Routing Metric of Expected Delay in Multi-Radio Multi-Channel Wireless Mesh Networks

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Abstract —Many routing metrics have been proposed to improve the performance of wireless mesh networks (WMNs). Most of these routing metrics describe intra-flow and inter-flow interference respectively, which brings in adjustable parameters or results in non-isotonicity. However, the adjustable parameters, used to balance the intra-flow and inter-flow interference, are difficult to adapt to the network status, and non-isotonicity makes the design of routing metric complicated. In this paper, we propose an isotonic metric of expected delay (MED) in multi-radio multi-channel (MRMC) WMNs. In particular, MED uses the expected available bandwidth (EAB), which can capture the logical intra-flow and inter-flow interference uniformly, to estimate the delay of the path. In MED, both expected packet transmission delay and expected queuing delay are estimated to capture physical interference, logical interference, load and noise comprehensively. Simulation results show that the proposed metric can improve overall network performance effectively.

Index Terms—Wireless mesh networks, routing metric, load, interference, delay

I. INTRODUCTION

Wireless mesh networks (WMNs) are self-organizing, self-configuring, low-cost networks. WMNs are widely used in different scenarios, such as urban area networks, emergency communication networks, security networks and so on [1].

Since single-radio single-channel WMNs cannot satisfy the increasing demands for the traffic that is growing every day, multi-radio multi-channel (MRMC) WMNs are developed [2]. MRMC WMNs provide each node with multi-radio interfaces, which can improve the capacity of the networks and enhance overall network performance. Due to the limited spectrum resources, interference and congestion have great impact on network performance, so it is important to select a proper path according to the network status.

Routing metric is the core of routing protocols, which provides quantifiable values to judge the efficiency of the route [3]. Thus design of routing metrics plays a crucial role for finding efficient routes in the network. In recent years, many researchers focus on studying routing metrics to improve overall network performance of WMNs [4]-[12]. Existing routing metrics, which describe intra-flow and inter-flow interference respectively, may bring in adjustable parameters or result in non-isotonicity. Adjustable parameters, which are used to balance the intra-flow and inter-flow interference, are difficult to adapt to the change of network status. Non-isotonic routing metric does not support loop free routing as it cannot use Dijkstra’s or Bellman-Ford’s algorithm to calculate optimal paths, thus it makes the design of routing metric complicated. As a result, it is important to propose a routing metric, which can measure intra-flow and inter-flow interference uniformly.

In this paper, we propose an isotonic metric of expected delay (MED) in MRMC WMNs. MED uses expected available bandwidth (EAB) to measure logical intra-flow and inter-flow interference uniformly, which can avoid bringing in adjustable parameters or resulting in non-isotonicity. Both expected packet transmission delay and expected queuing delay are estimated in MED, which can describe physical interference, logical interference, load and noise comprehensively. MED can bypass congested areas and high-interference region, which can find efficient routes to transmit packets.

The rest of this paper is organized as follows: Section II reviews the previous work. In section III, we give the definition of EAB and propose MED routing metric. Section IV details the implementation of MED routing metric. Section V presents evaluation of our proposed MED routing metric using network simulator version 2 (NS-2) [13]. The conclusions and our future work are presented in Section VI.

II. RELATED WORK

Hop count [4] metric is the most commonly used routing metric in multi-hop wireless networks, which selects the path with the minimum hops. Hop count metric may not be a good approach as it does not consider about the characteristics of links.

One of the pioneering routing metrics is the expected transmission count (ETX) [5] metric. ETX periodically broadcasts probe packets to get delivery ratio and uses the number of transmissions (including retransmissions) to measure the link quality. ETX is defined as

$$ETX = \frac{1}{d_f \times d_r} \tag{1}$$

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where d_f is forward packet delivery ratio, d_r is backward packet delivery ratio.

Expected transmission time (ETT) [6] metric improves ETX by considering the difference of link transmission rates. ETT is defined as

$$ETT = ETX \times \frac{S}{B} \quad (2)$$

where S is the size of packet; B is the bandwidth (raw data rate) of the link, which is measured by sending probe packet pairs.

ETX and ETT can capture the physical interference and noise of the link, but logical interference and load are not considered [7].

Weighted cumulative expected transmission time (WCETT) [6] metric extends ETT into MRMC WMNS and further considers the intra-flow interference, which is defined as

$$WCETT = (1-\beta) \times \sum_{i=1}^{n} ETT(i) + \beta \times \max_{1 \le j \le k} X_j \quad (3)$$

$$X_j = \sum\nolimits_{hop\ i\ is\ on\ channle\ j} ETT(i) \quad (4)$$

where n indicates the total number of links on the path, k is the total number of available channels for multi-radio interfaces, β is an adjustable parameter, $ETT(i)$ is the expected transmission time of hop i, X_j reflects the intra-flow interference by calculating the sum of transmission times of hops on channel j.

WCETT is a non-isotonic metric. The component that WCETT uses to capture intra-flow interference may amplify interference, as it only counts the number of channels but not their relative positions. The adjustable parameter β is difficult to choose when network status changes. Moreover, WCETT may lead packets towards congested route as it fails to capture the load.

Interference aware routing metric (iAWARE) [8] uses the physical interference model to calculate interference ratio (IR) at each node. It combines IR with ETT to predict the inter-flow interference. iAWARE is non-isotonic like WCETT because of the component that is used to describe intra-flow interference. Lacking of load balancing parameters may lead packet towards congested area.

Metric of interference and channel-switching (MIC) [9] deals with inter-flow and intra-flow interference through interference-aware resource usage (IRU) and channel switching cost (CSC) respectively. MIC of path p is defined as

$$MIC(p) = \alpha \sum_{link\ l \in p} IRU(l) + \sum_{node\ i \in p} CSC(i) \quad (5)$$

$$\alpha = \frac{1}{N \times \min(ETT)} \quad (6)$$

where N is the number of network nodes, min(ETT) is the smallest ETT in the network.

IRU is defined as

$$IRU(l) = ETT_{ij}(c) \times \left| N_i(c) \cup N_j(c) \right| \quad (7)$$

where $ETT_{ij}(c)$ is the expected transmission time of link $l(i,j)$ over channel c, $|N_i(c) \cup N_j(c)|$ represents neighbors which interfere with the communication between node i and node j over channel c. $|N_i(c) \cup N_j(c)|$ is introduced to capture inter-flow interference in a static way, as it only considers the number of neighbors instead of the load.

CSC can capture the intra-flow interference between two successive links, which is defined as

$$CSC(i) = \begin{cases} w_1 & if\ CH(prev(i)) \ne CH(i) \\ w_2 & if\ CH(prev(i)) = CH(i) \end{cases}, \ 0 \le w_1 < w_2 \quad (8)$$

where the value of w_2 is from 0.3 to 5 [9]. If node i and its previous hop node, $prev(i)$, use the same channel, CSC will be set to a large value w_2, otherwise it will be set to a small value w_1.

As analysis above, MIC uses the adjustable parameters α, w_1 and w_2 to make IRU component around the same range as settings of CSC, but it is difficult to choose adjustable parameters to balance the intra-flow and inter-flow interference according to the dynamic network changes.

Contention aware transmission time (CATT) [10] and Interferer neighbors count (INX) [11] are based on protocol interference model which uses the concept of transmission range and interference range.

CATT of link l is defined as

$$CATT_l = \sum_{j \in N_l} \frac{L_j}{R_j} \quad (9)$$

where N_l is the total number of interfering links of link l, L_j is the packet length of link j, R_j is the data rate of link j.

INX of link (v,u) is defined as

$$INX(v,u) = ETT(v,u) \sum_{link\ (m,n) \in S(v,u)} r_{m,n} \quad (10)$$

where $ETT(v,u)$ is the expected transmission time of link (v,u), $S(v,u)$ indicates the number of interfering links of link (v,u), $r_{m,n}$ represents the available transmission rate of link (m,n).

CATT and INX are isotonic in nature, and they capture the intra-flow and inter-flow interference uniformly. However, CATT assumes that all the neighbors are interfering which may overestimate the interference; INX performs well only in low load scenarios, as it does not capture the load.

Metric of interference and channel diversity (MIND) [12] uses physical interference model and protocol interference model to capture the interference and load parameters.

$$MIND = \sum_{link\ i \in p}^{n} INTER\_LOAD_i + \sum_{node\ j \in p}^{m} CSC_j \quad (11)$$

where n is the number of links; m is the number of nodes of path p; $INTER\_LOAD_i$ is used to capture the physical interference, logical interference and load of node i; CSC_j is the same as (8).

MIND uses a passive monitoring technique and reduces the overhead caused by active probing mechanism. But MIND works locally at a node without judging the asymmetry of the links, which may introduce inaccuracies. Moreover, MIND uses CSC to capture the intra-flow interference independently like MIC, which also brings in the limitations of adjustable parameters.

Expected link performance (ELP) [7] metric takes into account the loss ratio, interference and capacity of the link. ELP of link $l(i,j)$ is defined as

$$ELP(l) = ELP_{Link\ Loss\ Ratio(l)} \times ELP_{Link\ Interference(l)} \times ELP_{Link\ Capacity\ Factor(l)} \quad (12)$$

$$ELP_{Link\ Loss\ Ratio(l)} = \alpha(1-d_f) + d_f[(1-\alpha)(1-d_r)] \quad (13)$$

$$ELP_{Link\ Interference(l)} = Max(AIR(i), AIR(j)] \quad (14)$$

$$ELP_{Link\ Capacity\ Factor(l)} = \frac{1}{Bandwidth(l)} \quad (15)$$

where α is a corrective term, d_f and d_r is the same as (1); $AIR(i)$ and $AIR(j)$ are the average interference ratio of node i and j respectively, which are used to capture the logical interference; $Bandwidth(l)$ is the ratio transmission rate of link l.

ELP captures the physical interference, logical interference, load and noise comprehensively, but it does not capture the intra-flow and inter-flow interference effectively.

As analysis above, existing routing metrics fail to capture the physical interference, logical interference, load and noise comprehensively while describing intra-flow and inter-flow interference effectively. Most of existing routing metrics describe intra-flow and inter-flow interference respectively, which brings in adjustable parameters or results in non-isotonicity. So it is important to propose an isotonic metric which can capture WMNs characteristics comprehensively and describe intra-flow and inter-flow interference uniformly.

III. Metric of Expected Delay

In this section, we propose an isotonic metric of expected delay, MED, in MRMC WMNs. In particular, EAB is proposed to calculate the MED for a path, which takes both logical intra-flow and inter-flow interference into account uniformly. By taking expected transmission delay and expected queuing delay into account, MED can estimate the physical interference, logical interference, load and noise comprehensively.

A. *Expected Available Bandwidth Model*

Carrier sense multiple access with collision avoidance (CSMA/CA) based media access control (MAC) protocol of IEEE 802.11 prevents the node from transmitting until the channel is idle. Logical interference is caused by the protocol (CSMA/CA) as the shared channel may be occupied by the nodes in interference range.

In this paper, both logical inter-flow interference (logical interference between nodes carrying different flows) and logical intra-flow interference (logical interference between nodes carrying the same flow) are taken into account. Fig. 1 shows the logical inter-flow and intra-flow interference of node u. Logical inter-flow interference is caused by nodes in interference range. If logical intra-flow interference exists between nodes that are two hops away, $prev(u)$ (node that is the previous hop of u in the path) and $prev^2(u)$ (node that is two hops precedent of node u in the path) may bring in intra-flow interference with u.

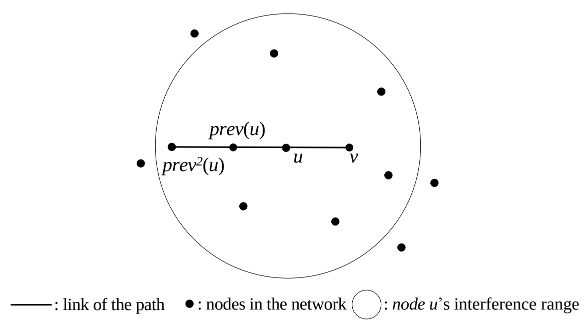

Fig. 1. Example of intra-flow and inter-flow interference

The channel idle time can capture the logical inter-flow interference and load in interference area, and it is an effective way to measure the channel utilization in wireless networks. The fraction of channel idle time during the past history can be a simple approximation of local available bandwidth under inter-flow interference [14], [15]. Since a node using IEEE 802.11 network interface card can observe the channel states, we use periodic monitoring technology to calculate the channel idle time, which has been widely used in simulations and testbeds [7], [14], [15]. By using the channel idle time of node u on channel i, $T_{idle,u}(i)$, during the period of time, T_{total}, we can estimate the available bandwidth of link $l(u,v)$ under logical inter-flow interference, $B_{Inter,l}(i)$, as

$$B_{Inter,l}(i) = B_{802.11} \times \frac{T_{idle,u}(i)}{T_{total}} \quad (16)$$

where i is the channel that link $l(u,v)$ uses, $B_{802.11}$ is the nominal bandwidth.

$B_{Inter,l}(i)$ can reflect logical inter-flow interference effectively, but it fails to weigh the logical intra-flow interference reasonably. The logical intra-flow interference will further influence the available bandwidth. For example, if $prev(u)$ in the path uses the same channel with node u, it competes for the channel with node u when node u wants to transmit packets. As $prev(u)$ and u compete for the channel fairly, the channel idle time that u can use is $T_{idle,u}(i)/2$, rather than $T_{idle,u}(i)$. So the available bandwidth of u under logical inter-flow and intra-flow interference is $B_{Inter,l}(i)/2$.

According to the analysis above, we prescribe the expected available bandwidth, EAB, under both logical intra-flow and inter-flow interference as

$$B_{avi,l}(i)=\begin{cases}B_{Inter,l}(i), CH(prev^2(u))\neq CH(prev(u))\neq CH(u)\\ B_{Inter,l}(i)/3, CH(prev^2(u))=CH(prev(u))=CH(u)\\ B_{Inter,l}(i)/2, else\end{cases} \quad (17)$$

where $B_{avi,l}(i)$ is the EAB of link l over channel i; $CH(u)$, $CH(prev(u))$, $CH(prev^2(u))$ are the channels that used by nodes u, $prev(u)$, $prev^2(u)$ to transmit respectively.

EAB captures both logical interference and load in the network. It uniformly measures the logical intra-flow and inter-flow interference in a simple way, which avoids bringing in the adjustable parameters or resulting in non-isotonicity.

B. *Metric of Expected Delay*

The expected delay of a link includes expected transmission delay and expected queuing delay. The expected transmission delay represents the predicted time required to send a packet over that link, including the time of retransmission. The expected queuing delay represents the predicted interval between the time a packet enters and the time it is served.

Unicasts along a link may not always be successful, so the expected transmission delay is determined by both the times of data transmissions required to send a packet successfully and the available bandwidth of the link. The expected transmission delay of link l over channel i, $T_{transmit,l}(i)$, is given by

$$T_{transmit,l}(i)=ETX_l(i)\times\frac{S}{B_{avi,l}(i)} \quad (18)$$

where $ETX_l(i)$ of link l over channel i is the expected times of packet transmissions required to send a packet over that link; S is the packet size; $B_{avi,l}(i)$ is the EAB that is estimated in Section III. A. In this paper, $ETX_l(i)$ is captured by periodically broadcasting probe packets per interface, which is similar to the method in [5].

The expected queuing delay is determined by the expected transmission delay and the load buffer of the link. As the instantaneous queue length changes rapidly, we use the weighted queue length $L_l(i)$ to represent the number of the packets in the buffer. A passive mechanism is used to get the queue length of a node. Node in the routing layer gets its own packets' number periodically by monitoring MAC layer buffer. In this paper, the period is 1s. Thus we use the current sample value $L_l^{now}(i)$ and previous value $L_l^{pre}(i)$ to weigh $L_l(i)$ as

$$L_l(i)=(1-\beta)L_l^{now}(i)+\beta L_l^{pre}(i) \quad (19)$$

where i is the channel that link l uses, β is the corrective parameter.

Thus the expected queuing delay of link l over channel i, $T_{wait,l}(i)$, can be expressed as

$$T_{wait,l}(i)=ETX_l(i)\times\frac{L_l(i)\times S}{B_{avi,l}(i)} \quad (20)$$

So the expected delay of link l over channel i, MED_l, is

$$\begin{aligned}MED_l&=T_{transmit,l}(i)+T_{wait,l}(i)\\&=ETX_l(i)\times\frac{(L_l(i)+1)\times S}{B_{avi,l}(i)}\end{aligned} \quad (21)$$

According to (21), the path metric $MED(p)$ of a given path p can be expressed as

$$MED(p)=\sum_{\text{link } l\in p} MED_l \quad (22)$$

As analysis above, the MED routing metric has following advantages:

1) MED considers the logical intra-flow and inter-flow interference uniformly, which avoids bringing in adjustable parameters or resulting in non-istonicity.

2) MED estimates both expected transmission delay and expected queuing delay to weigh the physical interference, logical interference, load and noise comprehensively.

3) MED uses cross-layer design, which is helpful in improving the overall network performance. In routing layer, it uses packet delivery ratio to capture the physical interference and noise of the link. In MAC layer, it monitors channel state to capture the logical interference and load.

4) Compared with the way that bandwidth is calculated by sending the packet pairs, MED estimates the available bandwidth by passive monitoring technique, which can reduce the overhead of the networks to a certain extent.

IV. Implementation Details

We extend the basic Ad hoc on-demand distance vector (AODV) [16] routing protocol to implement the MED routing metric in MRMC WMNs. Each interference acts as an independent entity and exchanges information with neighbors.

Since AODV is an on-demand routing protocol, it has no fixed routing update cycle. A node does not need to discover a route unless it needs to communicate with another node whose route is unknown. The source node initiates path discovery by generating route request (RREQ) packets per interface and transmitting RREQ packets to all neighbors. The RREQ contains the following fields: source IP address, destination IP address, source sequence number, MED value, $CH(prev(u))$, $CH(prev^2(u))$ and so on. As RREQ travels from source to destination, intermediate node automatically updates the value of MED and sets up reverse path to the source. When a node receives a RREQ packet which it has already forwarded, it forwards the RREQ packet again and updates the reverse path table if the accumulated value of MED metric is smaller than the best which it has already forwarded before. If a node is the destination or possesses a valid route to the destination, the node chooses a route with the smallest accumulated value of MED and generates a unicast route reply (RREP) packet. The RREP packet updates the value of MED and sets up forward path.

V. Performance Analysis

In this section, we evaluate the performance of MED on NS-2 in different scenes and compare MED with some common routing metrics, such as MIC, INX, CATT and ELP metrics. We expand NS-2 to support MRMC and modify AODV routing protocol to implement MIC, INX, CATT, ELP and MED routing metric.

A. Performance Evaluation Criteria

The performance evaluation criteria are described below.

Overall network throughput: it indicates the data bits successfully received by all destinations per unit time.

Average packet loss ratio: it indicates the ratio between number of packets received unsuccessfully by all destinations and total number of packets sent out by all sources.

Average end to end delay: it indicates the average amount of time that takes all packets from sources to the destinations.

Average route overhead: it indicates the ratio between the total number of routing control packets by all sources and the total number of successfully received data packets by the destinations [17], [18].

B. Simulation Results and Analysis on Grid Topology Networks

1) Performance comparison under different per flow rates

In this part, we simulate WMNs of 5×5 squared grids over 1000m×1000m. Other main simulation parameters are shown in Table I. We fix the number of flows as 5 and change the per flow rate to simulate different interference and load in the network. The obtained overall network throughput, average packet loss ratio, average end to end delay and average route overhead are shown in Fig. 2 to Fig. 5.

TABLE I: NS-2 SIMULATION PARAMETERS

Simulation Parameters	Values
Simulation Time	100 s
PHY/MAC Technology	802.11b/g
Data Rate	2 Mbps
Traffic Type	UDP
Packet Size	512 Bytes
Transmission Range	250 m
Interference Range	550 m
Propagation Model	Two Ray Ground
Antenna	Omnidirectional

Fig. 2 shows that MED's overall network throughput is always higher than MIC, CATT, INX and ELP. Most of the time, MIC performs worse than others, as it uses the adjustable parameters to balance the intra-flow and inter-flow interference, but it is difficult to adjust the parameters to the change of networks. Under low load condition, INX performs better than CATT, since INX captures the physical interference of network by calculating ETX. Under high load condition, CATT performs better than INX, as INX uses probe packets which may collide with data packets and result in packet loss. However, none of these metrics cater for the logical interference or load effectively. ELP and MED capture the logical interference, physical interference, load and noise comprehensively, so they perform better than MIC, CATT and INX. Moreover, MED performs better because it measures the logical intra-flow and inter-flow interference uniformly. The overall network throughput of MED improves 15.92%, 19.23%, 10.39% and 5.36% higher than INX, MIC, CATT and ELP respectively when per flow rate is 800 kbps. MED avoids the high-interference and congested routes in the network, so the overall network throughput is improved.

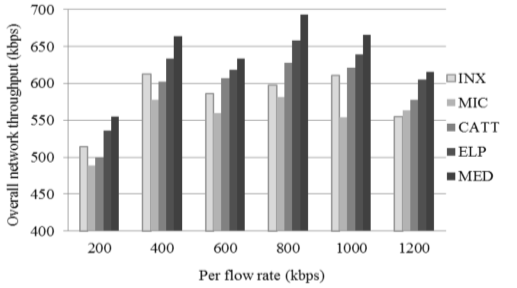

Fig. 2. Overall network throughput versus per flow rate on grid topology networks

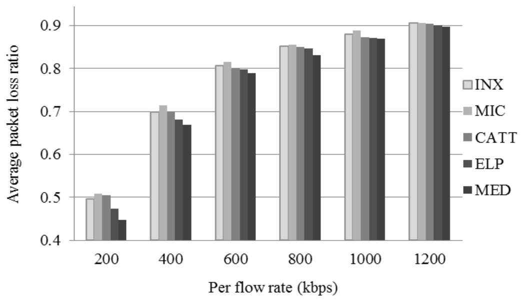

Fig. 3. Average packet loss ratio versus per flow rate on grid topology networks

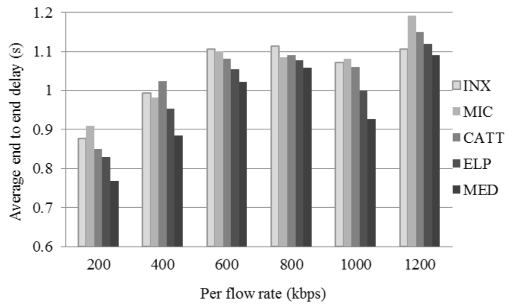

Fig. 4. Average end to end delay versus per flow rate on grid topology networks

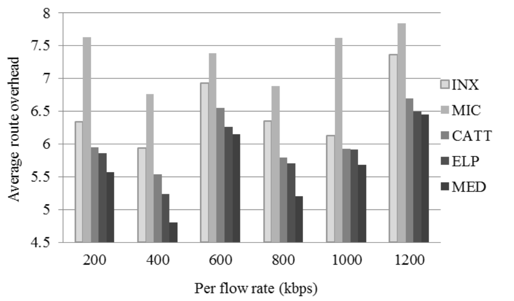

Fig. 5. Average route overhead versus per flow rate on grid topology networks

Fig. 3 shows that MED has lower average packet loss ratio than MIC, CATT, INX and ELP, which matches Fig. 2. As the per flow rate gets higher, the average packet loss ratio gets higher too. This is because of the growing interference and load level in the network.

Fig. 4 shows that MED's average end to end delay is always lower than MIC, CATT, INX and ELP. Delay caused by retransmission is not included in the end-to-end delay, because average end-to-end delay aims at packets that are received successfully. In this case, MED performs better than others since it takes queuing delay into account during the path selection phase. MED routes the packet to the low load and interference area, which avoids the delay due to congestion and high-interference.

Fig. 5 shows that MED is helpful to reduce the average route overhead compared with MIC, CATT, INX and ELP. Average route overhead relates not only to the total number of routing control packets generated by sources, but also to the number of packets received successfully. In MRMC WMNs, some control packets, such as RRER and RREQ, are sent through all interfaces, which increases the route overhead compared with single-radio single-channel WMNs. Probe packets, which are sent through all interfaces every second, increase the route overhead of network too. Furthermore, when the collision causes link breakage, the control packets, such as RREQ, RREP and RRER, will increase, thus the route overhead will increase accordingly. From Fig. 5, we can see that the average route overhead of MIC is higher than other metrics since MIC has much more packets cannot be received successfully. CATT avoids the overhead introduced by broadcasting probe packets, so it performs much better than MIC and INX. As MED has higher network throughput and less probe packets compared with INX and CATT, the average route overhead of MED is lower than other metrics.

Fig. 5 shows that the average route overhead may be greater than 1 [17], [18], since we care for the number of control and data packets rather than the size of control and data packets. Compared with data packets, the sizes of control packets are smaller. Such as, the probe packet is 137 Bytes. For example, when per flow rate is 400 kbps, the average route overhead of MED is 4.803527. However, the ratio between the total bits of routing control overhead generated by all sources and the total bits of successfully received data by the destinations is 0.497711, which is smaller than 1. Moreover, when the per flow rate changes, the ratio which cares for the different size of control packet and data packet is still smaller than 1.

2) Performance under different number of packet flows

To further prove that MED performs better than MIC, CATT, INX and ELP, we fix the per flow rate as 1000 kbps and change the number of flows to simulate different interference and load in the network. The obtained overall network throughput, average end to end delay, average packet loss ratio and average route overhead are shown in Fig. 6 to Fig. 9.

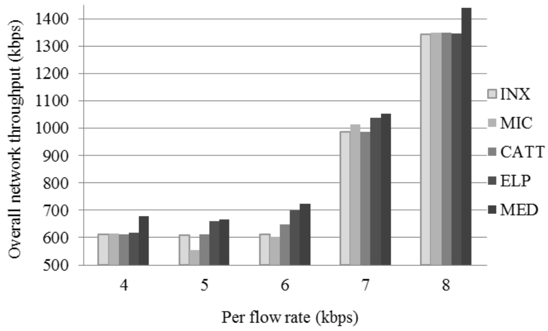

Fig. 6. Overall network throughput versus the number of flows on grid topology networks

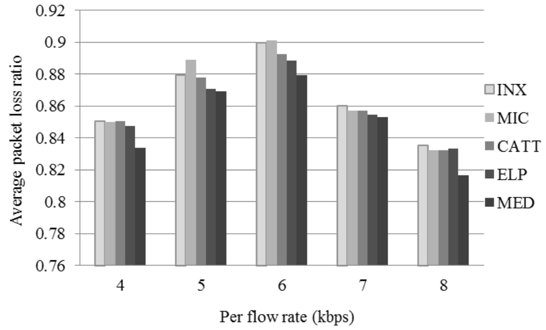

Fig. 7. Average packet loss ratio versus the number of flows on grid topology networks

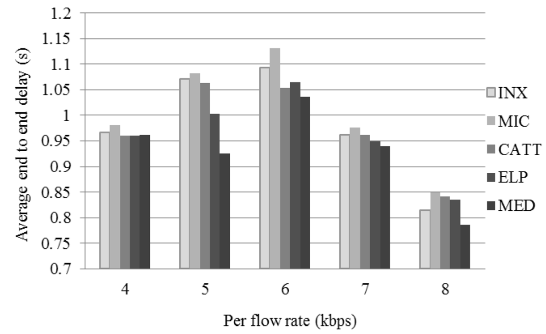

Fig. 8. Average end to end delay versus the number of flows on grid topology networks

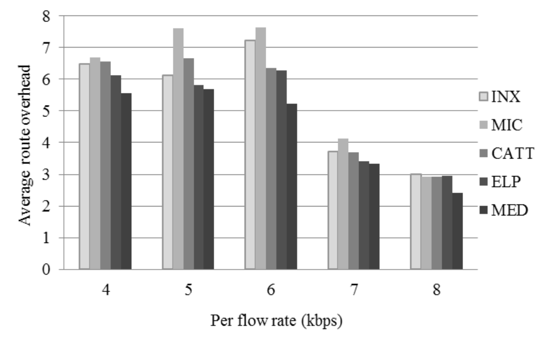

Fig. 9. Average route overhead versus the number of flows on grid topology networks

Fig. 6 to Fig. 9, we can see that MED improves the network performance effectively in different scenarios. MED outperforms INX, MIC, CATT and ELP in terms of overall network throughput, average end to end delay, average packet loss ratio and average route overhead. By taking expected transmission delay and expected queuing delay into account, MED can achieve interference awareness and load balance, which can bypass the congested areas and high-interference region.

C. Simulation Results and Analysis on General Topology Networks

In this part, we evaluate the performance in a random topology. 25 mesh routers are randomly placed in an area of 1000m by 1000m with necessary adjustment to maintain the connectivity. Other main simulation parameters are the same as Table I. We fix the number of flows as 5 and change the per flow rate to simulate different interference and load in the network. The obtained overall network throughput, average packet loss ratio, average end to end delay and average route overhead are shown in Fig. 10 to Fig. 13.

From Fig. 10 to Fig. 13, we can see that the overall network throughput, average packet loss ratio, average end to end delay and average route overhead of MED are better than INX, MIC, CATT and ELP, which is similar to the performance in grid topology. When per flow rate is 500 kbps, the overall network throughput of MED is 22.50%, 31.96%, 17.77% and 7.16% higher than that of INX, MIC, CATT and ELP respectively.

As analysis above, we can draw the conclusion that MED performs better than some common routing metrics. MED captures physical interference, logical interference, load, noise comprehensively and calculates intra-flow and inter-flow interference uniformly. MED can identify heavy load and heavy interference areas in the network, thus network performance is improved.

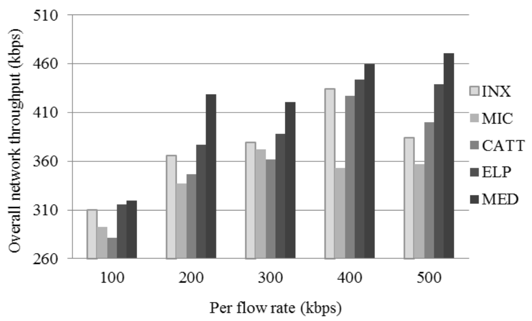

Fig. 10. Overall network throughput versus per flow rate on general topology networks

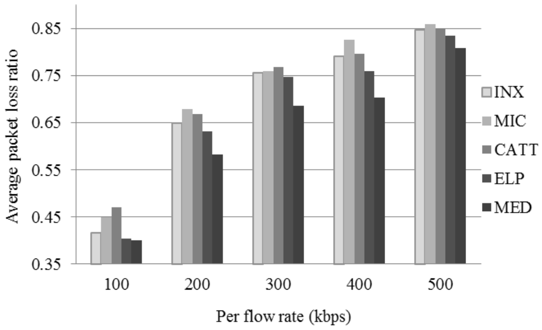

Fig. 11. Average packet loss ratio versus per flow rate on general topology networks

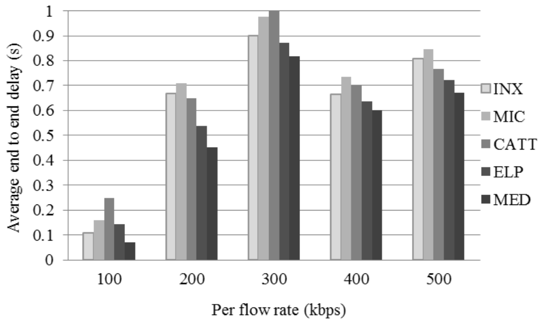

Fig. 12. Average end to end delay versus per flow rate on general topology networks

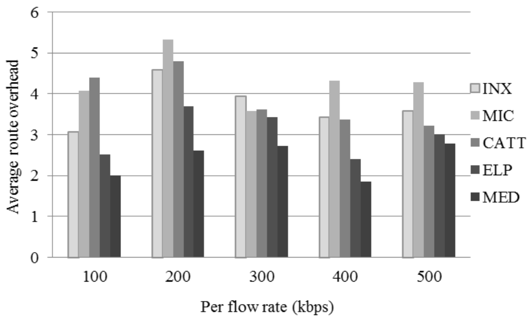

Fig. 13. Average route overhead versus per flow rate on general topology networks

VI. CONCLUSIONS

In this paper, we propose MED, an isotonic routing metric in MRMC WMNs. MED can capture WMNs characteristics comprehensively by calculating expected packet transmission delay and expected queuing delay. Particularly, MED uses EAB to capture the logical intra-flow and inter-flow interference uniformly, which avoids bringing in adjustable parameters or resulting in non-isotonicity. Furthermore, MED uses cross-layer design, which is helpful in improving the overall network performance. Simulation results show that MED performs better than some existing well-known metrics.

MED captures the expected times of packet transmissions by periodically broadcasting probe packets, which increases the route overhead of the network. Moreover, as the size of probe packet is different from the size of ACK packet and data packet, the delivery ratio calculated by probe packets may has a slight deviation. In the future, we will introduce passive monitoring techniques to get delivery ratio in order to reduce the overhead and capture the delivery ratio more accurately.

As wireless networks are greatly influenced by the environment, it is important to choose proper route according to the dynamic changes of the network. In the future, we will introduce the machine learning to choose the route adaptively and enhance the network overall performance.

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