Survey of Routing Metric in Wireless Mesh Networks

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Abstract. As an important technology in the construction of the next generation wireless communication system, Wireless Mesh Networks (WMNs) has the advantages of high bandwidth, flexible networking, wide coverage and low investment risk. Routing metrics have a great impact on network. Appropriate routing metrics can reduce intra-stream and inter-stream interference, improve throughput and reliability, achieve load balancing and eliminate network hot spots. At present, research on routing metrics for WMNs has made some progress. Relevant scholars have proposed various routing metrics, but no scholars have compared and classified these routing metrics. In this paper, the classical routing metrics in WMNs and the routing metrics proposed in the last ten years are studied. The following conclusions are drawn from these investigations. Firstly, delay, packet loss rate and bandwidth are the most commonly considered factors in routing metrics. Secondly, routing metrics separately describe the types of disturbances that lead to the introduction of variable constants. Thirdly, routing metrics often ignore the choice of gateway nodes. Finally, delay is the most important parameter of routing metrics. For example, the introduction of bandwidth and bottleneck channels is for more accurate calculation of delay. NS3 is used to simulate Hop Routing Metric (HOP) and Distance Routing Metric. The simulation results show that in a small network, Distance Routing Metric can effectively reduce the delay and increase the network throughput.

Keywords: Wireless Mesh Networks · Routing metric · NS3

1 Introduction

Since its birth in the 1960s, the development of network technology has been extremely rapid. Traditional Wireless Local Area Network (WLAN) provide stable network connections and large amounts of data traffic for billions of people around the world. With the rapid development of economy, users put forward higher requirements on the coverage, communication quality and carrying capacity of wireless network. However, in many cases, the existing wireless

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basic network can not be fully covered or the infrastructure construction is difficult. Therefore, Wireless Mesh Networks (WMNs) with advantages of flexible deployment, multi-hop transmission, wide coverage, low investment cost and low risk have been developed rapidly [1]. WMNs is a new network technology that separates from Ad Hoc Network and inherits part of WLAN [2].

Routing metrics have a great impact on network quality. WMNs have the characteristics of wide coverage, non-line-of-sight transmission and high bandwidth. Therefore, these characteristics of WMNs should be fully considered when select routing metrics [3]. Now, the routing metric used in WMNs is Air Time Link Metric (ALM). Although ALM considers protocol overhead, packet loss rate and transmission rate [4], ALM can not meet the requirements for large-scale WMNs. Although scholars have proposed various routing metrics, no scholars have sorted out these routing metrics or made comparative analysis.

Although the concept of WMNs has been proposed since the mid-1990s, WMNs did not attract widespread attention [5]. Until 2005, Nokia, Nortel, Tropos, SkyPilot and other companies launched wireless mesh products, and WMNs entered a period of rapid development [6]. Expected Transmission Count (ETX) as an earlier WMNs routing metric was proposed in 2003 by Couto of the Massachusetts Institute of Technology's Computer Science and Artificial Intelligence Laboratory. ETX is easy to implement and the link with low packet loss rate can be selected as the data transmission link. Then R. Raves et al. proposed Expected Transmission Time (ETT) on the basis of ETX [7]. ETT considers the impact of packet size and data transmission rate on network quality. ETT is widely used in WMN and lays a foundation for other routing metrics. Due to the advantages of WMNs, WMNs have developed rapidly in recent decades. Corresponding routing metrics for WMNs are developing rapidly. For example, the Enhanced Air Time Link Metric (E-ALM) was proposed in literature [12]. Multirate Routing Metric (MRM) was proposed in literature [16]. Gateway Selection Based Routing (GSBR) was proposed in literature [19].

However, although many researchers have proposed various routing metrics, but to the best knowledge of the authors, there are no open references compared and classified these routing metrics. And this motivates us to survey the routing metrics of the WMNs. The main contributions of this paper are as follows.

(1) The classic routing metrics in WMNs are surveyed, and the routing metrics proposed in the last decade are detailed and summarized.
(2) The advantages, disadvantages and applicable scenarios of the investigated routing metrics are analyzed. According to the characteristics of routing metrics, routing metrics are divided into three categories. (1) Single channel routing metrics. (2) Multi-channel routing metrics. (3) Routing metrics in multi-gateway WMNs.
(3) NS3 is used to simulate Hop Routing Metric (HOP) and Distance Routing Metric. The simulation results show that in a small network, Distance Routing Metric can effectively reduce the delay and increase the network throughput.

The rest of this paper is organized as follows. Section 2 briefly introduces the definition and network structure of WMNs, and the factors often considered in routing metrics are briefly introduced. Section 3 introduces some routing metrics suitable for single channel networks. Section 4 introduces some routing metrics suitable for multi-channel networks. Section 5 introduces some routing metrics suitable for multi-gateway networks. Section 6 uses NS3 to simulate the HOP and Distance Routing Metric and analyze the simulation results. Section 7 summarizes the entire article.

2 System Model and Link Metric Methods

WMNs contain three types of nodes. Mesh Point (MP), Mesh Access Point (MAP), Mesh Portal Point (MPP). All devices that support WMNs functionality can be called MP. You can view MAP as a special kind of MP but pure terminals (non-MP nodes, such as STA) must through MAP connect to WMNs [8]. WMNs accessing to the Internet or other networks needs to be achieved through MPP. MPP can be connected to the Internet through wired or wireless manner [2], and all data accessing the external network needs to be forwarded through MPP.

In WMNs, not all types of nodes can form links with each other. MP can be linked with MP, MAP and MPP. But MP can not be linked with STA. MAP can be linked with MP, MAP, MPP and STA. MPP can be connected with MP and MAP to form a link. But MPP can not be connected with STA to form a link. The WMNs structure is shown in Fig. 1.

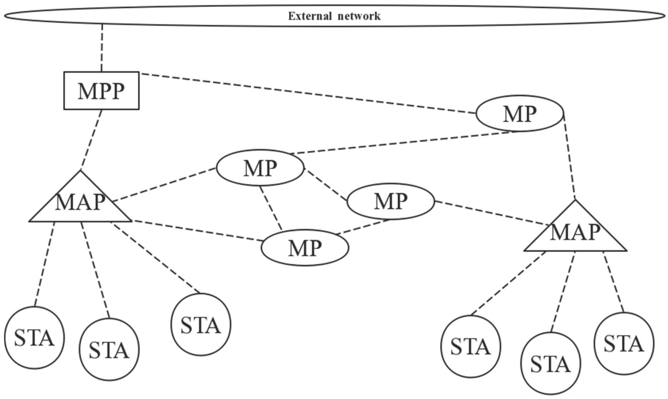

Fig. 1. WMNs architecture diagram

Link bandwidth, packet loss rate, packet length, transmission time, and queuing delay are all related to the link quality. Generally speaking, the wider the bandwidth, the higher the maximum transmission rate that the link can reach, and the better the quality of the corresponding link. Bandwidth is usually represented by the symbol B. The ratio of the number of packets lost to the total number of packets sent is the packet loss rate. The lower the packet loss rate, the better the quality of the link. The forward packet loss rate is often expressed by the symbol p_f and p_r represents the reverse packet loss rate. The data packet length is usually expressed by the symbol S. The time taken by the test packet from leaving one end of the link to being successfully received by the other end of the link is the transmission time. Queuing delay refers to the time from data enters the node packet queue to the data leaves the node.

Multi-channel network is more complex than single network channel. Intra-stream interference, inter-stream interference, physical interference and available bandwidth have to be considered in multi-channel network. The intra-stream interference is described as follows. When two links are very close (within the interference range) and use the same channel, the two links cannot work at the same time because of serious interference. Inter-stream interference is caused by the links in the selected path because the links outside the path use the same channel as the links of the path. Available bandwidth or weighted accumulated Expected Transmission Time (ETT) is usually used to represent intra-stream interference and inter - stream interference. For detailed description, refer to Unified Description of Interference and Load Routing Metrics (MIL) or Multi-rate Network Routing Metric (MRM). Due to various disturbances, the actual bandwidth of the link is not equal to the theoretical bandwidth of the link. Physical interference refers to interference caused by environmental noise and equipment noise. Physical interference is usually expressed by the interference ratio.

In multi-gateway networks, the gateway is usually selected based on the bandwidth and load of the gateway. The bandwidth of the gateway is the effective bandwidth that the gateway can use. The load of the gateway is usually expressed by the buffer queue length at the gateway interface. At present, there are few routing metrics consider of gateways.

3 Single Channel Routing Metrics

For WMNs, single channel network refers that all nodes in the wireless network use only one channel for communication. Single channel network is usually found in early wireless communication networks. Most of the current wireless networks use multi-channels for communication. However, the study of single channel routing metrics is the foundation of the study of multi-channels routing metrics, so the study of routing metrics in single channel network is meaningful.

3.1 One-Dimensional Routing Metric for Single Channel

Hop Metric. Hop count is the number of data forwarding from the source node to the destination node. The path with the fewest hops is the transmission path [8]. The metric has the advantages of simple implementation and low overhead. However, the shortcomings of Hop Metric (HOP) are prominent. HOP does not consider the link delay, interference, load, packet loss rate and other factors. So HOP is likely to lead to poor performance of the selected path.

Round Trip Time. Round Trip Time (RTT) link metric uses the average round trip time between the two ends of the link as a reference for routing selection [8]. The process of obtaining Round Trip Time is shown as follows. Each node broadcasts a probe packet at an interval of 500ms, and adjacent nodes receive the probe packet and respond to the probe packet in a non-preemptive manner. The response message contains a time flag to calculate RTT.

Packet Pair Delay. Packet Pair Delay is an improved version of the RTT. Packet Pair Delay mainly comes from the media competition between the sending node and other nodes and the packet retransmission caused by channel changing. Packet Pair Delay does not include queuing delay and processing delay [8]. The implementation process of Packet Pair Delay is as follows. Before a long data packet (length is 1000Bit), a short data packet (length of 137Bit) is sent (continuous transmission). Each adjacent node is responsible for calculating the receiving time difference between the two packets. The average value of this time difference is the link cost.

Link Priority. Link Priority Metric (LP) considers the business priority level. Link weights are determined according to the number and priority of data passing through the link over a period of time. Each kind of data has a real-time priority R. The data group needing high real-time has a high R value, and the data needing low real-time has a low R value [9]. LP over a period of time can be calculated by Formula (1).

$$R_l = \sum_{u \in l, i=0}^{m} k_i R_i + \sum_{u \in l, j=0}^{n} k_j R_j \;\; u, v \neq s \; or \; d \tag{1}$$

u, v represent the nodes at each end of the link l. s represents the source node. d represents the destination node. m is the number of service request level types through the u node. n represents the number of service request level types through the v node. k_i represents the number of communication service requests with priority R_i within a period of time on node u. k_j represents the number of communication service requests with priority R_j during a period of time on node v. R_i represents the priority level of the transmission packet. The higher the priority, the stronger the real-time performance.

The path with the smallest LP value is the selected path. LP of router can be calculated by Formula (2).

$$LP(r) = \sum_{l \in r} R_l \tag{2}$$

R_l indicates the priority level of link l. It can be calculated by Formula (1).

The LP implementation process is as follows. Firstly, data are divided into different priorities according to their time and reality requirements. The higher the real-time requirement of data, the higher the priority of data. Secondly, recording the number of data passing through the link and data priority in a period of time. Thirdly, the priority (R_l) of link l is calculated by formula (1). Finally, selection path.

3.2 Single Channel Two-Dimensional Routing Metrics

Expected Transmission Count. Expected Transmission Count (ETX) uses the expected number of transmissions that successfully transmitted to the destination node as a measure of link quality. ETX comprehensively considers delay and packet loss rate [8].

The path with the smallest sum of ETX is the selected path. The ETT_i of link i can be calculated by Formula (3).

$$ETX_i = \frac{1}{(1 - P_f)(1 - P_r)} \tag{3}$$

P_f and P_r respectively represent the uplink and downlink packet loss rates of link i.

ETT_p of path p can be calculated by formula (4).

$$ETT_p = \sum_{i \in p} ETT_i \tag{4}$$

Quantified Packet Loss Rate. The Quantified Packet Loss Rate uses the end-to-end path loss probability as the routing cost. The influence of packet loss rate and delay on routing quality is considered comprehensively [8]. The Quantified Packet Loss Rate with logarithmic characteristics is not suitable for direct link cost, so the logarithm of the Quantified Packet Loss Rate of the link is selected as the link cost. The parameter allocation process is shown in Table 1.

Table 1. Parameter allocation table

Link Quality	Sending Rate	Re	-Log(Re)	Cost
Q_3	90% ∼ 100%	0.95	0.05	1
Q_2	79% ∼ 90%	0.85	0.16	3
Q_1	47% ∼ 79%	0.65	0.43	8
Q_0	0% ∼ 47%	0.25	1.39	28

Modified ETX. Modified ETX (mETX) is an improved version of ETX. mETX solves the defect caused by the lack of consideration of channel changing in ETX [8]. mETX comprehensively considers the influence of packet loss rate and channel changing on routing quality [8]. The path with the smallest sum of mETX is the selected path. mETX of a link can be calculated by formula (5).

$$mETX = \exp(u_{\Sigma} + \frac{1}{2}\sigma_{\Sigma}^{2}) \tag{5}$$

$\sum$ represents the bit error rate within the grouping time (frame length), which is related to device implementation. u_{Σ} and σ_{Σ}^{2} represent the mean and variance of $\sum$ respectively.

Interference-Delay Aware. Interference-Delay Aware (IDA) comprehensively considers the impact of delay and physical interference on routing quality. Delay includes channel contention delay and transmission delay [10].

The average competition delay (ACD_i) of link i can be calculated by formula (6). The expected transmission time of link i (ETD_i) can be calculated by formula (7). The total delay of link i ($Delay_i$) is the sum of channel competition delay (ACD_i) and transmission delay (ETD_i). IDA of path p can be calculated by formula (9).

$$ACD_i = S_n \times \left(\frac{(1 - PEP)\left(1 - (2 \times PEP)^R\right)}{(1 - PEP^R)(1 - 2 \times PEP)} \times CW_{\min} + \frac{1}{2} \right) \tag{6}$$

$$ETD_i = ETX_i \times \left(\frac{L}{BW_a} \right) \tag{7}$$

$$Delay_i = ACD_i + ETD_i \tag{8}$$

$$IDA(p) = \sum_{i \in p}^{n} Delay_i \times (1 - IR_i) \tag{9}$$

S_n represents the average slot utilization of node $n.PEP = 1 - d_f \times d_r$ represents packet error probability. $CW_{\min}$ represents the minimum competition window. R represents the backoff order. ETX_i represents the expected transmission times of link i, which can be calculated by formula (3). L represents the packet length. BW_a represents the available bandwidth of link i. n represents the number of links of path p. $IR_i = \frac{SINR_i}{SNR_i}$ represents the interference rate of node i, SNR_i represents the signal interference noise ratio of node i, and SNR_i represents the signal noise ratio of node i.

3.3 Single Channel Three Dimensional Routing Metrics

Expected Transmission Time. Expected Transmission Time (ETT) is developed from ETX, adding two parameters, bandwidth and message length. ETT comprehensively considers the influence of packet loss rate, delay and bandwidth on routing quality. The path with the smallest sum of ETT is the selected path

[8]. The ETT_i of link i can be obtained by formula (10). ETT_i of path P can be calculated by formula (11).

$$ETT_i = ETX_i \times \frac{S}{B} \tag{10}$$

$$ETT_p = \sum_{i \in p} ETT_i \tag{11}$$

S represents the average data length. B represents the current actual data transmission rate.

Link Priority-Interference and Delay Aware. Link Priority-interference and Delay Aware (LP-IDA) integrates LP and IDA. LP-IDA comprehensively considers real-time service delay and inter-stream interference [9]. LP-IDA (p) of path p can be calculated by formula (12).

$$LP - IDA(p) = \alpha(IDA(p)) + (1 - \alpha)LP(p) \tag{12}$$

Interference-Aware Routing. Interference-aware Routing (IAR) is based on channel utilization [6]. IAR comprehensively considers the influence of inter-stream interference, delay and bandwidth on routing quality. The IAR (i) of link i can be calculated by formula (13). The IAR (p) of the path p can be obtained by formula (15).

$$IAR(i) = \frac{1}{1 - \alpha} \times \frac{S}{B} \tag{13}$$

$$\alpha = \frac{T_{wait} + T_{collesion} + T_{backoff}}{T_{wait} + T_{collesion} + T_{backoff} + T_{success}} \tag{14}$$

$$IAR\,(p) = \sum_{i \in p} IAR_i \tag{15}$$

T_{wait}, $T_{collesion}$, $T_{backoff}$, $T_{success}$ respectively represents the waiting, collision, back-off and successful transmission time of a data packet.

Airtime Link Metric. Airtime Link Metric (ALM) is an approximate measurement method. ALM's main purpose is to reduce the difficulty of specific implementation and interaction [11]. ALM considers the transmission rate, channel quality and packet loss rate. The airtime cost of link can be obtained by formula (16).

$$C_a = \left[\frac{O}{n} + \frac{B_t}{r}\right] \times \frac{1}{1 - e_f} \tag{16}$$

O represents channel access overhead, including frame header, training sequence, channel access protocol frame, etc. n depends on implementation. B_t represents the number of bits contained in the body of a data frame. r represents the data rate used under the current link conditions when the data frame (typical frame length is Bt) is transmitted. e_f represents the frame-error rate of data frame (typical frame length is Bt).

3.4 Four-Dimensional Routing Metrics for Single Channel

Enhanced-Airtime Link Metric. Enhanced- Airtime Link Metric (E-ALM) is improved on the basis of ALM. E-ALM introduced the Network Allocation Vector (NAV). E-ALM comprehensively considers the influence of channel overhead, protocol overhead, packet loss rate, node interference and bandwidth on network quality [12]. The cumulative average NAV value of links over a period of time can be calculated by formula (17). The average delay of links can be calculated by formula (18). The E-ALM of a path can be obtained by formula (19).

$$NAVC = \frac{\sum_{t_1=t_u}^{t_1=t_v} NAV_{t_1}}{t_v - t_u} \tag{17}$$

$$Delay\,(x) = \begin{cases} 2\ ms & if \quad x \le 0.2 \\ 2 \times e^{7.9(x-0.2)^2} & if \ \ 0.2 \le x \le 0.65 \end{cases} \tag{18}$$

$$C_\alpha\,(p) = \sum_{node\ \ n \in p} \alpha C_n + (1-\alpha)\,D_n \tag{19}$$

$x = NAVC$ represents the cumulative average NAV value over a period of time. $Delay(x) = 14.16ms\ \ (x > 0.65)$. C_n represents the air transmission time which can be calculated by formula (15). $D_n = Delay\,(x)$ represents the average delay, which can be calculated by formula (18), $0 \le \alpha \le 1$ the greater the α, the greater the proportion of the air delay in the criterion. The smaller the α, the greater the proportion of the time delay in the criterion.

3.5 Summary

Table 2. Comprehensive evaluation table of routing metric performance.

Routing metric	Packet loss rate	Delay	Interference	Real-time service	Channel change	Transmission rate	Channel protocol overhead	Reference label
Hop	–	–	–	–	–	–	–	[8]
RTT	–	Yes	–	–	–	–	–	[8]
LP	–	–	–	Yes	–	–	–	[9]
packet Pair Delay	–	Yes	–	–	–	–	–	[8]
ETX	Yes	Yes	–	–	–	–	–	[8]
Quantified packet loss rate	Yes	Yes	–	–	–	–	–	[8]
mETX	Yes	–	–	–	Yes	–	–	[8]
IDA	–	Yes	Yes	–	–	–	–	[10]
ETT	Yes	Yes	–	–	–	–	–	[8]
LP-IDA	–	–	–	Yes	–	–	–	[9]
IAR	–	–	Yes	Yes	–	Yes	–	[6]
ALM	Yes	–	–	–	–	Yes	Yes	[11]
E-ALM	Yes	–	Yes	–	–	Yes	Yes	[12]

In single channel networks, the most important considerations for routing metric is the delay and packet loss rate. Of course, interference, noise, transmission rate, channel bandwidth, etc. will also affect network quality. The comprehensive evaluation table of single-channel routing measurement performance is shown in Table 2

4 Multi-channel Routing Metrics

Currently, wireless networks often use multiple channels for data transmission. Multi-channel networks can enable nodes to use different channels to send and receive data at the same time without interference. Therefore, multi-channel can greatly increase network throughput and reduce delay.

4.1 Multi-channel Three Dimensional Routing Metrics

Multi-rate Dijkstra's Min-Cost. Multi-rate Dijkstra's Min-cost (MDC) is applied in a multi-rate network environment. MDC will determine the transmission rate of the node and the next hop sending node at the same time. MDC comprehensively considers the influence of channel interference, bandwidth and delay on routing quality [13]. The minimum path cost W_i from node i through forwarding node j to a given destination node d can be calculated by Formula (20). W_{ij}^r can be calculated by formula (21). In the case of using rate r, the link overhead can be calculated by formula (22).

$$W_i = \min_{r \in R, J \in G_P} \left\{ W_{ij}^r \right\} \tag{20}$$

$$W_{ij}^r = w_{ij}^r + W_j \tag{21}$$

$$w_{ij}^r = \frac{1}{p_{ij}^r} \times \frac{s}{r} \tag{22}$$

R represents the set of available rates. G_p represents the set of all nodes that have completed the minimum path cost calculation. W_{ij}^r represents the path overhead of the node i using node j as the forwarding node and using the rate r as transmission rate. w_{ij}^r represents the link overhead of node i to the next-hop node j using rate r, which can represent the degree of channel interference. W_j represents the minimum path overhead of the next hop node j to the destination node. P_{ij}^r represents the delivery probability of the link using rate r between node i and node j, and the link delivery probability is the probability of successful packet transmission.

4.2 Multi-channel Four-Dimensional Routing Metrics

Metric Based on Uniform Description of Interference and Load. Metric Based on Uniform Description of Interference and Load (MIL) uses the combination of link average load, effective bandwidth and data packet size to calculate link weights. MIL comprehensively considers the influence of load, intra-stream interference, inter-stream interference and physical interference on routing quality [14].

The data transmission quality of links is affected by inter-stream interference and physical signal strength [15]. In the case of inter-stream interference and physical interference, the effective bandwidth of the link can be calculated by formula (23).

$$B_{Inter,i} = \left(1 - \frac{TotalTime - IdleTime}{TotalTime}\right) \times B_{bas} \times \left(1 - \frac{\sum\limits_{k \neq v} P_u(k)}{\frac{P_u(v)}{r} - N}\right) \quad (23)$$

$TotalTime$ is the total passive detection time CBT_i. $IdleTime$ is the back-off time and the idle time when no data packets occupy the channel. B_{bas} represents the standard data rate of the link. $P_u(v)$ represents the signal power received by node u from node v. $P_u(k)$ represents the interference power from node k. N represents the received background noise power. r is the preset SINR threshold.

When link $S-A$ and Link $A-B$ use the same channel, the available bandwidth $B_{S-A,A-B}$ of link $S-A$ can be calculated by formula (24). Based on the above equivalent bandwidth, the MIL_i of link i can be calculated by formula (25).

$$B_{S-A,A-B} = \frac{B_{Inter,S-A} \times B_{Inter,A-B}}{B_{Inter,S-A} + B_{Inter,A-B}} \quad (24)$$

$$MIL_i = \overline{L_i} \times \frac{S}{B_i} \quad (25)$$

S represents the packet size. B_i represents the effective bandwidth of link i, which can be calculated by Formula (24). $\overline{L_i} = (1-\theta) \times L_{i-cur} + \theta \times L_{i-pre}$ represents the average load of link i. L_{i-cur} represents the current load value, and L_{i-pre} represents the previous load value.

4.3 Multi-channel Five-Dimension Routing Metrics

Multi-rate Routing Metric. Multi-rate Routing Metric (MRM) comprehensively considers the influence of inter-stream interference, delay, bandwidth and packet loss rate on routing quality [16]. In the network shown in Fig. 2, $ETT_{A-B}^{\text{inter}flow}$ and $ETT_{A-B}^{\text{intra}flow}$ of link $A-B$ can be calculated by formula (26) and (27) respectively.

$$MRM_i = ETT_i^{\text{inter}flow} + ETT_i^{\text{intra}flow} \quad (26)$$

$$ETT_{A-B}^{\text{inter}flow} = ETT_{A-B} + ETT_{F-G} \quad (27)$$

$$ETT_{A-B}^{\text{intra}flow} = ETT_{A-B} + ETT_{B-C} \quad (28)$$

$ETT_i^{\text{inter}flow}$ and $ETT_i^{\text{intra}flow}$ respectively represent inter-stream interference and intra-stream interference. ETT represents the expected transmission time.

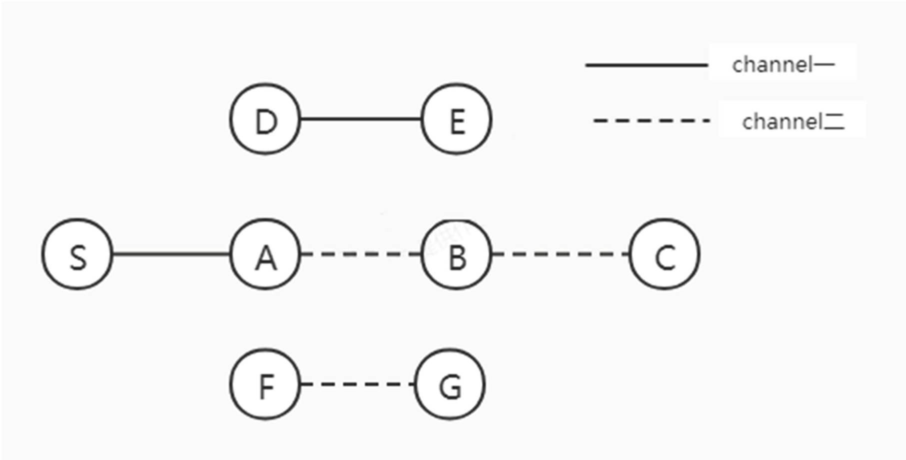

Fig. 2. Interference model diagram.

Weighted Cumulative Expected Transmission Time. Weighted Cumulative Expected Transmission Time (WCETT) is a routing metric specially designed for Multi-radio Link Quality Source Routing (MR-LQSR). WCETT is developed on the basis of ETT. WCETT comprehensively considers the impact of packet loss rate, bandwidth, intra-stream interference,delay and bottleneck channel on routing quality [8]. WCETT of a path can be calculated by formula (29) and (30).

$$X_j = \sum ETT_i \ (Hop\ i\ is\ on\ channel\ j)\ 1 \leq j \leq k \tag{29}$$

$$\text{WCETT} = (1-\beta) \times \sum_{i=1}^{\text{n}} ETT_i + \beta \times \max_{1 \leq j \leq k} X_j \ \ 1 \leq i \leq k \tag{30}$$

k represents the number of channels used by the path.

Interference Aware Routing Metric. Interference Aware Routing Metric (iAWARE) comprehensively considers the impact of packet loss rate, bandwidth, int-stream interference, delay and inter-stream interference on routing quality. The iAWARE of a path can be calculated by formula (31) [8].

$$AWARE = (1-\alpha) \times \sum_{1}^{n} \frac{ETT_l}{\min(IR_j(u), IR_j(v))} + \alpha \times \max_{1 \leq j \leq k} X_j \tag{31}$$

$$IR_l(u) = \frac{SINR_{l(u)}}{SNR_{l(u)}} \tag{32}$$

Metric of Interference and Channel Switching. Metric of Interference and Channel Switching (MIC) is an improvement of WCETT. MIC solves the problem of WCETT's inability to capture inter-stream interference and out-of-order. MIC comprehensively considers the impact of packet loss rate, bandwidth, intra-stream interference, delay and inter-stream interference on routing quality [8]. The MIC of path p can be calculated by formula (33), (34) and (35).

$$MIC = \frac{1}{N \times \min(ETT)} \sum_{l \in p} IRU_l + \sum_{l \in p} CSC_i \tag{33}$$

$$IRU_l = ETT_l \times N_l \tag{34}$$

$$CSC_j = \begin{cases} \omega_1, CH\left(prv\left(j\right) \neq CH\left(j\right)\right) \\ \omega_2, CH\left(prv\left(j\right) = CH\left(j\right)\right) \end{cases} \tag{35}$$

N is the number of nodes in the network. IRU_l refers to the use of interference-aware resources on link l. IRU_l includes the delay in the path and the influence on the utilization rate of resources in the entire network. N_l represents the set of nodes within the interference range during data transmission on the link l. CSC_i is the channel switching overhead of link i. CH_i is the channel used by node j to the next hop. $CH(prv(j))$ represents the channel used by the previous jump node j.

4.4 Multi-channel Six-Dimensional Routing Metrics

WCETTR Metric. WCETTR is an improved version of WCETT. Compared with WCETT, WCETTR considers intra-stream interference and inter-stream interference. In other words, WCETTR comprehensively considers the impact of delay, bandwidth, intra-stream interference, inter-stream interference, packet loss rate and bottleneck channel on routing quality [18]. The newly defined parameter N can represent the degree of inter-stream interference and bottleneck channel in the flow. The N of path P can be calculated by Formula (36). When link i and link j use the same channel, the value of $I\left(C_i == C_j\right)$ is 1, otherwise it is 0. WCETTR can be calculated by formula (37).

$$N = \max\left((1-\varepsilon) \sum_{j \subset In(i) \cap j \subset R} ETT_j \times I\left(C_i == C_j\right) + \varepsilon \times \sum_{k \subset In(i) \cap k \not\subset R} ETT_k \times I\left(C_i == C_k\right)\right) \tag{36}$$

$$WCETTR = (1-\beta) \times \sum_{i=1} ETT_i + \beta \times N \tag{37}$$

4.5 Summary

In multi-channel networks, delay and packet loss rate are still research hot spots. However, compared with single channel, multi-channel has its own characteristics. Intra-stream interference and inter-stream interference are research hot

Table 3. Comprehensive evaluation table of routing metric performance.

Routing metric	Delay loss rate	Transmission Rate	Physical Interference	Intra-stream Interference	Inter-stream interference	Node load	Loss Rate	Bottle-neck channel	Reference label
MDC	Yes	Yes	–	–	–	–	–	–	[13]
MIL	–	–	Yes	Yes	Yes	Yes	–	–	[14]
MRM	Yes	Yes	–	Yes	Yes	–	Yes	–	[15]
WCETT	Yes	Yes	–	Yes	–	–	Yes	–Yes	[16]
iAWARE	Yes	Yes	–	Yes	Yes	–	Yes	–	[8]
MIC	Yes	Yes	–	Yes	Yes	–	Yes	–	[8]
WCETTR	Yes	Yes	–	Yes	Yes	–	Yes	Yes	[18]

spots for multi-channel networks. At the same time, severe intra-stream interference and inter-stream interference will greatly reduce network throughput. Of course, there are also scholars studying other aspects such as node load and bottleneck channels. The comprehensive evaluation table of multi-channel routing measurement performance is shown in Table 3.

5 Routing Metrics in Multi-gateway Mesh Networks

Gateway is necessary for backbone WMNs and hybrid WMNs to access to Internet. Gateways are also called protocol converters. Gateways are used for both WAN and LAN interconnections. However, there is often more than one gateway in a network, and the quality of the network is closely related to the quality of gateway, so the choice of gateway has great significance for the improvement of routing performance. Currently, in WMNs routing research, the bandwidth and load of the gateway are usually considered.

5.1 Multi-gateway Four-Dimensional Routing Metric

Gateway-Selection Based Routing. Gateway-Selection Based Routing (GSBR) is based on backbone WMN, which combines PM with CI. GSBR comprehensively considers the influence of gateway load, intra-stream interference, packet loss rate and inter-stream interference on routing quality [19]. In route selection, the path with the minimum GSBR value is selected, and the GSGB of path p can be calculated by formula (38). The capacity factor of gateway G can be calculated by formula (39). The path quality PM_p of path p from router to gateway can be calculated by formula (41).

$$GSBR_{(G,p)} = \beta(1 - CI_G) + (1 - \beta)PM_p \tag{38}$$

$$CI_G = \frac{\sum_{i \in I_G} \frac{1+\alpha_i}{2} C_{a_i}}{\sum_{i \in I_G} C_{\max_i}} \tag{39}$$

$$PM_p = \max_{i \in p}(LM_i) + \prod_{i \in p} LM_i \tag{40}$$

$C_{\max_i}$ is the maximum capacity of interface i of gateway G, assuming the maximum capacity is 100. C_{a_i} is the available capacity of interface i. α_i is an adjustable constant, which can be obtained by formula (40). I_G represents the interface set of gateway G.

The link quality LM_i of link L using channel C can be calculated by Formula (42).

$$LM_l = \left(1 - \left(\frac{1}{2}\right)^n\right) \times \frac{\sum_{i \in N} P_{vR}(v_i)}{P_{\max}} + \left(\frac{1}{2}\right)^n \times \frac{1}{1 - p_f} \tag{41}$$

$$P_{\max} = \frac{P_{vR}(V_S)}{T} \tag{42}$$

n is the number of adjacent nodes in a hop range sharing the same channel. T is the threshold value. $P_{vR}(v_s)$ is the sending power from the sending end to the receiving end. $P_{vR}(v_i)$ is the interference power of interfering node i. p_f is the data packet loss rate. N represents the set of interfering nodes within the interference range of the receiving end node.

Best Path to Best Gateway. Best Path to Best Gateway (BP2BG) comprehensively considers the effects of physical interference, packet loss rate, bottleneck channel and gateway capacity on routing quality. BP2BG is derived from Distribution Available Capacity Indicator (DACI) and Link Quality Metric (LQM). The $DACI_G = CI_G$ of gateway G can be calculated by Formula (39) [20]. (LQM) considers packet loss rate and physical interference. The LQM_i of Link i can be calculated by Formula (44). Path quality $PQ_{S \to G}$ from route S to gateway G can be calculated by Formula (45).

$$LQM_i = \frac{\beta \times IR_i + (1 - \beta)\frac{1}{d_f}}{2} \tag{43}$$

$$PQ_{S \to G} = \frac{Max_{k \in p}(LQM_k) + \prod_{k \in p} LQM_k}{2} \tag{44}$$

IR_i is the interference ratio of link i, the definition is the same as that of MIL. d_f represents the number of probe packets successfully transmitted.

$BP2BG_{(g,p)}$ can be calculated by formula (46).

$$BP2BG_{(g,p)} = \frac{\alpha(1 - DACI) + (1 - \alpha) PQ}{2} \tag{45}$$

5.2 Summary

Table 4. Comprehensive evaluation table of routing measure performance.

Routing metric	Gateway load	Packet loss rate	Intra-stream interference	Inter-stream Interference	Physical interference	Gateway capacity	Reference label
MDC	Yes	Yes	Yes	Yes	–	–	[19]
MIL	–	–	–	–	Yes	Yes	[8]

There is often more than one gateway in a network, so the choice of gateway is very important. Currently, in routing metric, the bandwidth and load of gateway are mainly considered. The capacity of the gateway is limited, and if the gateway is selected with heavy load, the network throughput will be limited. Therefore, the load of the gateway is also an aspect that should be considered in the multi-gateway network routing metric. The comprehensive evaluation table of multi-gateway routing measurement performance is shown in Table 4.

6 Routing Simulation and Performance Analysis

NS3 is a discrete event simulator. NS3 is a free software, an open source project written in C++. For windows systems, you can run NS3 by installing a virtual machine. Common virtual machines are Vmware, Virtualbox, VMLite WorkStation, Qemu, etc.

6.1 OLSR Simulation

Optimized Link State Routing (OLSR) provides the optimal path based on the number of route hops. Create Ad-hoc nodes, and the channel, physical layer and MAC layer all use the wifi protocol. There are 50 nodes randomly distributed in the area of 180×160. In the same network scenario, change the number of nodes to observe changes in throughput and delay, and compare the performance of the HOP and Distance Routing Metric. The resulting graph is shown in the Fig. 3 below.

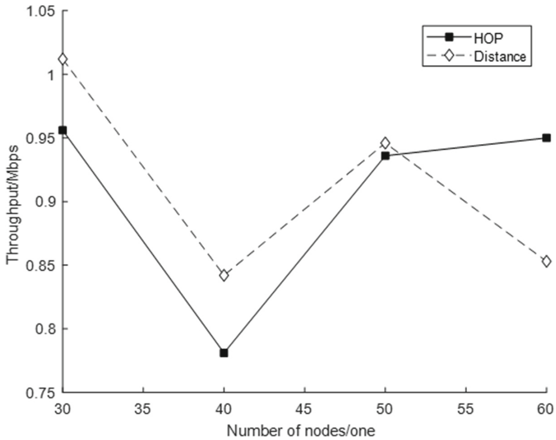

Fig. 3. A comparison of throughput between HOP and Distance Routing Metric.

By comparison, when the number of nodes is less than 50, Distance Routing Metric has a larger throughput. When the number of nodes is approximately

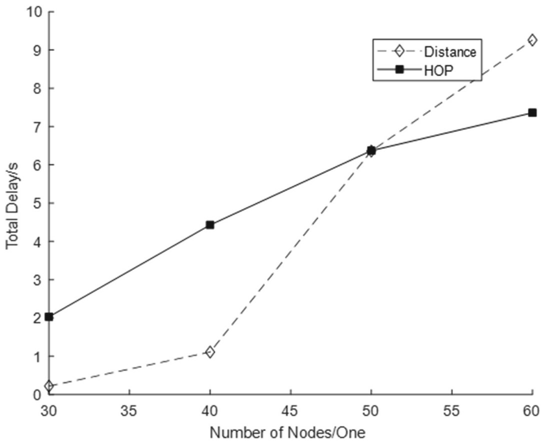

Fig. 4. A comparison of total delay between HOP and Distance Routing Metric.

greater than 50, HOP has a larger throughput and the performance of the HOP is better at this case (Fig. 3).

By comparison, when the number of nodes is approximately less than 50, the total delay of Distance Routing Metric is small, and the performance of Distance Routing Metric is better at this case. When the number of nodes is approximately greater than 50, the total delay of the Distance Routing Metric is greater than the total delay of HOP, and the performance of the HOP is better at this case (Fig. 4).

7 Summary and Prospect

As one of the evolution directions of the next generation wireless communication network, WMNs has the advantages of high bandwidth, easy deployment and maintenance, wide coverage, low cost and so on. Routing metric is a key technology in WMNs, which is of great significance for improving network performance. In this paper, the classical WMNs routing metrics and the recent ten years of WMNs routing metrics are carefully studied. According to the characteristics of each routing metric, the characteristics and applicable scenarios are described in this paper. NS3 simulation software was used to simulate HOP and Distance Routing Metric.

As a key technology of WMN, routing metrics should be diversified. The appropriate routing metrics should be selected for different scenarios. For different network quality requirements, it is also necessary to select appropriate routing metrics based on the focus of the requirements. At present, the consideration of routing metrics is relatively single, often focusing on factors such as delay, packet loss rate, and link quality. Less consideration is given to factors such as service priority, link priority, and inter-stream interference between some orthogonal channels. Therefore, it is a good research direction to combine routing metrics and channel allocation schemes.

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