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routing protocol leading to a new WMN routing protocol called AODV-mMHEB and evaluated in a multi-channel, multi-radio and multi-rate WMNs using simulation.

II. RELATED WORK

Designing routing metrics has a significant impact on performance in wireless mesh networks. This section presents some popular metrics proposed by the research community.

A. Expected Transmission Count (ETX)

De Couto et al. [8] proposed the ETX metric. The ETX metric finds paths with the fewest expected number of transmissions and re-transmissions needed to deliver a packet to its destination. The metric predicts the number of re-transmissions required using per-link measurements of packet loss ratios in both directions of each wireless link. The primary goal of the ETX design is to find paths with high throughput, in spite of losses. The measurements show that, ETX improves the throughput of multi-hop routes by up to a factor of two over a minimum hop-count metric. ETX metric captures the effects of both packet loss ratios and path length. ETX selects the path by using the following equation:

\[
ETX = \frac{1}{d_f \times d_r}
\]  

(1)

Where \(d_f\) is the forward delivery ratio, and \(d_r\) is the reverse delivery ratio.

In addition, ETX is an isotonic metric, which guarantees easy calculation of minimum weight paths and loop-free routing under all routing protocols. However, the major shortcomings of the ETX metric is that it does not consider interference or the fact that different links may have different transmission rates. Another limitation of ETX is that it does not take into consideration the asymmetry of traffic on the wireless link [10].

B. Expected Transmission Time (ETT)

The ETT metric was also proposed by Draves et al. [9] in an attempt to address some of the limitations of ETX. ETT captures the effect of heterogeneity on the performance of the chosen path. The ETT is defined as the following:

\[
ETT = ETX \times \frac{\text{PacketSize}}{\text{Bandwidth}}
\]  

(2)

This metric is also isotonic. However, the drawback of ETT is that it does not capture inter-flow and intra-flow interference in the networks.

C. Weighted Cumulative Expected Transmission Time (WCETT)

To minimize the intra-flow interference, the WCETT routing metric was proposed by Draves et al. [9]. This routing metric reduces the intra-flow interference by minimizing the number of nodes on the path of a flow that transmit on the same channel. The WCETT is the first routing metric that captures channel diversity [1]. The WCETT of the path \(p\) is defined as follows:

\[
WCETT_p = (1 - \beta) \sum ETX + \beta MAXX_j
\]  

(3)

Where \(\beta\) is a tunable parameter between \(0 \leq \beta \leq 1\) which controls the preferences over path length versus channel diversity, and \(X_j\) represents the number of times the channel \(j\) is used on links in the end-to-end path.

Some of the weaknesses experienced by WCETT is because it is not isotonic and it does not solve the problem of inter-flow interference.

D. Expected Link Performance

The EPL metric was proposed by Ashraf et al. [10]. EPL uses both link quality and cross-layering to gather wireless channel information in order to estimate link performance. EPL also take into account the asymmetry of traffic on the wireless link. The authors in [10] proposed to solve the problem of asymmetry by assigning a higher weight to the forward link in order to moderate the asymmetry of the packets. This is because the reverse link is meant for the ACK packets which are loss resistant and would probably be successfully received almost regardless of estimated reverse delivery ratio. The authors in also calculate the link delivery ratio \(P\) as follows:

\[
P = \alpha d_f + (1 - \alpha) d_r
\]  

(4)

Where \(\alpha\) is the weight assigned to the forward delivery ratio \(d_f\) and is subject to \(0.5 < \alpha < 1\).

EPL takes into consideration the inter-flow and intra-flow interferences as well as the asymmetry of the packets to estimate the link quality. However, EPL was only evaluated in a single-radio scenario. Another drawback of EPL is that, it uses cross layering which usually lead to loss of the protocol layer abstraction.

E. Multi-Hop Effective Bandwidth (MHEB)

The MHEB routing metric was proposed by Li et al. [11]. MHEB provides a generic approach to calculate the achievable bandwidth along a path, taking the impacts of inter-flow and intra-flow interference and channel diversity into account. Li et al. developed an approach to compute the achievable bandwidth under inter-flow interference (ABIF). In order to accurately capture the inter-flow interference, the authors in [11] combined the ETX metric with a newly proposed interference degree ratio to evaluate the achievable bandwidth under the inter-flow interference (ABITF). The routing metric MHEB is defined as the weighted average of ABIF and ABITF. The authors in [11] evaluated the ABITF at a link \(i\) as follows:

\[
ABITF_i = (1 - IDR_i) \times \frac{\text{Bandwidth}_i}{ETX_i}
\]  

(5)

Where IDR_i is the Interference Degree Ratio for a link \(i\), Bandwidth_i is the original bandwidth at a link \(i\), and ETX_i denotes the expected transmission attempts for a successful transmission over link \(i\).

Authors in [11] also computed the ABIF as follows:
\[ \text{ABIRF} = \frac{\text{Bandwidth}_x \times \text{Bandwidth}_y}{\text{Bandwidth}_x + \text{Bandwidth}_y} \] (6)

Where \( \text{Bandwidth}_x \) is the maximum bandwidth for a channel \( x \), and \( \text{Bandwidth}_y \) is the maximum channel for the channel \( y \). Using (5) and (6) the authors in [11] compute MHEB as follows:

\[ \text{MHEB} = \beta \times \min \text{ABITF}_i + (1 - \beta) \times \text{ABIRF} \] (7)

Where \( \beta \) is a tunable parameter and subject to \( 0 \leq \beta \leq 1 \).

The MHEB routing metric effectively captures the effects of inter-flow and intra-flow interference, and channel diversity along a path. However, it does not guarantee optimal path selection. Authors in [11] also evaluated the performance of MHEB using fixed mesh nodes. These could cause a bias in the results as mesh client nodes in WMNs are usually mobile.

III. PROPOSED ROUTING METRIC: IMPROVED MULTI-HOP EFFECTIVE BANDWIDTH (iMHEB)

Our new metric, namely iMHEB, is an enhancement of the MHEB routing metric. The iMHEB takes into consideration the asymmetry of traffic on the wireless links as proposed by authors in [10]. As proposed by authors in [11], ABITF at a link \( i \) is given by the equation (5). Our metric computes an improved Achievable Bandwidth under Inter-Flow Interference (iABITF) by biasing the weight towards the forward link; that is, assigning a greater weight to the forward link in order to reduce the asymmetry of packets. The equation to compute iABITF at a link \( i \) is given as follows:

\[ \text{iABITF}_i = (1 - \text{IDR}_i) \times \frac{\text{Bandwidth}_i}{\text{ad}_f(1-\alpha)dr} \] (8)

After rearranging (8), we have the following:

\[ \text{iABITF}_i = (1 - \text{IDR}_i) \times \text{Bandwidth}_i \times [\alpha d_f + (1 - \alpha) d_r] \] (9)

Where \( \text{IDR}_i \) is the Interference Degree Ratio for a link \( i \), \( \text{Bandwidth}_i \) is the original bandwidth at a link \( i \), \( \alpha \) is the weight assigned to the forward delivery ratio \( d_f \), and is subject to \( 0.5 < \alpha < 1 \) as proposed by the authors in [10]. \( d_r \) is the reverse delivery ratio.

The achievable bandwidth under intra-flow interference is the same as in (6). From (9) and (6), we can therefore define our proposed routing iMHEB as follows:

\[ \text{iMHEB} = \beta \times \min \text{iABITF}_i + (1 - \beta) \times \text{ABIRF} \] (10)

Where \( \text{iABITF}_i \) is as defined in (9) and \( \text{ABIRF} \) is as defined in (6); \( \beta \) is a tunable parameter and is subject to \( 0 \leq \beta \leq 1 \).

IV. ROUTING METRIC IMPLEMENTATION

In this section, we first briefly describe the AODV routing protocol. We then present the flow chart for the implementation of the iMHEB routing metric into the reactive routing protocol AODV.

A. Ad-Hoc On Demand Distance Vector

AODV routing protocol is a reactive routing protocol which was first proposed by an IETF Internet draft in 1997. According to Belding-Royer and Perkins [12], AODV was proposed to meet the following goals:

- Minimal control overhead.
- Minimal processing overhead.
- Multi-hop path routing capability.
- Dynamic topology maintenance.
- Loop prevention.

The operation of AODV is done using the following two mechanisms: route discovery and route maintenance [12].

Route discovery: This is a mechanism by which a source node wishing to send a packet to a destination node obtains dynamically a source route when it does not have a route in its routing table.

Route maintenance: Once a route has been established, the source node will maintain the route for as long as it needs it. The movement of nodes not lying along the active route does not affect the routing to that path’s destination.

B. Flow Chart of the Implementation

The step on how the iMHEB is implemented into the AODV routing mechanism is show in the Figure 1. An additional field was used on the Route Request (RREQ), Route Reply (RREP) and Route Error (RERR) messages format. The iMHEB routing metric was computed from Equation (9).

When a source node has data to transmit to an unknown destination node, it incorporates the iMHEB routing metric into the RREQ and then broadcasts a RREQ for that destination. At each intermediate node, when a RREQ is received, a route to the source is created. If the receiving node has not received this RREQ before, it is not the destination and if does not have an up to date route to the destination, it rebroadcasts the RREQ. If the receiving node is the destination or has an up-to-date route to the destination, it generates a RREP. The iMHEB is incorporated in the RREP; which is then unicast to the source node. As the RREP propagates, each intermediate node creates a route to the destination. When the source node receives the RREP, it keeps a record of the route to the destination in its routing table before it can begin to transmit. If the intermediate node is not ready to receive an RREP, it then generates an RRER. The iMHEB is then incorporated into the RERR before the local route repair mechanisms start.
V. SIMULATION SETUP

The WMN modeled consists of 20 mesh clients, a Wireless Local Area Network (WLAN) server and 4 mesh routers distributed in grid (5x5) 1000m x 1000m square area. Each mesh router had more than one interface and used more than one channel. The mesh nodes had applications running over TCP/IP and UDP/IP. They supported wireless multi-rate communication with rates of up to 11Mbps. The mesh nodes implemented moved using the Random Waypoint mobility model with a speed of 2 meters per second and a pause time of 100 seconds. The WLAN server had applications running over TCP. The interference range was set to 200 meters. The MAC protocol used was the IEEE 802.11b. The traffic sources followed the FTP traffic with packet sizes of 512 bytes. Our simulation was done using the discrete event simulator OPNET modeler 14 [13] and each scenario was run for 3600 seconds.

The performance metrics used for this paper are the throughput, delay, and routing overhead as a function of the load; that is under light and heavy FTP traffic loads.

The throughput is the sum of data packets generated by every source in the network. It is expressed in bits per second. So high throughput is desirable in wireless networks. The delay is the time it takes for a packet to be transmitted from the source node to the destination nodes. It is expressed in seconds. Short delay is desirable. The routing overhead is the total number of control packets generated by a routing protocol. Low routing overhead is desirable.

In this paper, two profiles were modeled:

- **FTP light**: that is, under light load conditions. Under light load, the download and upload is done at a rate of one file per hour (1file/hour) with a file size of 10 000 bytes [14].
- **FTP heavy**: that is, under heavy load conditions. Under heavy load, the download and upload is done at a rate of 10 files per hour (10files/hr) with a file size of 100,000 bytes [14].

![Figure 1: Flow chart of the AODV-iMHEB](image-url)
The routing metrics WCETT [9] and MHEB [11] were also incorporated in AODV for performance comparison resulting respectively to the routing protocols AODV-MHEB and AODV-WCETT. An additional field was added to the AODV protocol to calculate ABIRF, ABITF and ABTF, hence to update the routing metrics MHEB and iMHEB when a route request or a route reply is received by a node. The calculation is based on the number of packets received in 10 seconds. The value of $\alpha$ was set to 0.75 as in [10] and the value of $\beta$ was set to 0.5 as in [11].

VI. RESULTS AND DISCUSSION

A. Throughput Comparisons

Figure 2 and Figure 4 represent the throughput of AODV-iMHEB, AODV-MHEB, and AODV-WCETT under light and heavy FTP load respectively. Under light and heavy FTP traffic load, Figure 3 and 4 respectively show that the routing protocol AODV-iMHEB outperforms AODV-MHEB and AODV-WCETT routing protocols.

This great discrepancy is firstly due to the fact that AODV-iMHEB routing protocol chooses the path with the least interference and the least latency from the source node to the destination node, resulting in a higher throughput. Secondly, it is also due to the fact that AODV-iMHEB takes into account the asymmetry to improve the link quality estimation by assigning a higher weight to the forward delivery ratio. Hence, the optimal path selection used by the protocol AODV-iMHEB is improved.
Under light load, Figure 3 shows that AODV-MHEB performs better than AODV-WCETT since the AODV-MHEB considers both inter-flow and intra-flow interference while AODV-WCETT only takes into account intra-interference; that is, AODV-WCETT routing protocol always considers all links in the computation of intra-flow interference even if they are not within the other nodes interference ranges. Consequently, the routes created sometimes suffer from high levels of interferences; resulting in a low throughput.

B. Delay Comparisons

In terms of delay, Figures 4 and 5 respectively show the delay comparison under light and heavy load of the routing protocols AODV-WCETT, AODV-MHEB and AODV-iMHEB. Under light load, Figure 4 shows AODV-MHEB and AODV-iMHEB routing protocols are competing for the shortest delay. But under heavy load, Figure 5 shows that AODV-iMHEB has a better delay than AODV-MHEB. That is due to the fact that the AODV-MHEB routing protocol under light load attempt to accurately estimate the link quality and interference of the path but under heavy load, the AODV-MHEB suffers from approximate estimations leading the protocol not to optimally reduce its delay under heavy load. Figures 4 and 5 respectively illustrate that the routing protocol experiences the longest delay under light and heavy load. This is due to the fact that the AODV-WCETT routing protocol does not choose the best route because it does not explicitly capture the effect of inter-flow interference amongst the links leading to its poor delay.

C. Routing Overhead Comparisons

In terms of routing overhead, the performance of the AODV-iMHEB, AODV-MHEB and AODV-WCETT routing protocols for light and heavy load is respectively illustrated in Figures 6 and 7. The results showed that under light and heavy HTTP loads, the AODV-iMHEB routing protocol experiences the highest routing overhead. This is firstly due to the fact that AODV-iMHEB constantly sends control packets to update its routes for optimal path selection; this creates more traffic in the network resulting in high overhead. Secondly, the constant transmission of control packets done by the iMHEB routing metrics results in a longer computational time for the route selection calculation. This leads to a high routing overhead. Thirdly, the complexity of the routing metric as shown in Equation (10), causes the nodes to take longer to compute the AODV-iMHEB routing metric. This could also result in a high overhead.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we developed a novel On Demand routing protocol for multi-radios multi-channels WMNs. The proposed routing protocol based on the iMHEB metric improves the commonly used link-quality estimation technique by taking into account the asymmetry of data on the wireless link. Our new routing protocol efficiently chooses the route with the least inter-flow and intra-flow interference. As a result, our routing protocol simultaneously achieves link quality awareness, load balancing, inter-flow and intra-flow interference awareness. In future, an attempt would be made to minimize the complexity of the routing metric to reduce the high routing overhead experience by the AODV-iMHEB routing metric. Attempt would also be made to implement iMHEB into another reactive routing protocol such as DSR. Future work can further implement the iMHEB routing metric in a random topology and then compare the results obtained with the results from the grid topology as used in this paper.

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