for use of multiple radios, the protocol disregards the heterogeneous mix of Mesh Routers and Mesh Clients. The significant difference in the performance levels of the two types of nodes may cause degraded execution for a protocol that does not regard them as distinct.

Fourthly, the AODV protocol causes nodes to reply to the first arriving RREQ. This ultimately favours the least congested route instead of the shortest route. This assumption is founded purely on the basis that the first packet to reach the node over the least number of hops must have traversed through the least congested path. What this does not take into account is that the RREQ packet being sent is often in the size of a few bytes. This does not accurately represent the medium to be subsequently used for sustained traffic flows sent over the same path, and hence affects performance.

Thorough analysis of the AODV protocol through simulations has pointed out many deficiencies in its implementation. Use of the protocol in WMNs has also displayed its lack of adaptation to their differing and unique nature, for optimum performance. Solutions to some of these problems have however been attempted by integrating different methods of route discovery in the network layer by modifying the standard AODV protocol discussed above.

3. Variants of the AODV Protocol

Modifications to the AODV protocol have been made in order to tackle some of the shortcomings outlined above. Adaptation for the WMN structure and its particular characteristics are made in some of these modifications. Each respective author of the modified AODV has employed a different Routing Metric and conducted simulations of their implementation. The AODV variants that will be discussed in this paper are;

- Link Quality Aware AODV (LQ-AODV)
- AODV-Path Accumulation (AODV-PA)
- AODV-Spanning Tree (AODV-ST)
- AODV-Hybrid Mesh (AODV-HM)

3.1. LQ-AODV

The LQ-AODV [11] utilises a link quality metric alongside the hop-count metric of the standard AODV protocol. Both the route discovery process as well as the Route Maintenance process is modified in order to avoid links with possibly bad signal quality. For route discovery, Signal-to-Noise Ratio (SNR) feedback from the physical layer provides link quality between two nodes. Monitoring the SNR, each node maintains link quality statistics of all the control and data packets received from its immediate neighbours. Wireless links with a SNR below a predetermined level are considered bad quality links, and disregarded from the route discovery process. However, if no link is found that passes the predetermined threshold, then weak links are re-included and only hop count is employed in order to preserve network connectivity. A new “hand-off” Route Maintenance notion is proposed which eliminates the use of Hello packet probing, as in the standard AODV protocol, and employs an early link failure notification by using feedback from the physical layer of the OSI model.

The route discovery process makes use of the SNR. However, SNR is a relatively unstable representation of the link quality as it is subject to interference and varies greatly over short periods of time. The authors of the LQ-AODV routing protocol adaptively calculate a Smoothed-SNR (SSNR) metric. Denoting the SNR value of the n^{th} packet sent by any node A as $S_{n,A}$, the SSNR value to node A can be formulated as follows:

$$SSNR_{n,A} = \sum_{i=0}^{n} \alpha(1-\alpha)^{n-i} S_{i,A}$$

Where α is a tunable parameter between 0 and 1. This formula smoothes out the SNR graph, as each illustrative SNR value gradually loses its influence for a bigger α value, eliminating affects of fading and fluctuations [4]. To implement this, the authors propose a Route Selection Mechanism. This involves adding a 32-bit Route Quality (RTQ) field into the packet header of the RREQ sent out by the standard AODV. Each node updates the RTQ field of the RREQ with its current SSNR only if it is the first node to receive the RREQ or if the RTQ value in the packet header is larger than the current SSNR value of the node. This ensures that the signal quality of the weakest link is always retained by the RTQ in the packet header.

The use of signal quality information in the RTQ headers allows the protocol to make an informed decision regarding selection of a communication path between nodes. If this information does not satisfy the requirements then the protocol falls back to the standard AODV mode of route discovery. For route maintenance, the authors propose using the same link information to detect connectivity between nodes. Instead of using Hello packet probing, LQ-AODV sends out a RERR packet when it detects that a link has a signal quality lower than the specified threshold. As the connectivity is measured at the link layer it permits early notification of a poor quality link, which in turn allows the source to begin the route discovery process before the connection is actually lost. Hence, the disruption is brief with minimal loss of packets.

3.2. AODV-PA

Design of the AODV-PA [5] involves the amalgamation of the standard AODV protocol along with the source route accumulation technique of the Dynamic Source Routing (DSR) protocol. DSR essentially uses a similar process for route discovery and maintenance as AODV [6]. However, instead of using routing tables, DSR accumulates intermediate node addresses on its RREQ and RREP packets. Nodes learn routes from the information in the RREQ and RREP packets and store them in a routing cache. Upon receiving a RREP, the source node knows the entire route to the destination. If a link break is detected, the node simply tries a different path if it has an alternative route cached. The scheme makes extensive use of the routing cache, which helps in lowering the routing overhead by reducing the frequency of route discoveries.

Incorporating the route caching procedure of DSR into the standard AODV protocol, the routing process achieves what the authors term 'Path Accumulation'. This involves intermediate nodes adding their own addresses during the route discovery process to the RREQ and RREP packets being generated or forwarded in the network. However unlike DSR, routing tables are utilised to maintain fresh routing entries by invalidating old ones, which in turn improves the routing accuracy of the protocol.

As a node receives a RREQ packet, it updates the route to the source node. In addition, checks are made for intermediate nodes accumulated in the path. If an entry for an intermediate node does not exist, the routing table is updated. If a route entry for a node does exist, then the hop count to that node is checked. If this happens to be less than the previous entry, a fresher entry is made with the same sequence number.

The prime advantage of the AODV-PA protocol is that a single route discovery process populates the routing tables with routes to all nodes comprising a path. This route discovery also updates the routing tables of nodes that had prior routes to other nodes in the network. This essentially decreases the number of route discovery processes as compared to the standard AODV protocol, thereby, improving the packet delivery and reducing the routing overhead.

3.3. AODV-ST

AODV-ST [9] is a hybrid routing protocol developed specifically for infrastructure mesh networks. The protocol has been designed with the aim of providing Internet access to Mesh Clients with the help of one or more gateways. AODV-ST uses a proactive strategy to discover routes between the Mesh Routers and the gateways, and a reactive strategy to find routes between Mesh Routers. In the proactive case, the gateways periodically broadcast special RREQ packets to initiate the creation of spanning trees. All nodes receiving these RREQ packets create a reverse route to the gateway. These nodes also send a gratuitous RREP packet to the gateway in order to enable the formation of forward routes. All subsequent RREQ packets with a better routing metric are used to update the existing reverse route to the gateway before being re-broadcasted in the network.

For inter Mesh Router communications, a RREQ is sent with a set 'destination only' flag. A RREQ with a set 'destination only' flag can only be responded to by the destination and prohibits other intermediary nodes from responding. The flag ensures that most up-to-date path information is received by the source of the route query.

AODV-ST uses the Expected Transmission Time (ETT) [3] routing metric, which measures the expected time needed to successfully transmit a fixed-size packet on a link.

$$ETT = ETX \times \frac{SZ}{BW}$$

Where ETX is the expected transmission count required to send a single packet on a link. SZ is the packet size and BW represents the bandwidth of the link.

AODV-ST has primarily been designed for single-radio wireless nodes and, hence, cannot exploit the full potential of multi-radio nodes in the network. Neither does it differentiate between different types of nodes in hybrid WMNs.

3.4. AODV-HM

AODV-HM [8] can effectively perform mesh-aware routing in a hybrid WMN. The protocol endeavours to involve Mesh Routers into the routing process such as to make maximum use of their in built capabilities. The protocol makes use of a dynamic channel assignment technique, which is integrated with the AODV routing process. The channel assignment technique, which operates in a distributed manner, helps in achieving channel diversity over established routes.

The AODV-HM route discovery mechanism permits development of routes traversing Mesh Routers with minimal number of Mesh Clients. The routes developed in this manner thus comprise mostly of static nodes. These routes are, hence, more stable and offer improved delivery rates with a lower control packet overhead. To do so AODV-HM replaces the default hop-count routing metric with Min (Hop-Count − Mesh-Router-Count). By selecting routes which minimise this metric, AODV-HM can guarantee that the established routes primarily consist of Mesh Routers.

AODV-HM also integrates a channel assignment mechanism with the AODV route discovery process, which diversifies channel usage between multi-radio nodes during the formation of routes. In this case, multiple links can exist between neighbouring multi-radio nodes. However, the precise link (interface) to be used between such nodes is independent of the routing metric.

In AODV-HM, nodes forwarding a RREQ packet also recommend a channel, which is subsequently used to communicate with the next hop. In order to minimise co-channel interference, nodes recommend least loaded channels for next hop communication. All interfaces, which have a Transmit Interface Queue (IFQ) length below a certain threshold, are selected as possible candidates for the optimal channel selection. The channel information of these free or least loaded interfaces is then retrieved through a physical layer hook. The IFQ lengths are then normalised using the contemporary raw date rate of the interface.

Table 1. Comparison of AODV Variants

Protocol	Metric	Implementation	Advantages	Disadvantages
AODV	Hop Count	8-bit field added to the RREQ header that is incremented at each intermediary node.	– Simple to implement – Shortest path routing – Loop freedom – Support for multi-radio nodes	– Not interference aware – Shortest path is not always the best path – Poor support for multi-radio nodes – Poor channel diversity
LQ-AODV	SSNR	32-bit field added to the RREQ header that represents the least smoothed SNR of a link on the path.	– Eliminates use of links with poor SNR – Seamless fallback to default AODV – Interference aware using local SNR	– Non-optimal path creation due to intermediary RREQ filtering – Does not take into account the link rates – Accurate computation of SNR is non-trivial. – Lacks support for multi-radio nodes
AODV-PA	Hop Count	n * 32-bit fields added to the RREQ header that represent the IP addresses of the 'n' nodes in the source route	– Capability for extensive local route repairing – Single route discovery disseminates more routing information – Global knowledge available at destination	– Non-optimal path creation due to intermediary RREQ filtering – Not interference aware – Lacks support for multi-radio nodes – Increased byte overhead due to source routing
AODV-ST	ETT	8 or more bit field added to the RREQ header that provides the accumulative sum of the ETT on all links comprising a path.	– Caters for both intra and inter-flow interference – Support for multi-radio nodes	– Non-optimal path creation due to intermediary RREQ filtering – No channel diversity – Packet overhead due to periodic probe packets and packet pairs
AODV-HM	Mesh Router Count and Recommended Channels	4-bit counter indicating the number of Mesh Routers and a 7-bit field, which advertises the optimal channel to be used for the Reverse Route.	– Node aware routing – Channel diverse routing – No requirement for extraneous probe packets – Support for multi-radio nodes	– IFQ lengths are not applicable when there is no ongoing traffic. – Measuring the precise IFQ lengths in real-time is non-trivial. – IFQ based channel selection requires access to the current raw channel rate

If a hop shares multiple channels with the sender of the RREQ packet, it will receive multiple copies of it. If possible, the node will create a reverse route via the recommended channel (interface). These routes, which are established using channel diverse hops, help in minimising the contention for the medium and thus lower the latency of the network.

4. Comparison

Table 1 provides a comparison between the different variants of the AODV routing protocols. All protocols use different routing metrics to optimise the routes. The four main characteristics of any good routing metric are path length, link capacity, packet loss ratios and interference [12]. All four characteristics have direct impact on the latency and packet delivery ratio of the network.

The standard AODV endeavours to minimise the path lengths but does not take into consideration the other three characteristics. As AODV processes RREQ packets on a 'first come first serve basis' the hop-count metric is often ignored in congestion scenarios. Similarly path length, without taking into account the other routing metric characteristics, is not a good path representative. In addition, AODV offers poor support for multi-radio nodes and achieves channel diversity on a purely random basis.

Although, LQ-AODV tries to assign maximum weight to poor performing links it is still unable to find optimal paths. This essentially occurs due to the filtering of any optimal RREQ packets arriving subsequent to the first received RREQ. In addition LQ-AODV does not take into account the link data rates for e.g. a link with a low SNR but higher rate may perform better than a slow link with a higher SNR. The protocol also offers no inherent support for multi-radio nodes and is, hence, not able to exploit the channel diversity offered by these nodes.

AODV-PA is able to improve the redundancy in the network by establishing multiple concurrent paths in a single instance of the route discovery process. AODV-PA also suffers from the problem of filtering optimal RREQ packets as observed in LQ-AODV. In addition, AODV-PA offers no remedy for both intra and inter flow interference. The routing metric is purely based on hop counts and fails to scale under multi-hop and high load conditions. AODV-PA has no optimisation for multi-radio nodes and cannot form channel diverse routes. The route discovery process of AODV-PA also incurs additional byte overhead due to the propagation of additional node information in the control packets.

AODV-ST makes use of the well know ETT routing metric, which takes into account the link capacity, packet losses and interference. Similar to LQ-AODV and AODV-PA, AODV-ST also suffers from the problem of filtering optimal RREQ packets and, hence, forms sub-optimal paths. AODV-ST offers no channel diversity features and thus cannot take advantage of the increased frequency spectrum offered by the multi-radio nodes. The computation of the ETT metric is generally carried out using periodic probe packets and packet pairs. The probe packets are generally broadcasted in the network and thus reduce the available bandwidth.

AODV-HM is a node-aware routing protocol that can successfully differentiate between the multi-radio Mesh Routers and single-radio Mesh Clients. AODV-HM endeavours to maximise routing via the Mesh Routers such as to minimise the load on the Mesh Clients. The interface selection on multi-radio nodes is carried out in such a way as to achieve maximum channel diversity. In cases, where channel diversity cannot be achieved, AODV-HM uses the IFQ lengths to select the correct interface on a multi-radio node. The IFQ length, when normalised by the link rate, gives an accurate representation of the link capacity and interference levels. Thus AODV-HM is able to exploit the potential of the Mesh Routers and achieves effective performance in a wireless mesh network.

All protocols endeavour to select optimal paths during the route discovery phase. However, no protocol makes an attempt to optimise paths in real time. As the nodes in a wireless mesh network are generally mobile, the network topology remains in a fluid state. Consequently, the optimal paths that are discovered during a route discovery do not remain effective due to the ever varying inter-flow interference. Thus a routing protocol that optimises route development both during discovery as well as during its subsequent use can significantly improve the performance of a wireless mesh network.

5. Conclusions

Wireless mesh networks are used to provide connectivity in a region, without necessitating a fixed infrastructure. The network is generally formed using an ad-hoc routing protocol, which enables communication in a dynamic topology. AODV is a well know routing protocol, which is currently being used in a number of mesh products. However, as AODV was actually developed for single-radio nodes, it shows degraded performance in densely populated mesh networks. In this paper, we have discussed and compared four variants of the AODV protocol, which can be used to establish a hybrid wireless mesh network. All four protocols have their peculiar advantages and disadvantages. However, a common problem in most of the protocols is their inability to exploit the wide frequency spectrum offered by the Mesh Routers. This generally results in uneven utilisation of the channels, which causes higher contention for the wireless medium, thereby, causing severe packet losses and increased latency. Similarly, in addition to effective channel diversity, improved routing metrics are also required that take into account the path lengths, link capacities, packet loss ratios and interference in the network.

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