An interference and load aware routing metric for Wireless Mesh Networks

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Abstract: This paper proposes a load and interference-aware routing metric for wireless mesh networks, named Channel Utilisation and Contention Window Based (C2WB) metric. Our metric assigns weights to individual links which are proportional to the links service times estimated from both channel utilisation and the average contention window of the CSMA/CA mechanism. The path metric, combined from individual link weights, accounts for both load and interference of the links on the path. Thus the C2WB metric helps the routing protocol to balance the traffic and to improve the network capacity by avoiding routing the traffic through congested areas.

Keywords: ad hoc; mesh; wireless; routing; cross-layer; routing; load-aware; interference-aware.

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1 Introduction

Wireless networks are traditionally designed to be used as access networks to a wired network such as the internet. Such networks typically use one-hop wireless links to connect mobile clients to Access Points (APs) that are directly attached to the wired network. The advantage of these networks is their simplicity; however, they may fail to provide sufficient connectivity and coverage and require an important budget for the wired infrastructure if it is necessary to cover large areas such as cities, metro stations and so on. Recently, there has been a growing interest in extending the coverage of the wireless access networks. Wireless Mesh Networks (WMNs) is an emerging network technology that offers wireless broadband connectivity. WMNs have been attracting a lot of researches (Akyildiz et al., 2005; Raniwala and Chiueh, 2005), commercial (Mesh network Inc., 2007; Radiant Networks, 2007), and standardisation (Joint SEE-Mesh/Wi-Mesh Proposal to 802.11 TG, 2006) interests in recent years. They can provide a cost-effective and flexible solution for extending broadband services to areas where cabling is difficult.

In WMNs, most of the nodes are either static or minimally mobile and do not rely on batteries. Eriksson et al. (2006) suggest that the goal of routing algorithms is hence to improve network capacity or the performance of individual communications, instead of dealing with mobility or minimising power consumption. The technical challenges in WMNs include load balancing, optimal routing, network auto-configuration, fairness and mobility management. Since most users of WMNs are interested in accessing the internet or using services provided by some servers, the traffic is mainly directed towards Gateways (GWs), or from GWs to clients. Based on the specific requirements of WMNs, we believe that a good routing protocol should find paths with minimum delay, maximum data rate and low levels of interference. In this sense, an effective routing metric, which is used by routing protocols, must be able to capture the quality of the links effectively.

The quality of a wireless link can be considered under two components:

- quality of transmission media/channel itself
- how difficult it is to seize the transmission media/channel.

The former component depends on Frame Error Rate (FER) and data rate of the link while the latter depends on the current amount of traffic on the channel. From our point of view, both of these components can be captured effectively by using the service time, which is defined in the research of Carvalho and Garcia-Luna-Aceves (2003), as a metric for link quality:

> "The MAC-layer frame service time is the time interval between the time instant that a packet starts to contend for transmission and the time instant that the packet either is acknowledged for a correct reception by the intended receiver, or is dropped."

It is clear that the quality of transmission media significantly affects the transmission time, which is the time used to successfully transmit a frame on the channel, in terms of both data rate and number of retransmissions. The current amount of traffic on the channel is reflected by the deferring time, the time a node has to wait because of other transmissions, which is also a part of the service time. The formal definitions of transmission time and deferring time are presented in Section 2.1.

In this paper, we propose a routing metric that fully accounts for the link quality in WMNs. Our metric assigns weights to individual links which are proportional to the service times of those links. The metric is based on both channel utilisation and FER of the link. The individual link weights are combined into a path metric which is more or less proportional to the end-to-end delay of the path. Thus the C2WB routing metric helps the routing protocol to improve network capacity by avoiding routing traffic through congested areas, as it effectively captures the interference effects of transmissions over the other wireless links.

The rest of this paper is organised as follows: Section 2 presents the proposed routing metric, the routing protocol into which the routing metric is integrated and its implementation in the Network Simulator (NS-2). Simulation results and their analysis are presented in Section 3. Section 4 discusses previous related work. Finally, conclusions are drawn in Section 5, followed by Acknowledgements and References.

2 C2WB: Interference and load aware routing metric

2.1 Delay model for shared wireless channel access

We first discuss a MAC-layer delay model for shared wireless channel access in the Distributed Coordination Function (DCF) mode of IEEE 802.11. The model allows us to look into the composition of service time, and find out which parameters play important roles in this composition. Based on this analysis, our routing metric is built to effectively capture the wireless link service time, which reflects the quality of the link.

Before going into details of the model, we would like to briefly describe how a transmission happens in DCF mode. The DCF access method is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) principle. The CSMA/CA gives the same priority to each node contending for an empty time slot, which guarantees long-term fairness in access probability. Before a node starts a frame transmission, it has to sense the channel. If the channel is idle for at least a period equal to the Distributed Inter Frame Space (DIFS), the frame is transmitted directly. Otherwise, the node enters a back-off stage, and randomly sets its back-off counter to a value between zero and value of the Contention Window (CW). The back-off counter is decreased by one unit for every time slot the channel is sensed to be idle, and frozen if the channel is sensed to be busy. When the back-off counter reaches zero, the node starts transmission. Upon the correct reception of a frame, the receiver has to send an Acknowledgment frame (ACK) after a period equal to the Short Inter Frame Space (SIFS). If the sending node receives the ACK, the transmission is considered successful, otherwise the sending node assumes a collision, doubles the value of its current Contention Window, randomly resets its back-off counter, and retransmits the frame when the back-off counter reaches zero again.

Based on the description above, the MAC-layer frame service time to transmit a frame through an IEEE 802.11 wireless link is made of three components: back-off time, deferring time and transmission time.

- *back-off time*: the time required for the back-off counter to reach zero when the channel is idle
- *transmission time*: the time from the starting of transmission until ACK is received successfully
- *deferring time*: the time a node has to stop decreasing its counter due to the busy state of the channel over which it tries to transmit a frame.

Let FER_l be Frame Error Rate of a given link l, which represents the percentage of the frames sent out without receiving ACK. Since the value of the back-off counter is uniformly distributed between zero and the value of the current CW, we can consider that the back-off counter at each back-off stage equals half of the CW of that stage. Then the total back-off time T_{bac} is computed as the weighted average of the CWs that a frame transmission has to undergo before being received successfully (Beuran et al., 2007). Table 1 shows the probability of a successful transmission at each stage, where r is the maximum back-off stage.

The back-off time on a link l is computed as follows:

$$T_{\text{bac,l}} = \frac{\sum_{i=0}^{r}\left(FER_l^i(1-FER_l)\sum_{j=0}^{i}\frac{CW_j}{2}\right)T_{\text{slot}}}{\sum_{k=0}^{r}FER_l^k(1-FER_l)} = \left[\frac{2(1-FER_l)(1-(2FER_l)^{r+1})}{(1-2FER_l)(1-FER_l^{r+1})}-1\right]\frac{CW_0}{2}T_{\text{slot}} \tag{1}$$

with $CW_j = CW_0 2^j$ (following the binary exponential back-off mechanism), T_{slot} is the slot time.

The transmission time on link l, $T_{\text{trans},l}$, includes the time to transmit the payload, the headers of the frame, and the time to receive an ACK. The transmission time also includes the number of retransmissions that need to be performed until the frame is received successfully.

Table 1 Back-off stage

Stage	*Probability*	CW^a	*Back-off time*
0	$1-FER_l$	CW_0	$\frac{CW_0}{2}$
1	$FER_l(1-FER_l)$	CW_1	$\frac{CW_0+CW_1}{2}$
...	...	...	...
i	$FER_l^i(1-FER_l)$	CW_i	$\sum_{j=1}^{i}\frac{CW_j}{2}$
...	...	...	...
r	$FER_l^r(1-FER_l)$	CW_r	$\sum_{j=1}^{r}\frac{CW_j}{2}$

[a]Contention Window.

The number of retransmissions on link l, $N_{r,l}$, can be approximated as:

$$N_{r,l} = \frac{1}{1-FER_l}. \tag{2}$$

The total transmission time on link l, $T_{\text{trans},l}$, is derived as follows:

$$T_{\text{trans},l} = N_{r,l}\left(\frac{PL}{D_{\text{rate},l}} + \frac{p\_hdr + m\_hdr}{B_{\text{rate}}} + SIFS\right) + \frac{ACK}{D_{\text{rate},l}} + DIFS = \frac{1}{1-FER_l}\left(\frac{PL}{D_{\text{rate},l}} + \frac{p\_hdr + m\_hdr}{B_{\text{rate}}} + SIFS\right) + \frac{ACK}{D_{\text{rate},l}} + DIFS \tag{3}$$

where PL is the payload size, p_hdr and m_hdr are Physical-layer and MAC-layer header sizes respectively, $D_{\text{rate,l}}$ is the data rate on link l, B_{rate} is the basic rate, and ACK is the size of ACK frame.

The diferring time depends both on the back-off time, transmission time, and how busy the channel is. In order to determine the busyness of a channel, we define channel utilisation at node n, c_n, *as the fraction of channel time in which channel is sensed busy by node* n. The value of c_n does not include the time node n uses the channel for its own transmissions. The channel utilisation is expressed as:

$$c_n = \sum_{k \neq n}\left(\frac{M_{k,T_s}}{T_s}\frac{1}{R_k}\right) \tag{4}$$

where M_{k,T_s} is the number of bits at physical layer sent by node k, which is in carrier-sense range of node n, during a certain time interval T_s, and R_k is the data rate at which M_{k,T_s} is sent. The carrier-sense range represents the range in which a transmission can trigger carrier-sense detection at the radio interface of the node (Nguyen et al., 2007).

Assuming that channel utilisation at node n is c_n, it means that the idle time and busy time (in which channel is used by other nodes) of the channel are proportional to $1-c_n$ and c_n, respectively. The deferring time on link l, $T_{\text{def},l}$ is computed as:

$$T_{\text{def},l} = \frac{c_n}{1-c_n}(\mathrm{T}_{\text{bac},l} + T_{\text{trans}}). \tag{5}$$

The service time, $T_{\text{ser},l}$ on link l, is the sum of back-off time, deferring time and transmission time:

$$T_{\text{ser},l} = T_{\text{bac},l} + T_{\text{def},l} + T_{\text{trans},l}. \tag{6}$$

To see the impact of back-off time and deferring time on the service time, we compute P_l as the portion of back-off and deferring time in service time on the link l:

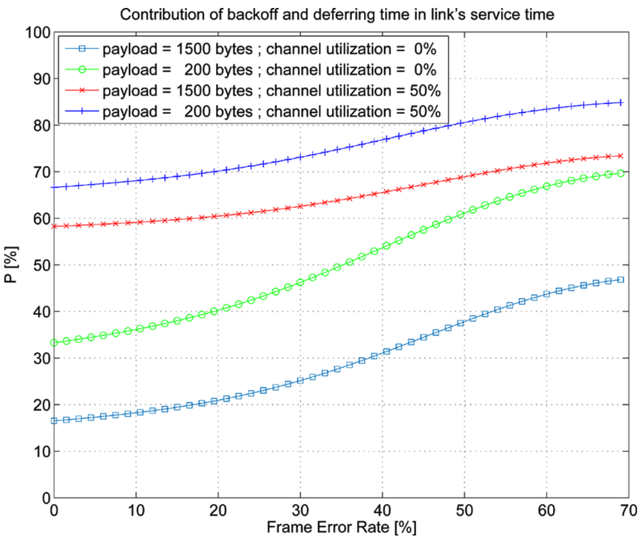
$$P_l = \frac{T_{\text{bac},l} + T_{\text{def},l}}{T_{\text{ser},l}}. \tag{7}$$

From equations (7), (5)–(3), we have:

$$\begin{aligned} P_l &= \frac{T_{\text{bac},l} + \frac{c_n}{1-c_n}(T_{\text{bac},l} + T_{\text{trans},l})}{T_{\text{bac},l} + \frac{c_n}{1-c_n}(T_{\text{bac},l} + T_{\text{trans},l}) + T_{\text{trans},l}} \\ &= \frac{T_{\text{bac},l} + c_n T_{\text{trans},l}}{T_{\text{bac},l} + T_{\text{trans},l}}. \end{aligned} \tag{8}$$

The value of P_l depends on payload size (equation (3)) which varies with different applications. There were several measurements, such as Kotz and Essien (2005), Tang and Baker (2000), and Balachandran et al. (2002) to discover the distribution of packet sizes in wireless environments. All studies reported that: from 60% to 70% of packets were smaller than 200 bytes, and small packets (smaller than 100 bytes) and large packets (around 1500 bytes) dominate traffic over WLAN (Wireless Local Area Network). Figure 1 shows the contribution of back-off time and deferring time to service time when FER varies with payload size equals 200 bytes and 1500 bytes, channel utilisation equals 0% and 50% respectively. The IEEE 802.11 parameters used to compute the results are summarised in Table 2.

Figure 1 Contribution of back-off and deferring time to service time (see online version for colours)



The results point out that, with the increase of channel utilisation or FER, back-off and deferring time contribute a significant amount to service time, so they cannot be ignored. The adoption of WLAN standards that allow transmitting at higher rates, such as IEEE 802.11g or IEEE 802.11n also encourages this conclusion, since they reduce the transmission time and thus increase the contribution of back-off and deferring time as a result. Another reason which supports our conclusion is the error-prone characteristic of wireless links in mesh networks. The measurement of an unplanned 802.11b mesh network in the study of Bicket et al. (2005) shows that the median packet loss rate is 20%, and nearly a quarter of the links have loss rates of 50% or more. Since they measured the links loss rate at layer-3, we believe that the average FER of those links are much higher because of the retransmission mechanism used in CSMA/CA.

Table 2 The IEEE 802.11 parameter values

Parameter	*Value*
MAC header	272 bits
Physical header	192 bits
ACK	304 bits
Data rate	11 Mbps
Basic rate	1 Mbps
Slot time	20 µs

2.2 C2WB: Contention Windows Based metric

Our proposed routing metric assumes an architecture like that shown in Figure 2. The upper part is the wired internet and the internet gateways. These gateways connect the wireless mesh routers to the internet. The middle layer consists of wireless mesh routers that connect to both internet gateways and mesh clients through wireless links. The wireless mesh routers form a wireless backbone network to provide internet connectivity to mesh clients. Mesh clients can access the internet by relaying their packets through the wireless backbone. Mesh clients can be connected to the wireless backbone in either single-hop mode or multi-hop mode.

C2WB is a routing metric that leverages real-time radio channel quality information to maximise the achieved throughput of a WMN. Nodes gather link state information about the WMN, and use it to compute the best routes to the gateway. Although the topology of WMNs is static, the quality of a wireless link could vary significantly over time, and this variation needs to be considered in routing metric.

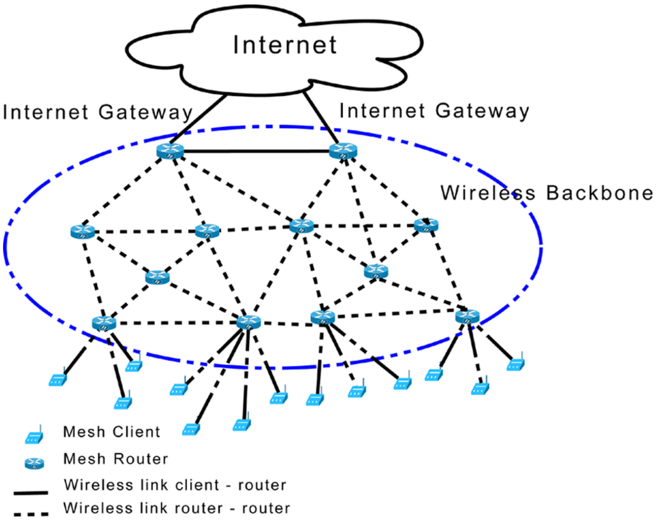
Intuitively, a routing metric should incorporate all factors that affect the quality of a wireless link. These factors include:

i the current physical data rate,

ii the contentions among nodes sharing the same radio channel

iii the Frame Error Rate of the wireless link.

Figure 2 Wireless Mesh Network architecture (see online version for colours)



The items (i) and (iii) are mostly captured by routing metrics such as ETT (Richard et al., 2004), mETX (Koksal and Balakrishnan, 2006), iAWARE (Subramanian et al., 2006), but not the contention with other links. Contention among nodes (ii) is partially addressed by iAWARE and MIC, but this routing metrics use heuristic approaches. C2WB uses service time as a metric to approximate quality of the link, and thus includes all the factors above without using any heuristic approach .

2.2.1 *Estimation of link's service time*

The proposed routing metric, C2WB, estimates service time through the current Average Contention Window of CSMA/CA and current channel utilisation. Considering a wireless link l from node n to node m, let $\overline{CW_l}$ and c_n be the Average Contention Window of the link l, and channel utilisation from the node n point of view, respectively (please see equation (4) for the definition of c_n).

From Table 1, the Average Contention Window, $\overline{CW}$, is expressed as a function of Frame Error Rate (FER_l) of link l and value of Contention Window at stage 0 (CW_0) as showed in study of Nguyen et al. (2008):

$$\overline{CW_l} = \frac{\sum_{i=0}^{r}(FER_l^i(1-FER_l)CW_i)}{\sum_{i=0}^{r} FER_l^i(1-FER_l)} = \frac{(1-FER_l)(1-(2FER_l)^{r+1})}{(1-2FER_l)(1-FER_l^{r+1})}CW_0. \tag{9}$$

Back-off time

Considering both equations (9) and (1), we have the following relation between the Average Contention Window and Back-off time:

$$T_{\mathrm{bac}}, l = \left(\overline{CW_l} - \frac{CW_0}{2}\right)T_{\mathrm{slot}}. \tag{10}$$

Transmission time

Transmission time can be estimated by using equation (3), however, the equation is very complicated due to various parameters of the CSMA/CA mechanism. To simplify equation (3), we use Efficient Bandwidth, which accounts for the real data rate after removing transmission time of overheads such as physical-layer overhead, MAC-layer overhead, and the time waiting for ACK frame, etc.. This method is similar to the one used in the research of Awerbuch et al. (2006). The values of Efficient Bandwidth is given in Table 3.

Table 3 Efficient Bandwidth

	Efficient bandwidth [Mbps]	
Operating rate [Mbps]	*RTS/CTS off*	*RTS/CTS on*
11.0	7.15	5.17
5.5	4.34	3.52
2.0	1.80	1.64
1.0	0.94	0.89

Using the Efficient Bandwidth, which is inspired by the research of Awerbuch et al. (2006) called B_e, equation (3) can be re-written as:

$$T_{\mathrm{trans},l} = \frac{1}{1-FER_l}\frac{PL}{B_e}. \tag{11}$$

Deferring time

Deferring time is derived from equations (5) and (9) as:

$$T_{\mathrm{def},l} = \frac{c_n}{1-c_n}(T_{\mathrm{bac},l} + T_{\mathrm{trans},l}). \tag{12}$$

Following equation (6), the estimation of service time, based on the Average Contention Window and Channel Utilisation, is:

$$\begin{aligned} T_{\mathrm{ser},l} &= T_{\mathrm{bac},l} + T_{\mathrm{def},l} + T_{\mathrm{trans},l} \\ &= T_{\mathrm{bac},l} + \frac{c_n}{1-c_n}(T_{\mathrm{bac},l} + T_{\mathrm{trans},l}) + T_{\mathrm{trans},l} \\ &= \frac{T_{\mathrm{bac},l} + T_{\mathrm{trans},l}}{1-c_n} \\ &= \frac{\left(\overline{CW_l} - \frac{CW_0}{2}\right)T_{\mathrm{slot}} + \frac{1}{1-FER_l}\frac{PL}{B_e}}{1-c_n} \end{aligned} \tag{13}$$

with $\overline{CW_l}$ being estimated from FER_l by using equation (9).

2.2.2 *Routing metric: C2WB*

According to the analysis in Section 2.1, we decide to use the service time as the link weight in our routing metric. There are two possible ways to convert the link weight into a path metric – one can sum up the per-link metrics of the path, while the other can take the maximum of the inverse of the per-link metrics of the path. The former approximates end-to-end delay of a packet while summing the per-link service time, and the latter tries to approximate the available bandwidth of the bottleneck link on the path. From our point of view, the former approach is better than the latter for two reasons. First, the longer the path which a packet traverses, the more radio resources are consumed, and hence the length of paths should be considered in the routing metric. Second, the isotonicity and monotonicity are important properties that have to be considered when designing a routing metric for multi-hop wireless networks, as emphasised in the research of Yang and Wang (2008). Basically, the isotonicity states that the order relation between the weights of any two paths is preserved if both of them have been added with a common third path. The monotonicity states that the weight of a path does not decrease when another path is added to it. In this sense, the isotonic property cannot be achieved with the latter approach.

The idea of taking the service time as the link weight is also encouraged by the study of Selfish Routing in the research of Roughgarden and Tardos (2002). In selfish-routing networks, each network user routes its traffic on the minimum-latency path available to it, given the network congestion caused by other users. The authors claim that if the latency of each link is a linear function of its congestion, then the total latency of the routes chosen by selfish network users is at most 4/3 times the minimum possible total latency. In the more general case, when the edge latency functions are assumed only to be continuous and non-decreasing in the edge congestion, the achieved total latency with selfish routing is no more than twice the minimum possible total latency.

We propose the C2WB routing metric which takes into account the frame service time of each link l on a path p. Node n is the sending node when considering link l.

$$\begin{aligned} C2WB &= \sum_{l \in p} T_{\text{ser},l} \\ &= \sum_{l \in p, n \in p} \frac{1}{1-c_n}\left[\left(\overline{CW_l} - \frac{CW_0}{2}\right) T_{\text{slot}} \right. \\ &\quad \left. + \frac{1}{1-FER_l}\frac{PL}{B_e}\right]. \end{aligned} \tag{14}$$

The methods to estimate $\overline{CW}$, c_n and FER_l are presented in Section 2.3. PL is the frame payload size. In our implementation, the value of PL is set to 1500 bytes.

It is well-known that a load-dependent routing metric, like C2WB, makes oscillations to the chosen routes, which is mentioned by Wang and Ito (2005). One of the reasons behind these oscillations is that the routing metric takes into account the intra-flow interference which is made by the traffic of the same flow but travelling on different links of the route. When a routing metric considers intra-flow interference, the more traffic is sent on a route, the more costly the route will be. To eliminate the side-effect of intra-flow interference to the stability of the network, we introduce some slight modifications in the IEEE 802.11 MAC-layer. With these modifications, the channel utilisation at a node n only accounts for the traffic which does not travel through node n. This means that the link weight in the C2WB is computed as an estimation of service time, without considering the traffic induced by flows that go through that link. The modifications are presented in detail in Section 2.3.3.

2.3 Implementation details

In this section, we describe the Optimised Link State Routing (OLSR) protocol (Jacquet et al., 2001) on which we implemented C2WB, and other implementation issues of C2WB routing metric, such as channel utilisation measurement, data rate and Contention Window estimations.

2.3.1 Operation of OLSR

The OLSR protocol is a proactive ad hoc routing protocol. Its operation is similar to the classic link state routing protocols. However, to avoid the overhead related to the advertising of the link state information, a clever flooding optimisation is used. The OLSR consists of four major elements:

- *Neighbour sensing*. Each OLSR node collects the information about its local neighbourhood by processing the received HELLO messages. Every node has to send HELLO messages periodically.
- *MPR selection*. From its neighbour set, OLSR agent chooses several nodes to act as Multi Point Relays (MPRs) that will be used to optimise flooding of route signaling packets. MPR selection is made carefully to make sure that all 2-hop nodes have a direct link with one of the MPR nodes.
- *Optimised flooding*. To decrease the overhead of advertising link state information, only MPR nodes send out the Topology Control (TC) messages. The TC messages that MPRs send only contain the links to their MPR selectors, so as to decrease packet size. This scheme reduces signaling overhead while still guaranteeing that there exists at least one route between each pair of nodes that are connected in the topology graph.
- *Route selection*. Routes are computed using link state information to find the shortest path between nodes in number of hops. The algorithm used is similar to the Dijkstra algorithm.

2.3.2 Data rate estimation

It is not easy to estimate the data rate of a multi-rate wireless link because of the diversities in wireless environments. In our implementation, a node estimates the data rate of wireless links based on the Signal to Noise Ratio (SNR) of the HELLO messages received from its neighbours. By investigating a simple scenario in which two nodes are moving far away from each other, and measuring the data rate of the link between them, we can determine the thresholds of SNR at which the data rate is changed. We are aware of the inaccuracy of this method in real-world experiments since the data rate is not always determined by SNR, and the value of SNR significantly varies even when the transmission distance is fixed. However, it is quite accurate in the simulation environment, and its simple nature is a definite advantage.

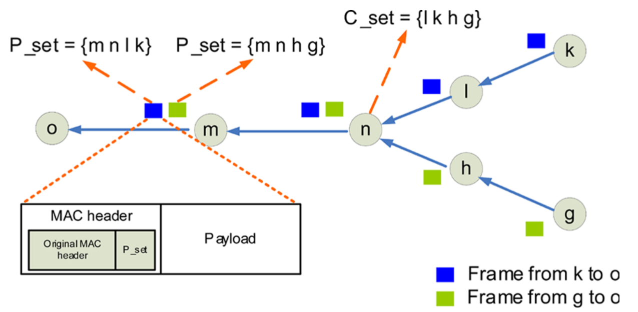
2.3.3 *Channel utilisation measurement*

A critical component of our routing metric is channel utilisation. To measure channel utilisation, a node periodically senses the media to determine whether it is idle or busy. There are two counters, one for busy sensing times and the other for total sensing times. The sensing interval is set to 1 ms in our implementation. We choose 1 ms as the value for sensing interval because it is more or less equivalent to the transmission time of a packet, with size equal to 1500 bytes, over a link whose data rate is 11 Mbps. After a certain time interval (2 s in our implementation), channel utilisation is computed by dividing the busy sensing times to the total sensing times. The value of 2 s is long enough for an accurate estimation of channel utilisation, but not too long for a quick response to congestion.

We try to eliminate the intra-flow interference which is harmful to the routing stability of a network by introducing a small modification to the MAC-layer. The idea is to trace, in the MAC-layer, the set of nodes through which a frame has passed. To do so, we assume that each node can be identified by an Identification number (ID). The MAC address of wireless interface can be used as ID, but to reduce required space to store it, ID can be generated by using a hash function with MAC address is input. A field is added to MAC-layer overhead to record all the nodes through which the frame have travelled. We name it as $passing\_nodes\_set$, denoted as P_set. Each node also maintains another set called $child\_nodes\_set$, denoted as C_set. C_set of node n is the set of nodes from which frames are sent through n. Figure 3 shows the P_set of frames sent out by node m and C_set regarding to node n. C_set of node n shows that frames from nodes l, k, h, g to Gateway will be forwarded by node n.

Information in P_set and C_set helps a node to determine if the frame being sent on the channel belongs to one of the flows handled by this node or not. For instance, if a node sees a frame whose P_set contains its ID, the node knows that the frame has passed through it, and hence it belongs to a flow handled by itself. As a consequence, the node eliminates the time used to transmit this frame when computing channel utilisation. The C_set allows a node to know which nodes are using it as an intermediate node on their paths to the Gateway(s). A node also eliminates the time used by nodes in C_set when computing channel utilisation. Since each node has only one path to Gateway at a certain moment, this method of determination is correct until nodes change their paths to Gateway. The C_set is cleared periodically to make sure that it is up-to-date. In our implementation, we clear C_set every 5 s, which is equal to the time interval at which nodes re-compute their routing table.

Figure 3 Passing nodes set and child nodes set (see online version for colours)



A side-effect of this approach is an increase of the MAC-layer overhead. We mitigate this issue by limiting the maximum number of items in P_set. For a given node n, this value depends on the number of nodes in carrier-sense range of n which a frame has to pass through before reaching node n. According to the values of carrier sensing ranges and transmission ranges at different data rates of the IEEE 802.11b as in the study of Awerbuch et al. (2006) (please see Table 5 in Section 3), the maximum number of items in P_set is set to 3 in our implementation. This means that the P_set stores the last three nodes through which the frame travels. Algorithm 1 outlines the algorithm used for building P_set, C_set, and computing channel utilisation.

2.3.4 *Contention window estimation and the value of the C2WB routing metric*

Using the same technique as the one for ETT measurement, we can determine the Frame Error Rate (FER) of a link as:

$$FER = 1 - d_f d_r \tag{15}$$

where d_f and d_r are delivery ratios of forward and backward links, respectively. They are measured using the periodic HELLO messages of OLSR.

The Average Contention Window of a link is computed from equation (9). The values of both Contention Window and Channel Utilisation are computed by the OLSR agents by querying some information from the MAC Layer. Two main changes have been made to the routing protocol to integrate the C2WB routing metric. First, in the new protocol, we modified the source code of OLSR in NS-2 so that the TC message includes the links to all neighbours instead of only the links to MPR node as in the original version. Second, TC messages are sent by all the nodes instead of by only MPR nodes. Those changes create additional overhead as signaling packets and they should be optimised in the future to obtain a good network performance.

Algorithm 1 Computing channel utilization

```
procedure SEND(f)                ▷ sending a frame f at MAC-layer
    if my_ID ∉ P_set then
        Adding my_ID to P_set
    end if
end procedure

procedure RECEIVE(f)             ▷ receiving a frame f at MAC-layer
    if destination = my_address then        ▷ if i am the destination
        if ∃(i ∈ P_set and i ∉ C_set) then
            Adding i to C_set
        end if
    else
        if (source ∈ C_set) or (my_address ∈ P_set) then
            flow_related ← 1
        else
            flow_related ← 0
        end if
    end if
    ...
    flow_related ← 0 ▷ setting flow_related to 0 at the end of frame reception
end procedure

procedure SENSING-CHANNEL        ▷ periodly sensing channel
    if (channel is idle) or (flow_related = 1) then
        idle_counter ← idle_counter + 1
    end if
    total_counter ← total_counter + 1
end procedure

procedure UPDATING-CHANNEL-UTILIZATION
        ▷ computing channel utilization from values of idle_counter and total_counter
    channel_utilization ← 1 − idle_counter / total_counter
end procedure

procedure CLEANING-C-SET
        ▷ cleaning C_set after a period of time
    C_set ← { }
end procedure
```

3 Performance evaluation

The performance of the proposed routing metric C2WB is compared with performances of ETX and ETT by using NS-2 (The network simulator – NS-2, 2006) with the OLSR extension provided by the MAXIMUM project (MANET Simulation and Implementation at the University of Murcia, 2007) and Weverton Luis da Costa Cordeiro (OLSR extension for NS-2, 2008). The IEEE 802.11 MAC and physical parameters are modified to match the published specifications of the IEEE 802.11b Lucent ORiNOCO wireless PC Card in Proxim, ORiNOCO 11b Client PC Card Specification, data sheet (2004) (see Table 4), a commonly used wireless card. Since the Carrier Sense (CS) threshold has not been published, we assume that it is a little greater than the environment thermal noise which is usually considered to be −100 dBm. In this paper, we set CS threshold to −99 dBm. We used the free space propagation model in all of our simulations. Setting transmission power to −20 dBm may seem quite small, however, from our point of view, it is only a matter of proportions, and does not affect to the validity of results. There are some cases in which a low transmission power is used on purpose in order to decrease the interference. Moreover, the transmission ranges we obtain with the above parameters (Table 5), are close to the ranges of indoor environment, and the real-world ranges which are shown in the research of Anastasi et al. (2004).

Table 4 The parameters for ORiNOCO wireless PC card

Parameters	*Values*
Transmit frequency	2.437 GHz
Transmit power	−20 dBm
11.0 Mbps receive threshold	−82 dBm
5.5 Mbps receive threshold	−87 dBm
2.0 Mbps receive threshold	−91 dBm
1.0 Mbps receive threshold	−94 dBm
Carrier sense threshold	−99 dBm
Thermal noise	−100 dBm

Table 5 The ranges using in simulation experiments

Operating rate [Mbps]	*Maximum range* [m]
11.0	28
5.5	40
2.0	60
1.0	88
Carrier sense range	100

The OLSR parameters used in our simulation are the default values, as follows: HELLO messages are sent every 2 s, and TC messages are sent every 5 s. The NS-2 extension for multi-rate support is provided by DEI Telecommunication Group (A new 802.11 implementation for NS-2, 2008). Auto Rate Fall-back (ARF), presented by Kamerman and Monteban (1997), is used as Rate Adaptation algorithm in all simulations. The performance is evaluated in terms of average end-to-end throughput, packet delay, and packet loss. Each data point in the graphical results is computed as the average of 10 different simulations with different seed values.

In the first scenario, we show that C2WB metric can recognise network traffic load and effectively route new traffic flow around the congested area. The simulation was conducted in an area of 270 m × 270 m, and included 49 nodes (see Figure 4). For the traffic flow, TCP bulk traffic source was used, with the packet size set to 1460 bytes. Constant Bit Rate (CBR) is used for the Interference flow. The distance between rows and the distance between columns are equally set to 45 m. At the beginning of the simulation, there is a flow from node 0 to node 4 called Interference traffic. This interference traffic creates an area where traffic load or channel utilisation is higher than in other areas. What will happen if node 37 wants to send traffic data to node 25 with different routing metrics (ETX, ETT, and C2WB)? We study the behaviour of the routing metrics in the presence of interference traffic. By increasing the data rate of interference flow, we can see the effectiveness of each routing metric in routing traffic around the congested area.

Figure 4 Scenario of congested area (see online version for colours)

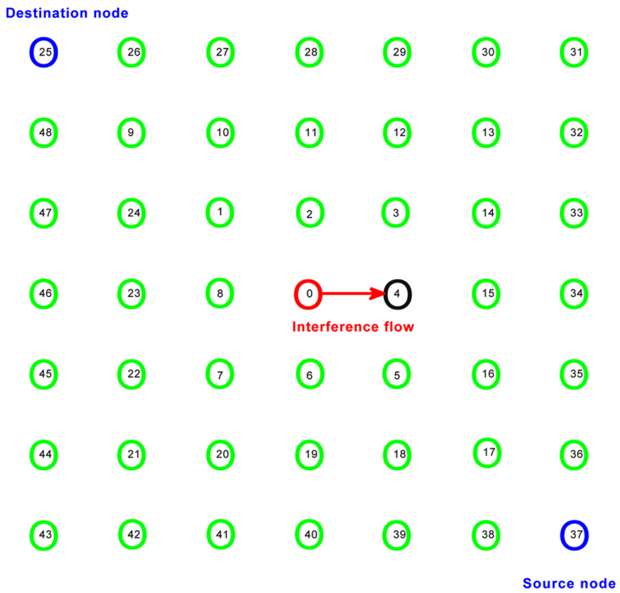
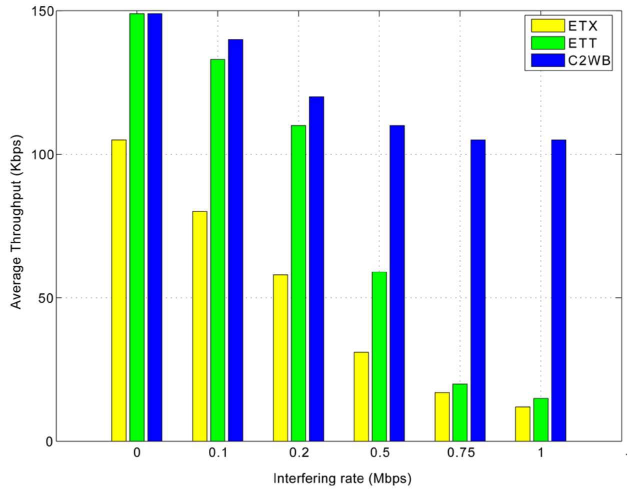


Figure 5 shows the results of the first scenario. At a low rate of the Interference flow, C2WB has the same behaviour as ETX and ETT. Since ETX does not take into account link data rate, it prefers longer hops with low data rate and leads to a lower throughput when compared with ETT and C2WB. When the data rate of the Interference flow increases, ETX and ETT are more sensitive than C2WB. Both ETX and ETT suffer from the increasing of interference traffic, which leads to the decreasing in average throughput. During the time period when C2WB completely ignores the congested area, C2WB will route traffic on a longer path around it. C2WB has the ability to detect a hot spot in the network, so that the routing protocol can route data avoiding this area. Thus the flow throughput is not affected very much by interference flow when C2WB is used. The results show that C2WB outperforms both ETX and ETT in the presence of an interference flow.

Figure 5 Sensitivity of routing metric to interfering traffic (see online version for colours)



In the second scenario, we show the performance of the C2WB metric in a general wireless mesh network. The topology consists of 225 nodes uniformly distributed in an area of 630 m × 630 m, as shown in Figure 6. There are 10 source nodes which are chosen randomly in each simulation. There are 4 fixed gateways, including nodes numbered 49, 57, 65, and 73. All the sending nodes are located to the closest gateway as destination for their own traffic. A TCP bulk traffic source was used with packet size set to 1460 bytes. We measured the traffic received at each gateway to compare the performance of different routing metrics.

Table 6 shows the average end-to-end throughput, packet delay and loss rate of the second scenario. Since ETT does not balance the traffic between nodes in the network, it creates highly congested areas in which data packets suffer from long delay and high packet loss rate. Table 6 shows that C2WB can increase average throughput by 70%, and decrease average packet loss rate by 40% compared to those values with ETT, with the cost of a slight increase in packet delay. Figures 7 and 9 show clearly the superiority of C2WB over ETX and ETT in terms of throughput and packet loss rate. In Figure 8, it seems that the average delay with C2WB is a little greater than the average delay with both ETX and ETT, however, this is due to the fact that we only plot delay of the packets that are received successfully at the Gateways. A large amount of packets is lost with both ETX and ETT (see Figure 9), and this is not taken into account when plotting CDF of packet delay. When C2WB is used, interference between flows is reduced significantly. The decrease of interference makes Standard Deviations of all the performance metrics smaller than those of ETX or ETT (see Table 6). In this scenario, ETX has a slightly lower packet loss rate comparing to ETT because ETX prefers longer hops than ETT does, hence the number of intermediate nodes is fewer than that of ETT. However, average flow throughput of ETX is still smaller than that of ETT because ETX chooses the path with long hop distances, but low operating rates.

Table 6 Routing metrics performance

	Throughput [Kbps]		*Delay* [ms]		*Loss rate* [%]	
Metric	*AVG*[a]	*STD*[b]	*AVG*[a]	*STD*[b]	*AVG*[a]	*STD*[b]
ETX	23.4	14.3	175.3	59.7	20.9	8.7
ETT	28.2	19.3	162.8	49.6	23.2	9.5
C2WB	47.6	14.1	171.1	28.6	14.0	2.7

[a]Average.
[b]Standard deviation.

Figure 6 An example scenario for the second simulation experiment (see online version for colours)

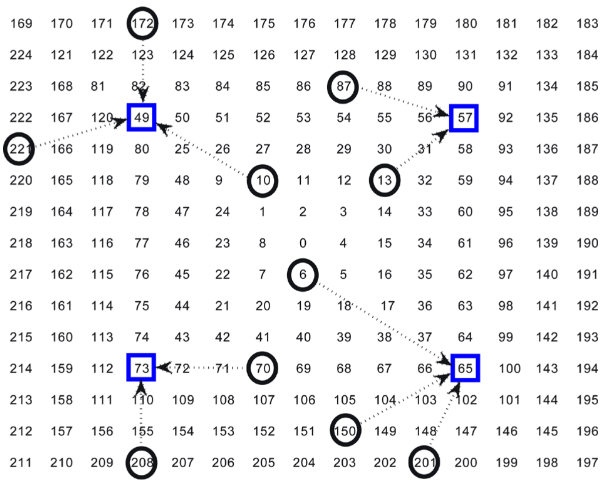
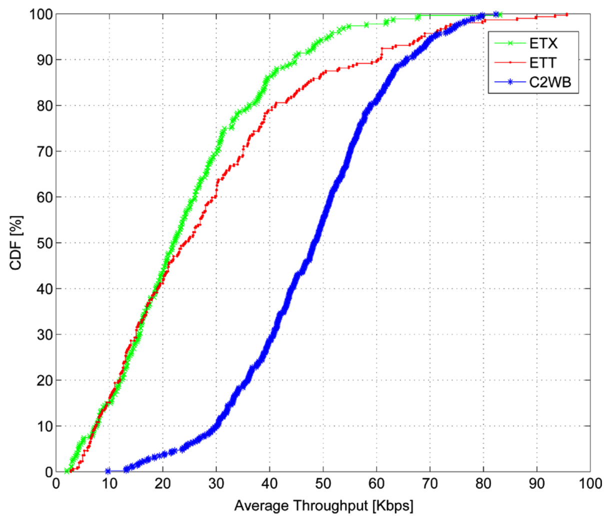


Figure 7 Distribution of throughput for the second experiment (see online version for colours)



4 Related work

Due to the existence of many parameters that affect wireless link quality, such as channel load, inter-flow/intra-flow interferences, link stability, etc., a load and interference-aware routing protocol plays an important role in WMNs. Load balancing may

Figure 8 Distribution of packet delay for the second experiment (see online version for colours)

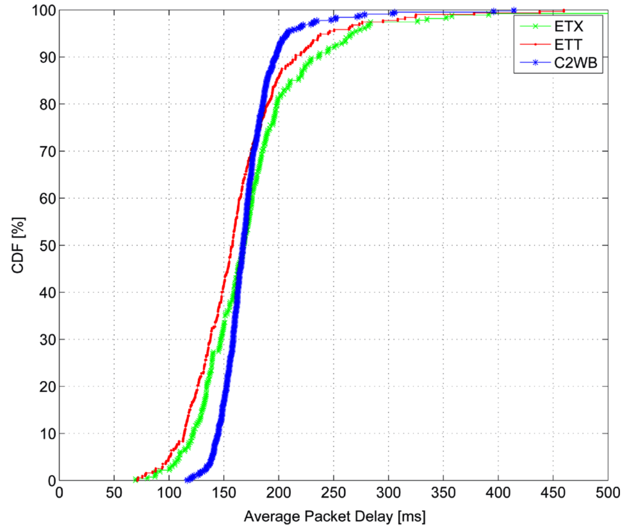
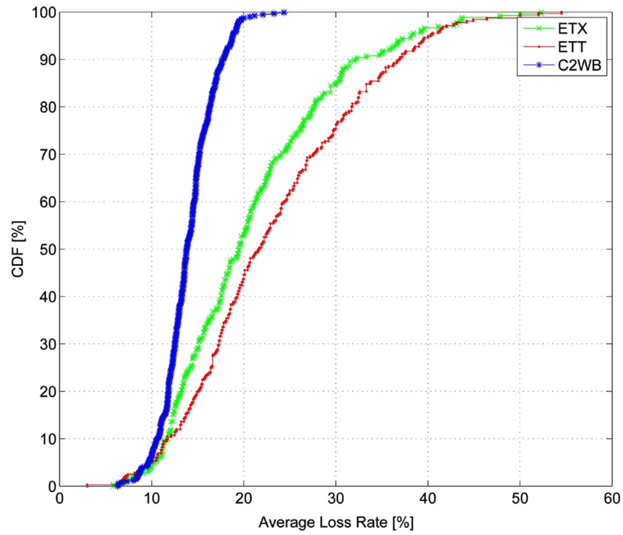


Figure 9 Distribution of packet loss rate for the second experiment (see online version for colours)



be achieved through gateway-based load balancing, path-based load balancing or router-based load balancing. Each of these approaches tries to estimate the path quality by a so-called routing metric.

Routing metrics are very critical to network performance. A good routing metric should carry enough information about the link quality so that a node can determine the best path to reach to a gateway. Recently proposed routing metrics for WMNs include hop-count (Johnson et al., 2001; Perkins and Pravin, 1994; Perkins and Royer, 1999), Expected Transmission Count (ETX) (De Couto et al., 2003), Expected Transmission Time (ETT) (Richard et al., 2004), Weighted Cumulative ETT (WCETT) (Richard et al., 2004) and Metric of Interference and Channel-switching (MIC) (Yang et al., 2005), modified ETX (mETX) (Koksal and Balakrishnan, 2006), Effective Number of Transmissions (ENT) (Koksal and Balakrishnan, 2006), and iAWARE (Subramanian et al., 2006).

4.1 Hop count

Hop-count is the most commonly used routing metric in many routing protocols for multi-hop ad hoc networks such as AODV (Perkins and Royer, 1999), DSR (Johnson et al., 2001), and DSDV (Perkins and Pravin, 1994). This metric reflects the path length in number of hops, thus in most cases the shortest path is used. However, from the hop-count metric we cannot determine the characteristics of the wireless links in the path, such as link load, transmission rate, packet loss ratio, and interferences; therefore, using hop-count metric may not lead to a good network performance.

4.2 Expected Transmission Count (ETX)

The ETX routing metric, proposed by De Couto et al. (2003), is defined as the expected number of MAC layer transmissions for successfully delivering a packet through a wireless link. ETX reflects the difficulty with which the MAC layer sends a packet to its destination. The weight of a path is defined as the summation of the ETX values of all links along the path. In this way, ETX considers both path length and packet loss ratio. However, ETX fails to capture the link transmission rate or the interference from other links.

4.3 Expected Transmission Time (ETT)

The ETT routing metric, put forward by Richard et al. (2004), is an improvement on ETX made by considering the differences in link transmission rates. ETT is defined as the amount of time which is needed to transmit a packet through the link. The weight of a path is the summation of the ETT values of all links on this path. Despite the improvement with respect to ETX, ETT still fails to capture the interferences among different links.

4.4 Weighted Cumulative Expected Transmission Time (WCETT)

The WCETT routing metric, proposed by Richard et al. (2004), introduces an enhancement to ETT by taking into account the intra-flow interference. The WCETT tries to reduce the number of nodes, along the path, that transmits on the same channel. It captures the intra-flow interference of a path since it gives low weights to the paths that have more diversified channel assignments on their links which is equivalent to having lower intra-flow interference. Although WCETT can capture the intra-flow interference, it fails to consider explicitly the effects of inter-flow interference. Hence, WCETT may route traffic to congested areas.

4.5 Metric of Interference and Channel Switching (MIC)

The *MIC* (Yang et al., 2005) routing metric improves the WCETT by capturing both intra-flow and inter-flow interference as presented in the research of Yang et al. (2005). It introduces *IRU* (Interference-aware Resource Usage) for inter-flow interference and *CSC* (Channel Switching Cost) for intra-flow interference. The ETT and the number of neighbour nodes are used to compute the IRU. CSC takes into account the intra-flow interference by comparing the current link and the previous link. If the current link uses the same channel as the previous link then the CSC of the current link will be assigned a higher value. IRU does not consider the real traffic load from other links, but just the number of neighbours. In this way, IRU does not reflect the real interference to the considered link.

4.6 Modified ETX (mETX) and Effective Number of Transmissions (ENT)

One critical problem of wireless networks is fast changes in wireless link quality. Metrics based on an average value which is computed on a time-window interval, such as ETX, cannot follow this variation. To deal with this issue, modified ETX (Koksal and Balakrishnan, 2006) and ENT were proposed (Koksal and Balakrishnan, 2006). The difference between mETX and ETX is that ETX considers probe packet losses, while mETX considers losses at bit level. The ENT metric, presented by Koksal and Balakrishnan (2006), was proposed as an alternative approach. ENT measures the number of successive retransmissions per link considering the variance. ENT computation is based on probe packets. It limits routing computation from the links that have number of retransmissions more than an acceptable threshold, according to the higher layer requirements, by assigning to their link cost an infinite value.

4.7 iAWARE

iAWARE, proposed by Subramanian et al. (2006), is another metric which is derived from ETT that also considers link-quality variation. This metric uses Signal to Noise Ratio (SNR) and Signal to Interference and Noise Ratio (SINR) to incorporate interference into the routing metric. The higher the interference, the higher the value of iAWARE is. By doing so, iAWARE considers intra-flow interference, inter-flow interference and medium instability. However, there are several disadvantages of iAWARE. Firstly, the non-isotonicity of iAWARE makes it harmful to routing protocols, as mentioned in the research of Yang and Wang (2008). Secondly, while iAWARE can be an indicator of link quality, it is not justified as a routing metric because of the non-additivity when both SNR and SINR are incorporated into the metric.

4.8 Load balancing

The above routing metrics do not consider load balancing. Load balancing can be achieved by using multi-path routing protocols. In multi-path routing protocols, each node maintains multiple paths from itself to a set of GWs. Based on the routing metric used, the node chooses one path, called best path to route its traffic. If the current best path is congested, the node can switch to one of the remaining paths. There are some multi-path routing protocols for ad-hoc networks such as those in the research of Nasipuri and Das (1999), and Marina and Das (2001). In such protocols, the paths are established by selecting maximal disjoint paths.

5 Conclusion

In this paper, we address the problem of selecting efficient paths in WMNs. We developed Channel Utilisation and Contention Window Based metric (C2WB), a routing metric for load balancing in WMNs. C2WB metric is proportional to the service time of a given link, which is estimated from both channel utilisation and the average Contention Window of the CSMA/CA mechanism of IEEE 802.11. In this sense, C2WB selects the paths that have the smallest effective delay, and hence have the highest effective capacity.

The basic features of the proposed scheme were described and compared with well-known existing similar schemes. Quantitative evaluation has been carried out using the NS-2 simulation tool. The simulations show that C2WB can increase average throughput by 70% and decrease average packet loss rate by 40% compared with ETT, with smaller jitter. The improvements are even greater when compared to ETX. Based on these results, we have unambiguously demonstrated that the proposed routing metric is superior in performance to ETX and ETT. The present work also opens up several future investigation directions, such as extensions of the proposed scheme for load balancing in multi-radio and multi-channel networks.

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