# A Novel Routing Algorithm Based on Load Balancing for Multi-Channel Wireless Mesh Networks

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## Abstract

In this paper, we study a novel routing algorithm based on load balancing for multi-channel wireless mesh networks. In order to increase the network capacity and reduce the interference of transmission streams and the communication delay, on the basis of weighted cumulative expected transmission time (WCETT) routing metric this paper proposes an improved routing metric based on load balancing and channel interference (LBI_WCETT), which considers the channel interference, channel diversity, link load and the latency brought by channel switching. Meanwhile, in order to utilize the multi-channel strategy efficiently in wireless mesh networks, a new channel allocation algorithm is proposed. This channel allocation algorithm utilizes the conflict graph model and considers the initial link load estimation and the potential interference of the link to assign a channel for each link in the wireless mesh network. It also utilizes the channel utilization percentage of the virtual link in its interference range as the channel selection standard. Simulation results show that the LBI_WCETT routing metric can help increase the network capacity effectively, reduce the average end to end delay, and improve the network performance.

***Keywords:*** Wireless mesh networks (WMN), channel interference, channel switching delay, channel allocation, multi-channel routing

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## 1. Introduction

Wireless mesh network (WMN) is a wireless network which has multi-hop, self-organizing and self-healing characteristics [1]. As wireless mesh networks have the characteristics of high reliability, scalability and low investment cost, they have become the key technology for solving the "last mile" bottleneck problem.A Wireless mesh network consists of mesh nodes and mesh routers. The mesh routers form the mesh wireless backbone net which provides multi-hop connection to mesh terminals through interaction with cable networks. Wireless mesh networks are different from traditional wireless networks, they are not only compatible with the existing wireless networks but also support multiple types of network access approaches. WMNs represents the next generation development direction of networks [2].

The multi-radio multi-channel wireless mesh network can enhance the capacity, scalability, and robustness of the network, but will increase the complexity of the system. The major problems in multi-radio multi-channel wireless mesh networks are the channel allocation strategy and routing protocol [3-5]. (1) Although two nodes are located within the transmission range of each other, they cannot communicate with each other if they share no common channel. This implies that the channel assignment strategy indeed determines the network topology. Meanwhile, routing selections are based on this type of given network topology, so the channels distributed in the wireless mesh networks have an effect on the routing algorithm. (2) the routing algorithm aims at selecting the best path for a source node according to the routing metric. Along the route, the traffic carried on every link, which adopts specific channel to connect, may change as time goes by. Meanwhile, the quality of some links may fluctuate over time due to the variable environmental conditions of the wireless system. To achieve better performance, it is imperative to adjust channel distribution in the network according to the traffic load variation. Thus the channel allocation strategy and routing algorithm should be considered jointly. However, most of the related works focused on channel allocation and routing separately.

Literature [6] proposes a load aware channel assignment for multi-interface wireless mesh networks, which has considered the link interference and channel load factors. However, algorithms proposed in the paper, only consider the link interference or node interference as the basis of channel allocation, the link load situation during the channel allocation process is not considered. For channel allocation algorithms, literature [7] proposes a novel distributed channel assignment algorithm CBLA (Cluster-Based Load-Aware), which takes advantage of both static and dynamic channel assignment approaches. CBLA uses clustering to reduce the complexity of the channel assignment problem, and estimates the traffic load by low-overhead statistical information of local packets. Adaptive dynamic channel allocation results in a better link load equilibrium. It also introduces a new routing metric, which combines hop count, channel diversity and cluster information together. Literature [8] proposes a new multi-channel allocation strategy based on the interference model. This strategy first stratifies the wireless mesh network and then allocates channels according to the priority of layers. By alleviating channel interference of the network, it promotes the throughput of each node, in the wireless mesh network and thus to increase the whole network throughput. For multi-channel routing algorithms, literature [9] proposes a routing metric called "weighted cumulative expected Transmission time" (WCETT) on the basis of expected Transmission time (ETT) that takes account of the expected packet transmission time and channel diversity along the path. Nevertheless, the WCETT does not consider the load on every channel and cannot

achieve load balance among different channels. Literature [10] proposes a routing metric called weighted cumulative expected transmission time with load balancing (WCETT-LB) for wireless mesh networks. WCETT-LB enhances the basic WCETT by incorporating load balancing into the routing metric. WCETT-LB provides a congestion aware routing and traffic splitting mechanism to achieve global load balancing in the network.

There are mainly three problems in multi-channel routing algorithms in current research,

(1) Channel interference. Multi-channel routing in wireless mesh networks is very challenging due to interference among different transmissions. If there is interference between two transmissions which interfere with each other and are using the same channel, then they cannot transmit data packets at the same time.

(2) Channel switching delay. If the working frequency of the transceiver changes 10MHz, it will bring 10ms delay. If there are a lot of traffic in the network, the impact of routing performance generated by channel switching can not be ignored.

(3) Load balancing. In the process of the operation of actual networks and the network simulation, when the network traffic flow reaches a certain level, the network performance will decline noticeably, and the packet transmission delay and the packet loss ratio will increase. Thus it is necessary to implement effective load balancing in a routing protocol.

Based on the above analysis, this paper proposes a novel routing algorithm based on load balancing for multi-channel wireless mesh networks. The algorithm is divided into into two stages. The first stage is channel allocation. In order to solve the interference problem in the network, the algorithm builds a conflict graph according to the network topology. Meanwhile it uses the link load estimation model to calculate the initial traffic load of each link, and calculates the potential interference link set for each link in the wireless mesh network. Then according to the initial traffic load and the potential interference link set, it calculates a weight value for each node in the conflict graph. After that according to the weight value of the nodes in decreasing order, a channel is assigned for each node in the conflict graph. The second stage is routing. First, we divide the channel interference into intra-flow interference and extra-flow interference which can help reduce the interference in the network effectively. Second, a concept called channel switching delay is taken into account..And also considered the effect generated by channel switching on the transmission of the other links. Thus the calculation of the data transmission delay of a node pair, involves the transmission delay of the forwarding node and the channel switching delay. Third, we will also consider the actual link load. At last we propose an improved routing metric LBI_WCETT based on the WCETT routing metric, which considers the channel interference, channel diversity, link load and the delay brought by channel switching.

The rest of the paper is organized as follows. Section 2 discusses the related work. Section 3 gives the network model of the wireless mesh network. Section 4 describes the channel allocation algorithm. Section 5 describes a new routing metric for the routing algorithm based on load balancing. Section 6 presents the simulation results. Section 7 gives the conclusion of our work.

## 2. Related Work

In this section we review some of the important existing methods that describe multi-channel routing algorithms. In [11], the authors propose and evaluate one of the first IEEE 802.11 based multi-channel multi-hop wireless mesh network architectures. They

develop a set of centralized algorithms for channel assignment, bandwidth allocation, and routing. They also present a distributed algorithm utilizing only local traffic load information to dynamically assign channels and to route packets in a later paper [12].In [9] Draves et al. present a new metric named Expected Transmission Time/Weighted Cumulative ETT(ETT/WCETT), for multi-radio, multi-hop wireless networks which can be used for finding a high-throughput path between the source and destination. They also present a Multi-Radio Link-Quality Source Routing (MR-LQSR) protocol by incorporating this metric. A mathematically formulated joint channel assignment and routing algorithm is proposed in [13], which has taken into account the interference constraints, the number of channels in the network and the number of radios available at each mesh router. A link layer protocol to manage multiple channels is proposed in [14], which can be implemented over existing IEEE 802.11 hardware. And it also proposes a routing protocol that operates over the link layer for multi-channel, multi-interface ad hoc wireless networks. A quality of service (QoS) routing protocol based on interference-aware topology control is proposed in [15]. It presents a novel definition of co-channel interference, and based on this concept, also presents an effective heuristic for the minimum Interference Survivable Topology Control (INSTC) problem which seeks a channel assignment for the given network such that the induced network topology is interference-minimum among all K-connected topologies. A distributed channel allocation algorithm based on the traffic-aware joint routing algorithm is proposed in [16], which allocates the channels according to the established tree topology routing algorithm. Algorithms presented above uses the tree topology, in order to maintain the tree topology,each node will produce a large amount of control information, and then will generate a lot of network overhead. A protocol of joint channel allocation and cross-layer routing is proposed in [17], which introduces a novel concept called channel utilization percentage (CUP). Then a metric parameter named channel selection metric is designed, which actually reflects not only the channel status but also the capacity of corresponding node to seize it. But the computation of the channel utilization is so complicated that it is not suitable for a network with complex structure.

## 3. Network Model

### 3.1 Network Model

A wireless mesh network can be represented by an undirected connection graph $G=(V, E)$, where $V$ is the node set of the wireless mesh network, $E$ is the collection of links connecting two nodes. If two nodes are in each other's coverage range, then there will be an edge between the two nodes in graph $G$. This indicates that they can transmit data to each other directly. Typically, different connection graphs correspond to different network topologies. The orthogonal channel set in the network is $CH=\{1, 2, 3,\ldots, K\}$, where $K$ is the total number of the available channels in graph $G$. The available channel set of node $v_i$ is $CH(v_i)$, and $CH(v_i) \in \{1,2,3...K\}$, which is used to indicate the available channel set of node $v_i$. $N=|V|$ is the total number of nodes in the wireless mesh network. $I(v_i)$ is the number interfaces of node $v_i$, and this paper assumes that there are two interfaces for each node in the network.The node set $CN$ is used to record the nodes in the conflict graph which have been assigned channel successfully, and we will put the node $l_{ij}$ into the node set $CN$.

Suppose that the nodes in the wireless mesh network distribute in a plane and each mesh router is configured with a full end to the antenna RF. Also, suppose that each radio terminal has a coverage range $R$ and an interference range $R'$. If a receiving node is in the coverage

range of other two nodes, then the transmission between the two nodes may produce interference. Generally, we let $R'=2R$.

### 3.2 Network Conflict Model and Related Definition

Due to the nature of the wireless medium, the transmission process will be affected by the multi-access interference severely. Two interfering links cannot engage in successful transmission at the same time if they transmit on the same channel. Thus we can take advantage of the conflict graph [18] to model such interference. A conflict graph for a mesh network is defined as follows. Consider a graph $G(E, V)$, with nodes corresponding to routers in the mesh and edges between the nodes corresponding to the wireless links. In a conflict graph $G_c(E_c, V_c)$, for each edge $e_{ij} \in E$ in a connection graph $G$, there is a corresponding node $l_{ij} \in V_c$ in a conflict graph $G_c$. There is an edge $e_{lmnlij}$ between $l_{mn}$ and $l_{ij}$ in the conflict graph if and only if $e_{mn}$ and $e_{ij} \in E$ interfere with each other. As an example of a conflict graph, **Fig. 1** shows the topology of a wireless mesh network with six nodes. **Fig. 2** shows the corresponding conflict graph. The interference model used here is the protocol interference model, where the interference region is within the scope of the two-hop nodes. The relationship between the connection graph $G$ and the conflict graph $G_c$ is shown as **Fig. 1** and **Fig. 2**.

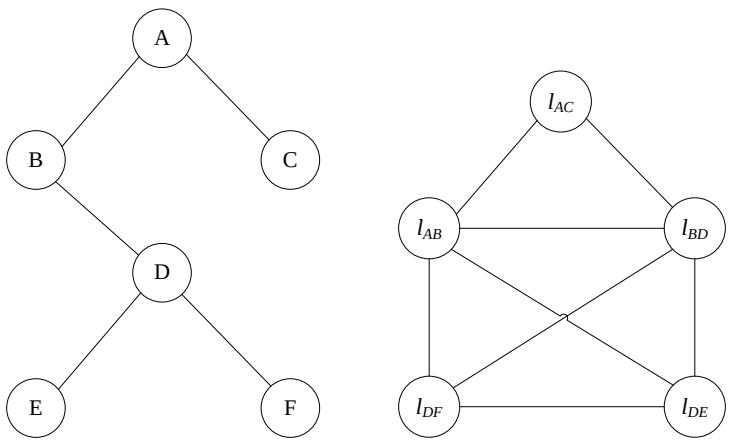


**Fig. 1.** Topology of a wireless mesh network **Fig. 2.** Corresponding conflict graph

According to the above assumptions, some related definitions are given as follows,

***Definition 1***. Interference degree of node $l_{ij}$ in the conflict graph, $|I(l_{ij})|$. According to the protocol interference model [19], $I(l_{ij})$ is used to represent the potential link interference set of the node $l_{ij}$ in the conflict graph. So the interference degree $|I(l_{ij})|$ is the number of potential interference links of node $l_{ij}$, namely the number of neighbor nodes of a node in the conflict graph $G_c$.

***Definition 2***. Matrix $A=\{a_{ik}\}$, $N\times K$ matrix, $i=0, 1,\ldots, N-1$ and $k=0, 1,\ldots, K-1$. It is used to indicate the situation of the channel assignment for node $v_i$. If channel $k$ is assigned to node $v_i$ by the channel allocation algorithm, then let $a_{ik}=1$, else $a_{ik}=0$. Matrix $A$ is used to calculate the utilization situation of channel $k$ in the interference link set of link $e$.

***Definition 3***. channel utilization percentage, $O(v_c, k)$. It is used to indicate the channel utilization percentage of channel $k$ in the interference node set of link $v_c$. The calculation of $O(v_c, k)$ is as follows:

$$O(l_{ij},k)=\sum_{e_{mn}\in I(l_{ij})}\frac{a_{mk}\times a_{nk}}{|I(l_{ij})|+1} \tag{1}$$

When assigning a channel to a node $l_{ij}$ in the conflict graph, we will calculate the available channel set of node $l_{ij}$ first, then calculate the channel utilization percentage of the channels in the available channel sets of the interference links of node $l_{ij}$. At last, the channel with the lowest channel utilization percentage will be assigned to node $l_{ij}$.

***Definition 4***. Matrix $F=\{f_{ij}\}$, $N\times N$ matrix, $i, j=0,1,\ldots,N-1$. It is used to record the channel which is assigned to node $l_{ij}$ in the conflict graph during the channel allocation process. If channel $k$ is assigned to node $l_{ij}$, then let $f_{ij}=k$.

## 4. Channel Allocation Algorithm

### 4.1 Calculation of Weight Value *w*

In the channel allocation algorithm, a channel will be assigned to each node in the conflict graph according to the link interference and the link load. A weight value will be given to each node in the conflict graph first. Then calculate the weight value $w_l$,as follows:

$$w_l=a\cdot\frac{|I(l)|}{|E_c|}+b\cdot\phi_l \tag{2}$$

where $|E_c|$ is the total number of the edges in the conflict graph $G_c(E_c, V_c)$. We know that node $l_{ij}$ in the conflict graph corresponding to the link $e_{ij}$ in the connection graph, so $\phi_l=\phi_e$. $a,b$ are the factors of potential link interference and link load respectively, and $0\le a,b\le 1$, $a+b=1$. In order to adjust the proporation of link interference and link load while calculating the weight value for each vertice in the conflict graph, we can adjust the value of $a$ and $b$. If the value of $a$ is bigger, then we will tend to consider the link interference more. If the value of $b$ is larger, then we tend to consider the link load more. In this paper, the channel allocation algorithm not only considers the link interference but also the link load, so we set $a=0.5, b=0.5$ in the simulation experiments. The larger the weight value of the node, the more serious the link interference, the greater the link load, and the link will become the bottleneck of the network more easily. Thus the node with the largest weight value in the conflict graph will be assigned a channel first by during the channel allocation algorithm.

We use the expected link load estimation model to calculate the initial link load, which is proposed in [4]. The calculation of the initial link load, $\phi(l)$ is as follows:

$$\phi(l)=\sum_{s,d}\frac{|P_l(s,d)|}{|P(s,d)|}\times L(s,d) \tag{3}$$

where $L(s, d)$ is the estimated load between the node pair $(s, d)$ in the traffic model. $|P(s, d)|$ is the number of acceptable paths between the pair of nodes $(s, d)$, and $|P_l(s, d)|$ is the number of acceptable paths between $(s, d)$ that pass the node $l$ in the conflict graph.

This Formula (3) says that the initial expected load on a link is the sum of loads from all acceptable paths, across all possible node pairs, that pass through the link. Because of the assumption of uniform multi-path routing, the load that an acceptable path between a node pair is expected to carry is the expected load between the node pair divided by the total number of acceptable paths between them. Although the results of this approach are not 100% accurate, it provides a good starting point to kick off the iterative refinement process.

### 4.2 Channel Allocation Algorithm

Suppose that there are two interfaces for each node in the wireless mesh network to communication with each other. The maximum available channel set of each node is *CH={1, 2, 3}*. The purpose of the channel allocation algorithm is to assign a channel *k* which has a minimum interference and load balancing to each link *e* in the wireless mesh network.

Step1 Build the conflict graph $G_c(E_c, V_c)$ according to the connection graph $G(E, V)$, shown in Fig. 1. Let $CN=\{\}$.

Step2 According to the Formula (3), a weight value is be given to each node in the conflict graph $G_c(E_c, V_c)$.

Step 3 According to the weight value of the node in decreasing order, assign a channel to each node in the conflict graph.

(1) There are 3 possible cases during assigning channel to each node in the conflict graph:

a) If the number of channels assigned to the nodes of both ends of the link is less than $I(v_i)$, then we calculate the available channel set of the link. And according to the Formula (1) to calculate the channel utilization percentage of the channel in the available channel set within the interference links of the link. At last, the channel with the lowest channel utilization percentage will be assigned to the link.

b) If one node of both ends of the link which the number of channels assigned to the node is equal to $I(v_i)$, then we will assign a channel with the lowest channel utilization percentage from the node's available channel set to the link.

c) If two nodes of both ends of the link which the number of channels assigned to the node are equal to $I(v_i)$, then comparing the available channel sets of the two nodes. If there are common channels shared by the two nodes, we will pick the common channel with the lowest channel utilization percentage and assign it to the link. Otherwise, we will pick a channel from one node and a channel from the other node, merge them into one channel, and assign this merged channel to the link.

If a channel *k* has been assigned to a node $l_{ij}$ in the conflict graph successfully, then modify the corresponding values in the matrix *A*, let $a_{ik}=1$, $a_{jk}=1$, also matrix *F*, let $f_{ij}=k$, and put the node into the set *CN*, let $CN=\{l_{ij}\}$.

(2) Modify the conflict graph $G_c(E_c, V_c)$. If a channel *k* has been assigned to a node $l_{ij}$ in the conflict graph successfully, then compare the node $l_{ij}$ with the current node set *CN*. If there is an edge between node $l_{ij}$ and a node $l_{mn}$ which is in the node set *CN*, compare the channels assigned to the two nodes. If $f_{ij}=f_{mn}$, then keep the conflict graph unchanged, else delete the edge from the conflict graph. Because the two potential interference links have been assigned different channel, the interference between the two links has disappeared.

Step4 If the node set *CN* is equal to the set $V_c$, then end the channel allocation algorithm.

As an example, a weight value is given to each node in the conflict graph $G_c(E_c, V_c)$. Suppose that after weight values in the conflict graph have been given as shown in Fig. 3.

According to the weight value of the node, we will assign a channel to node $l_{BD}$ in the conflict graph first. The channel allocation process is as follows,

Suppose that $CH(v_B)=\{2, 3\}$ and $CH(v_D)=\{1, 2, 3\}$.

Calculate $CH(l_{BD})=\{2, 3\}$.

Calculate the channel utilization percentage of cannel 2 and channel 3 within the interference range of node $l_{BD}$, since node $l_{BD}$ is the first to be assigned, so

$O(l_{BD}, 2)=0$,

$O(l_{BD}, 3)=0$.

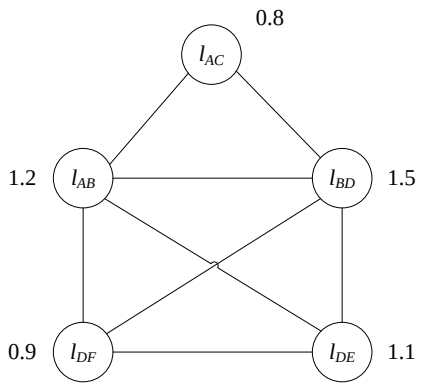


**Fig. 3.** Conflict graph after assigned weight value

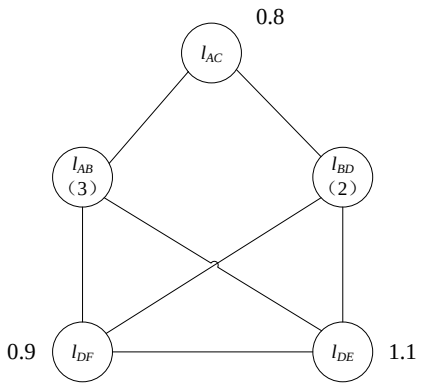


**Fig. 4.** Conflict graph after channel allocation for the first node

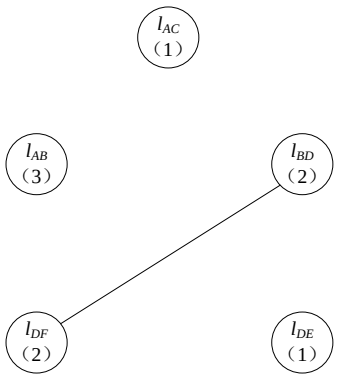


**Fig. 5.** Conflict graph after channel allocation

Since the channel utilization percentage of channel 2 and channel 3 is 0, so channel 2 or channel 3 will be assigned to $l_{BD}$ randomly. Suppose that channel 2 is assigned to the node $l_{BD}$, then modify matrix A, let $a_{B2}=1$, $a_{D2}=1$. Modify matrix $F$, let $f_{BD}=2$. Then put the node $l_{BD}$ into the set $CN$, $CN=\{ l_{BD} \}$.

Next, we will assign channel to node $l_{AB}$, and the channel allocation process is as follows,

Suppose that $CH(v_A)=\{1, 2, 3\}$, $CH(v_B)=\{2, 3\}$.

Calculate $CH(l_{AB})=\{2, 3\}$.

Calculate the channel utilization percentage of cannel 2 and channel 3 within the interference range of link $e_{BD}$:

$O(l_{AB}, 2)=0.2$,

$O(l_{AB}, 3)=0$.

Thus channel 3 will be assigned to node $l_{AB.}$ Modify matrix A, let $a_{A3}=1$, $a_{B3}=1$. And modify matrix $F$, let $f_{AB}=3$. Then put the node $l_{AB}$ into the set $CN$, let $CN=\{l_{BD}, l_{AB}\}$. If $e_{lBDlAB}=1$, then compare the value of $f_{AB}$ and $f_{BD}$. If $f_{BD} \neq f_{AB}$, then delete the edge from the conflict graph. The conflict graph changes from **Fig. 3** to **Fig. 4**.

We use the same method to assign a channel to each node in the conflict graph according to the weight value of the node in decreasing order until the channel allocation is over, as shown in **Fig. 5**.

# 5. Multi-channel Routing Algorithm

## 5.1 Multi-channel routing metric

(1) WCETT routing metric

WCETT (Weighted Cumulative Expected Transmission Time) routing metric [14] is specifically for wireless mesh network. It not only considers the link quality, but also considers the link bandwidth. A new parameter ETT (Expected Transmission Time) is defined as follows:

$$ETT = ETX \cdot \frac{S}{B} \tag{4}$$

$$ETX = \frac{1}{d_f \times d_r} \tag{5}$$

where $S$ indicates the packet size, and $B$ indicates the link bandwidth. ETX (Expected Transmission Count) is a routing metric based on the link quality. It is the estimated times of transmitting a packet successfully on the link. $d_f$ is the probability of transmitting a packet to the receiving end successfully. $d_r$ is the probability of receiving the ACK packet successfully. Thus the estimated time of transmitting a packet successfully is ETX multiplied by the time of transmitting the packet.

$$WCETT = (1-\beta) \cdot \sum_{i=1}^{n} ETT_i + \beta \cdot \max_{1 \le j \le k} X_j \tag{6}$$

WCETT routing metric considers the bandwidth, packet loss rate and channel diversity through the weight assignment. The first parameter of WCETT is the ETT sum of all the links on the path. The other parameter is the estimated time that a packet takes along the path, and it can be regarded as the point-to-point delay time of the packet on the path. $X_j$ is the sum of the ETT of all the links on channel $j$. Suppose that there are $K$ channels on a *n-hop* path in the wireless network, $X_j$ can be defined as follows,

$$X_j = \sum_{hopionchanelj} ETT_i, 1 \le j \le K \tag{7}$$

Since the WCETT routing metric considers the channel diversity on the path, so it can improve the network throughput in a certain extent. However, each node on the path calculates the value of link ETT, different values of link ETT,are just accumulated simply, without considering the situation of channel distribution on the path. Thus, it cannot reflect the internal channel interference of the path accurately. And WCETT metric do not consider the load on the path, so it does not have the load-balancing function.

(2) multi-channel routing metric based on the load balancing

a) channel interference

There are two kinds of data stream interference in wireless mesh networks [15], inter-stream interference which is the interference generated by the external flow and intra-stream interference which is the interference generated by the internal flow, as shown in **Fig. 6**. According to the protocol interference model, $e_{BC,}$, $e_{CD}$, and $e_{AB}$ are intra-stream interferences on Path 1. $e_{FG}$ ,$e_{EF}$, and $e_{GH}$ are intra-stream interferences on Path 2. $e_{BC}$ and $e_{FG}$ are inter-stream interferences. If interference exists between different links in the network, they cannot transmit data stream at the same time. In order to eliminate these two interferences, the channel allocation algorithm must assign different channels to the links with mutual interference.

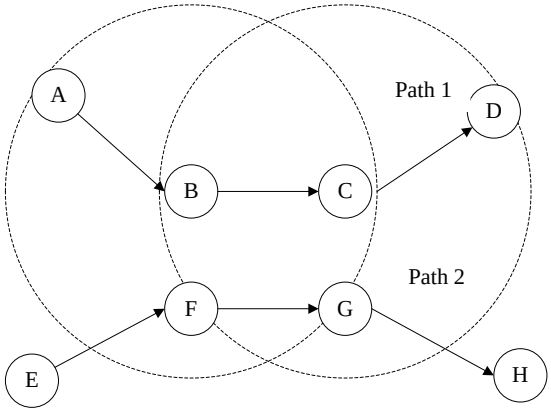


**Fig. 6.** Data stream interference model

Links will generate interference only when the same channel is assigned to them on the basis that they are in each other's interference range. Therefore, this paper modifies the calculation of ETT, to consider the channel interference. For a link $e_{AB}$ on the path, the calculation of ETT is modified as follows:

$$Interference\_ETT_{AB} = ETX_{AB} \cdot \frac{S}{B} \cdot \sum_{i=1}^{|I(e_{AB})|} \delta + \sum_{i=1}^{n} (ETX_i \cdot \frac{S}{B} \cdot \delta) \tag{8}$$

$$\delta = \begin{cases} 1, f_i = f_{AB} and i \in I(e_{AB}) \\ 0, other \end{cases}$$

where $S$ is the packet size and $B$ is the link bandwidth. The first part of Formula (8) is the interference generated by the external flow, and the second part is the interference generated by the internal flow to link $e_{AB}$. So the calculation of ETT in this paper not only considers the interference generated by the external flow, but also considers the interference generated by the internal flow.

b) channel switching delay

When the channel selected by the next hop in the routing algorithm is different from the current channel, channel switching will happen [20]. If the working frequency of the transceiver changes 10MHz, it will bring 10ms delay. If there are a lot of traffic in the network, the impact on routing performance caused by channel switching cannot be ignored. Therefor, channel switching delay is the nonzero delay generated by process during which the transceiver of a mesh node switches from one channel to another channel.

If the channel switching time of the two paths is the same, then the effect generated by the channel switching on the transmission of the other links should be considered. Suppose that node $A$ want to establish a route to node $F$, as shown in **Fig. 7**. There are 2 possible paths: $A$-$C$-$E$-$F$ and $A$-$D$-$E$-$F$, and they have the same channel switching time. But if we choose the first path, the channel switching of node $C$ will affect the data transmission of link $e_{BC}$ and $e_{AC}$, and this situation cannot appear on the second path. So the routing metric proposed by this paper should consider the impact on the node $v_i$ and the links connected to it while node $v_i$ is switching channel. We will select the node which has fewer neighbor nodes as the next hop in the case of the same channel allocation. Suppose that the time of channel switching one time is $T_{switch}$, then the total channel switching delay of link $e_{AB}$ (the $i$-th hop on the routing path) is defined as follows:

$$t_{switch}^{i} = \begin{cases} 0, f_{i-1} = f_i \\ T_{switch} \cdot \dfrac{|Neighbor(v_A)|}{N}, other \end{cases} \tag{9}$$

where $Neighbor(v_A)$ is the neighbor set of node $v_A$, and $N$ is the total number of nodes in the wireless mesh network.

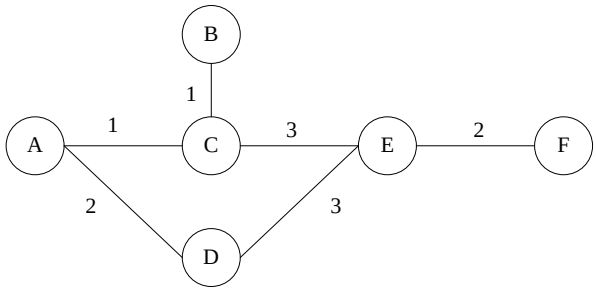


**Fig. 7.** Effect generated by channel switching on routing

Data transmission delay of a node pair is composed of the transmission delay of the forwarding node and the channel switching delay between the sending node and the receiving node in wireless mesh networks. Thus for a link $e_{AB}$ on the path, we modify the calculation of ETT as follows:

$$Interference\_ETT_{AB} = ETX_{AB} \cdot \frac{S}{B} \cdot \sum_{i=1}^{|I(e_{AB})|} \delta + \sum_{i=1}^{n} (ETX_i \cdot \frac{S}{B} \cdot \delta) + t_{switch}^{AB} \tag{10}$$

(3) load balancing

As WCETT routing metric do not consider link load in the route selection process, in order to achieve load balancing in wireless mesh network, increase the network throughput and improve the network performance, we should consider the link load $\phi^{'}(i)$ in the route selection process. $\phi^{'}(i)$ is the actual load assigned to link $i$, and the detailed calculation method of $\phi^{'}(i)$ will be introduced in section 5.3.

According to the above analysis, a multi-channel routing metric based on load balancing (LBI_WCETT) is proposed. It considers the link interference, channel switching delay and link load. The calculation of LBI_WCETT is as follows:

$$LBI\_WCETT = \alpha \cdot \sum_{i=1}^{n} Interference\_ETT_i + \beta \cdot \max_{1 \le j \le k} X_j + \gamma \cdot \frac{\phi(i)^{'}}{C(i)} \tag{11}$$

where $C(i)$ is the estimated capacity of link $i$, which will be introduced in section 5.2, and $0 \le \alpha, \beta, \gamma \le 1$, $\alpha + \beta + \gamma = 1$.

## 5.2 Link Capacity Estimation

Link capacity refers to the maximum amount of information that can be accepted by each link in unit time. To evaluate the effectiveness of a multi-channel routing algorithm, we need to calculate the capacity of each virtual link. Link capacity is determined by the number of all virtual links in its interference range that are assigned to the same channel, which is proposed in [4]. The purpose of link capacity estimation is to obtain the medium and long term share effective bandwidth of each virtual link. So link capacity estimation

is closely related to channel allocation and link load estimation. The calculation of link capacity $C(l)$ is as follows:

$$C(l) = \frac{\phi(i)}{\sum_{j \in I(i) \cap (f_i = f_j)} \phi(j)} \cdot C \tag{12}$$

where $\phi(i)$ is the expected load on link $i$, $I(i)$ is the set of all virtual links in the interference zone of link $i$, and $C$ is the sustained radio channel capacity.

Thus, we will calculate the link capacity estimation according to the channel allocation in the routing algorithm. The load assigned to the link cannot exceed the link capacity estimation. If it is exceeded, then we will re-trigger the channel allocation algorithm according to the current link load until an appropriate path is found for each node pair.

### 5.3 Multi-channel Routing Based on Load Balancing

The multi-channel routing algorithm based on load balancing does not consider the link capacity at the start. Preliminary estimate is calculated of the expected load of each virtual link in the wireless mesh network. And then it performs the channel allocation and routing algorithm iteratively. For simplicity, suppose that there are $S$ node pairs in the wireless mesh network, and the load of each pair is $L_s$, $s=\{1, 2, 3,..., S\}$. The the purpose of the routing algorithm is to find the best path $H$ for each node pair.

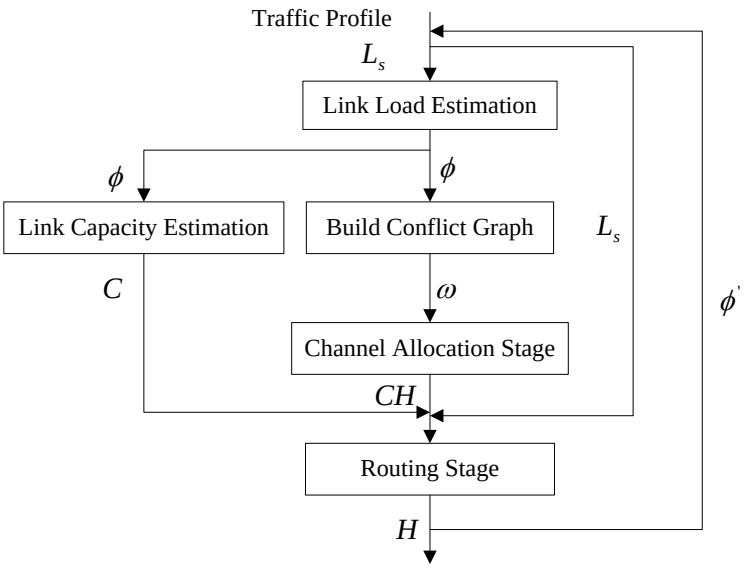


**Fig. 8.** Flow chart of multi-channel routing based on load balancing

Step1 Calculate the link load $\phi(i)$ according to Formula (3) for each link in the wireless mesh network.

Step2 Build the conflict graph $G_c(E_c, V_c)$ according to the connection graph $G(E, V)$. A weight value is given to each node in the conflict graph $G_c(E_c, V_c)$ according to Formula (2). Then according to the weight value of the node in decreasing order to trigger the channel allocation algorithm as described in Section 4.1.

Step3 The new channel allocation strategy is fed back to the routing algorithm, and the routing algorithm is as follows:

a) Calculate the link capacity estimation $C(i)$ for each link in the wireless mesh network;

b) Find the best path for each node pair ($s$, $d$) according to the routing metric LBI_WCETT proposed by this paper;

c) Modify $\phi^{'}(i)$ for each link $i$ on the path:

$$\phi^{'}(i) = \phi^{'}(i) + L_s$$

$\phi^{'}(i)$ is the actual load assigned to link $i$;

d) Decide according to the re-calculated link load $\phi^{'}(i)$:

If $\phi^{'}(i) > C(i)$, it indicates that the actual load assigned to link $i$ exceeds the link capacity estimation, the value of $\phi^{'}(i)$ is modified:

$$\phi(i) = \phi^{'}(i), \phi^{'}(i) = 0$$

And the channel allocation algorithm is re-triggered until an appropriate path is found for each node pair.

## 6. Performance Evaluation

In order to study the overall performance of the multi-channel routing algorithm based on load balancing proposed in this paper, NS2 network simulation tool is used to build a simulation environment of wireless mesh network[21]. The simulations are based on IEEE 802.11b/g standard. Simulation parameters are given in **Table 1**.

**Table 1.** Simulation settings

| Simulation parameter | value |
|---|---|
| transmission range | 250m |
| interference range | 500m |
| number of channels | 12 |
| number of interfaces | 2 |
| antenna | omni-directional |
| channel capacity | 10Mbps |
| traffic type | UDP |
| traffic pattern | CBR |
| $a$ | 0.5 |
| $b$ | 0.5 |
| $\alpha$ | 0.3 |
| $\beta$ | 0.3 |
| $\gamma$ | 0.4 |

Three simulation experiments are conducted to compare the performance effect among the routing metric LBI_WCETT proposed in this paper, WCETT and WCETT-LB routing metrics. Suppose that all the nodes in the wireless mesh network are static. In order to evaluate the effect of the load balancing of the LBI_WCETT routing metric proposed in this paper, we mainly focused on testing the performance of the network throughput, average end to end delay and packet loss rate.

(1) Network throughput is an important parameter to evaluate a network performance. Network throughput refers to the amount of data within a unit time through the network (or channel or interface). It depends on the current network load.

(2) Delay is the required time of a data packet transmitted from one end of a wireless network to the other end, including the transmission delay, propagation delay, processing delay and queuing delay. The average end-to-end delay is the average delay over all surviving data packets from the sources to the destinations.

$$\text{Average end-to-end delay} = \frac{\sum(\text{Time\_received} - \text{Time\_sending})}{\text{Num\_sending}} \tag{13}$$

(3) Packet loss ratio is the ratio of lost packets and the total number of transmitted packets in the transmission process, which is an important indicator to reflect the network status. The packet loss ratio should be controlled within a certain range while the data packets in the network are in a normal transmission.

### 6.1 Network Throughput

Experiment 1 tests the difference of the network throughput among LBI_WCETT, WCETT and WCETT-LB routing metrics while there are different traffic flows (5, 10, 15, 20, 25, 30, 35, 40), different number of nodes (20, 40) and different number of available channels (3, 6, 9, 12) in the wireless mesh network.

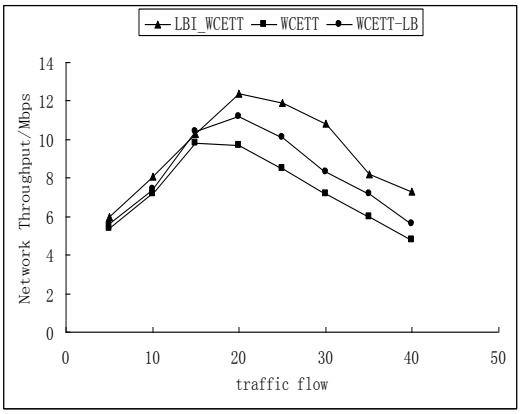


**Fig. 9.** Network throughput for different number of traffic flows in a 40-node network

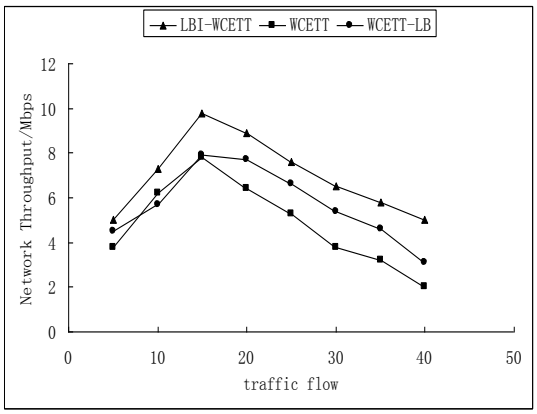


**Fig. 10.** Network throughput for different number of traffic flows in a 20-node network

Simulation results shown in **Fig. 9** and **Fig. 10** are that with the number of traffic flows increasing, the network throughput will increase first, then it will decrease. This is because that when the number of traffic flows reaches a certain level, the network will be in a congested state. The number of nodes in **Fig. 10** is smaller than the number of **Fig. 9**, thus the network is easier to reach a congested state. In the LBI_WCETT routing metric, we not only considered the channel interference and the initial link load in the channel allocation stage, but also consider the actual assigned load for each link in the network. Simulation results shown in **Fig. 10** indicate that LBI_WCETT routing metric is superior to WCETT and WCETT-LB routing metrics.

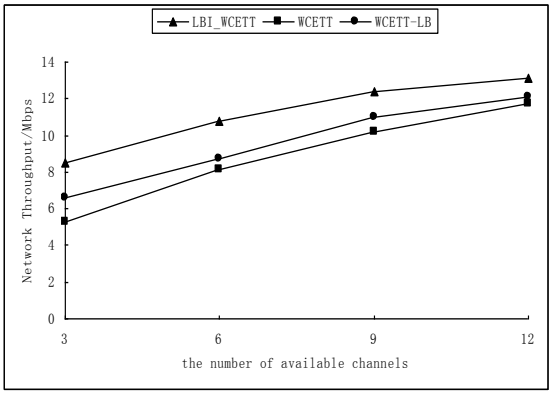


**Fig. 11.** Network throughput for different number of available channels

Difference of network throughput among LBI_WCETT, WCETT and WCETT-LB routing metrics are shown in **Fig. 11** while there are different number of available channels in the wireless mesh networks. Simulation results show that the throughput of the network which uses LBI_WCETT routing metric in the routing algorithm is always higher than that uses WCETT-LB and WCETT routing metrics. As shown in **Fig. 11**, the throughput of the network which uses LBI_WCETT routing metric is 1.6 times than that uses WCETT routing metric and 1.3 times than that uses WCETT-LB routing metric when there are 3 available channels in the wireless network. If there are 6 available channels in the wireless network, then the throughput of the network which uses LBI_WCETT routing metric is 1.3 times than that uses WCETT routing metric and 1.2 times than that uses WCETT-LB routing metric. If there are 9 available channels in the wireless network, then the throughput of the network which uses LBI_WCETT routing metric is 1.2 times than that uses WCETT routing metric and 1.1 times than that uses WCETT-LB routing metric. If there are 12 available channels in the wireless network, then the throughput of the network which uses LBI_WCETT routing metric is 1.1 times than that uses WCETT routing metric and 1.1 times than that uses WCETT-LB routing metric. From the above results, it can be seen that the fewer the number of available channels in the network, the better performance of the LBI_WCETT routing metric. This is because that if there are less available channels in the wireless network, then there will be more interference between the adjacent links. But in the channel allocation process, the algorithm using LBI_WCETT routing metric proposed in this paper uses the conflict graph model and considers both the link load and the link interference, so it can enhance the network transmission rate well and improve the network throughput.

### 6.2 Average End to End Delay

Experiment 2 tests the difference of the average end to end delay among LBI_WCETT, WCETT and WCETT-LB routing metrics. The simulation environment is the same as experiment 1.

Simulation results shown in **Fig. 12** and **Fig. 13** indicate that with the number of traffic flows increasing, the average end to end delay using all the three routing metrics will increase. But LBI_WCETT routing metric takes account of the channel interference in the channel allocation stage, the routing algorithm using it can adapt to the multi-channel environment better, and can reduce the collision probability of the communication greatly. It also takes account of the delay generated by channel switching in the routing stage, thus LBI_WCETT routing metric is superior to WCETT and WCETT-LB routing metrics. The difference of average end to end delay among LBI_WCETT, WCETT and WCETT-LB routing metrics are

shown in **Fig. 14** while there are different number of available channels in the wireless mesh networks. Also, we can see that the average end to end delay of the network which uses LBI_WCETT routing metric in the routing algorithm is always lower than that uses WCETT-LB and WCETT routing metrics. It also can be seen from **Fig. 14** that the fewer the number of available channels in the network, the better performance effect of the LBI_WCETT routing metric.

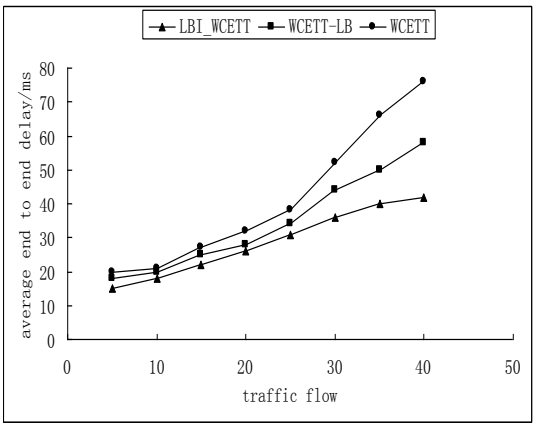


**Fig. 12.** Average end to end delay for different number of traffic flows in a 40-node network

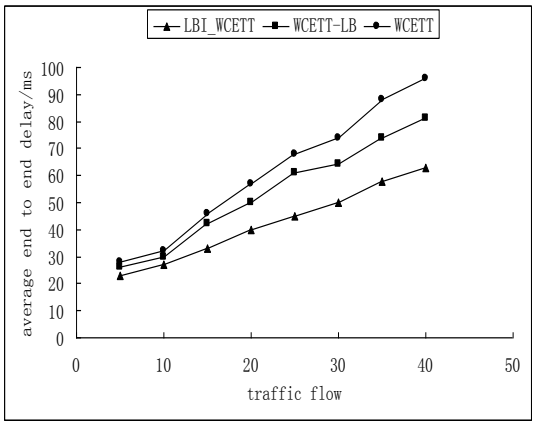


**Fig. 13.** Average end to end delay for different number of traffic flows in a 20-node network

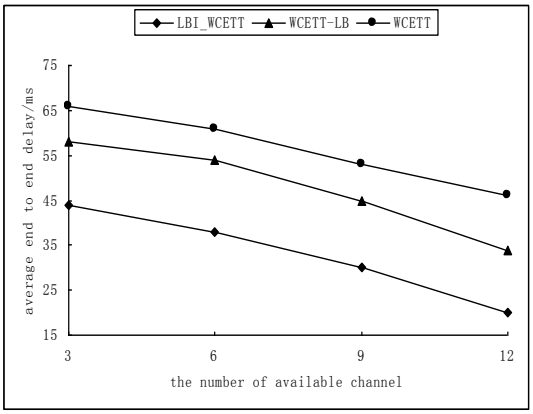


**Fig. 14.** Average end to end delay for different number of available channels

## 6.3 Packet Loss Ratio

Experiment 3 tests the difference of the packet loss ratio among LBI_WCETT, WCETT and WCETT-LB routing metrics. The simulation environment is the same as experiment 1.

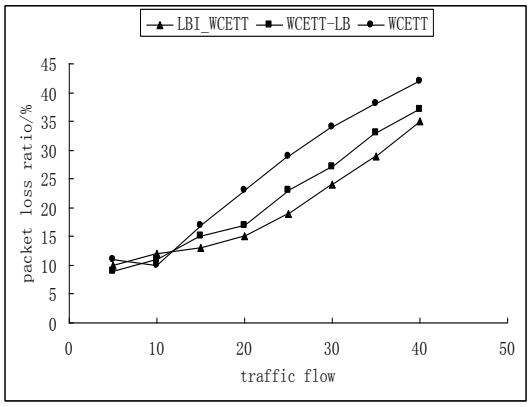


**Fig. 15.** Packet loss ratio for different number of traffic flows in a 40-node network

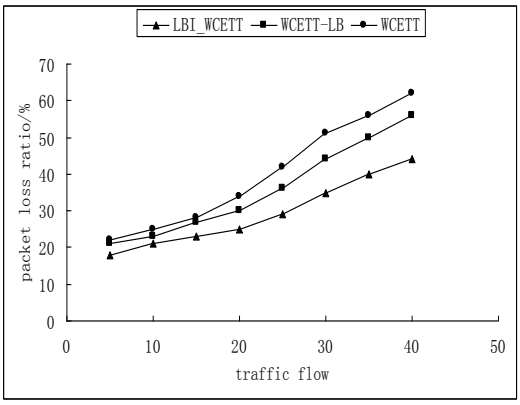


**Fig. 16.** Packet loss ratio for different number of traffic flows in a 20-node network

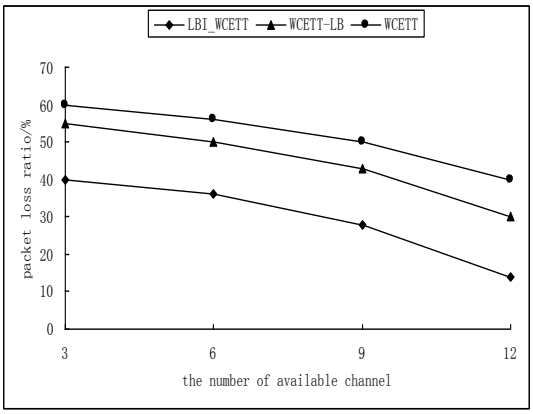


**Fig. 17.** Packet loss ratio for different number of available channels

Simulation results shown in **Fig. 15** and **Fig. 16** indicate that with the number of traffic flows increasing, the packet loss ratio using the two other routing metrics will increase. As shown in **Fig. 15**, as the network is not in a congested state and the collision probability is small, both of the packet loss ratio of the two routing metrics are small. And the performance advantage of LBI_WCETT is not obvious. As shown in **Fig. 16**, with the number of traffic flows increasing, the network will be in a congested state. As LBI_WCETT routing metric takes account of the channel interference and load balancing, the packet loss ratio of LBI_WCETT is lower than that for WCETT routing metric obviously. And as shown in **Fig. 17**, the packet loss ratio of the network which uses LBI_WCETT routing metric in the routing algorithm is always fewer than that uses WCETT-LB and WCETT routing metrics. So the performance effect of LBI_WCETT routing metric is superior to the WCETT-LB routing metric and WCETT routing metric. This proves that the LBI_WCETT routing metric is more accurate than the WCETT-LB routing metric and WCETT routing metric in measuring the link capacity.

## 7. Conclusion

Multi-hop wireless mesh network is a key technology for wireless broadband Internet access. However, the problem of low network throughput and large network delay of multi-hop wireless network leads to the result that wireless mesh networks cannot provide continuous and reliable bandwidth as wired networks. This paper proposes a novel centralized load-aware

multi-radio multi-channel routing algorithm in the wireless mesh network. First, the algorithm build a conflict graph according to the network topology. We use the link load estimation model to calculate each link load and the potential interference link set for each link in the wireless mesh network. And a weight value is assigned to each node in the conflict graph. Then according to the weight value of the node in decreasing order to assign a channel to each node in the conflict graph. At last, we present an improved routing metric LBI_WCETT, which considers the link interference, channel diversity, link load and the latency brought by the channel switching. Simulation results show that *LBI_WCETT* routing metric can help increase the network capacity effectively, reduce the average end to end delay and improve the network performance.

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