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Interference-Avoid Channel Assignment for Multi-Radio Multi-Channel Wireless Mesh Networks With Hybrid Traffic

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ABSTRACT Interference is the main factor that leads to the decrease in network performance in wireless mesh networks (WMNs). In this paper, we propose a load-balance and interference-avoid partially overlapped channels assignment (LBIA-POCA) scheme aiming to improve network throughput by the cooperative management of interfaces and channels. This scheme first assigns the interfaces of the neighbor nodes by the Huffman tree-based centralized allocation algorithm. Second, the links are divided into M non-interfering link sets according to the interference model, which are respectively scheduled in M time slots. At last, more time slots are further assigned for the links without interference, increasing the number of links that can be scheduled per time slot. The simulation results demonstrate that the proposed scheme performs well in WMNs with hybrid traffic, especially in throughput and packet loss rate.

INDEX TERMS Multi-radio multi-channel wireless mesh networks, partially overlapped channels, interference-avoid, channel assignment, load balance.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are potential technologies for building next-generation wireless communication systems, which have characteristics different from those of traditional wireless networks. There are a lot of advantages in many aspects, such as increasing bandwidth, flexible networking, improving network coverage, increasing network capacity, and reducing upfront investment. WMNs have attracted close attention from the academic community and industry and will be widely applied in recent years [1]. FIGURE 1 presents the architecture of hybrid WMNs. Three types of nodes exist in WMNs: Mesh Gateways (MG), Mesh Routers (MR), and Mesh clients (MC). MGs are connected to the wired network, which exchanges data between WMNs and wired network. MRs have the characteristics of the terminal and router. MCs receive Mesh services but do not have Mesh and routing functions. Point-to-point traffic and Internet-oriented traffic services coexist in large numbers in WMNs. A hybrid Mesh network is a fusion of an infrastructure Mesh network and a client Mesh network. The underlying client node has two modes of communication, one is to access the network through the router node, and the other is to communicate through peer-to-peer. The flexible communication mode of the client can avoid the congestion problem of the router to a certain extent, so the hybrid Mesh network has stronger network connectivity and higher network reliability.

Network capacity is an important factor in the performance of WMNs. Capacity reduction caused by interference from adjacent parallel transmissions is a major problem in WMNs. Multi-Radio Multi-Channel (MRMC) technology provides a more effective way to alleviate this problem, that is, MRMC equips each node with multiple radio interfaces and allows WMNs to use multiple channels [2]. Links on different channels can communicate in parallel, which greatly improves transmission efficiency and increases capacity of WMNs. In MRMC-WMNs, the interfaces of neighboring nodes can only communicate on the same channel. Therefore MRMC technology cannot fundamentally solve the capacity problem of WMNs and efficient channel assignment is still in need. IEEE 802.11 b/g and IEEE 802.11a radios utilize the

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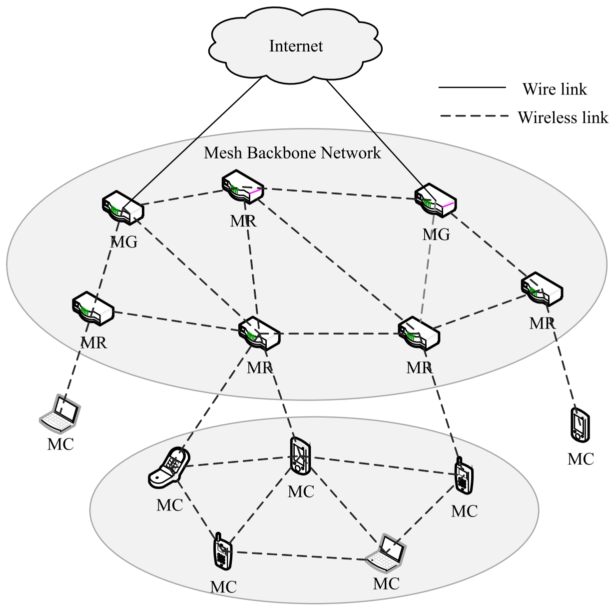


FIGURE 1. The architecture of hybrid WMNs.

2.4 GHz and 5 GHz frequencies respectively bands with 3 and 12 orthogonal channels in traditional communication system correspondingly. However, the scarcity of spectrum resources makes it easy for the network to assign the same channel to two links which are very close to each other, thus causing co-channel interference and the decrease of WMNs capacity [3]. Some studies have proved that rational design of Partially Overlapping Channel (POC) allocation schemes can effectively improve spatial multiplexing and the utilization rate of spectrum resource [4]–[6].

Many efforts have been devoted to designing efficient channel assignment schemes to improve network performance, though helpful, some limitations still exist as follows:

- Only the point-to-point traffic or Internet-oriented traffic services is considered in most studies, and there are few comprehensive considerations for the two types of traffic. With the popularity of emerging service, these two types of traffic will coexist in large numbers in WMNs.
- Current channel assignment schemes mostly only utilize orthogonal channels (OCs) to perform channel assignment [7]. Due to the limited number of OCs, it is difficult to ensure that all links have the proper channel assignment, and the resulting network interference may significantly reduce network performance.

According to the two limitations, we exploit the problem of partially overlapping channel assignment for 802.11b-based WMNs. Our contributions can be summarized as below:

- We comprehensively consider both point-to-point traffic and Internet-oriented traffic in WMNs, which matches the practical network.
- Aiming at the existing network capacity and interference of WMNs, we design the load-balance and interference-avoid partially overlapped channels channel assignment (LBIA-POCA) scheme combining the characteristics of MRMC and POC to improve the network throughput and reduce the packet loss rate.

The rest of the paper is organized as follows. The related works are briefly reviewed in Section 2. Section 3 describes the preparations, including the network model and interference model. Section 4 elaborates on the proposed LBIA-POCA scheme. Experimental results and conclusions are presented in Sections 5 and 6, respectively.

II. RELATED WORK

Researchers usually consider channel interference and load balancing when designing the channel allocation scheme. We first talk about network interference modeling. Many different schemes have been proposed for the interference modeling of WMNs, and the conflict graph is relatively straightforward to express the interference relationship between the links in the network. The multi-radio conflict graph [8] and the transmission conflict graph [9] are designed to simulate the inter-link interference between wireless links in unicast and multicast communications respectively, but both of them are designed for WMNs where only orthogonal channels (OCs) are exploited to execute data transmissions. Due to the difference of interference estimation for OCs and POCs, both of them are not applicable to POCs in WMNs. Wang *et al.* [10] simulate the path loss of the signal with the Two-ray Ground model. Based on the interference model of the protocol, the interference range of the co-channel nodes is deduced theoretically by node power and antenna gain, then the node interference range under different channel separations can be deduced by carrier sensing threshold. Compared with the measurement results, the obtained theoretical results can accurately reflect the relationship between the channel spacing and the POCs interference range that lead to good portability.

Another relatively important factor in channel assignment is load balancing. Ding *et al.* [11] assign a static and several dynamic interfaces for each mesh node, and proposes an adaptive dynamic channel assignment protocol, which take into account the optimization of throughput and delay of channel assignment. Then proposes a congestion-aware routing protocol to balance the channel usage in the network. Similar to the work [11], Bao *et al.* [12] divide the interfaces of each node in the network into three categories: static, dynamic, and adaptive interfaces, and corresponding channel assignment algorithms are designed for different types of interfaces. In particular, the adaptive interface can adjust the interface mode based on the link status and interface load. However, the proposed scheme only achieves the load balance between each node interface, but not the entire network traffic. Considering the overall network traffic, Li *et al.* [13] propose a centralized channel assignment scheme. Authors define the link occupancy frequency as the sum of the ratio between the number of links that may communicate with a link and the number of links between any two points in the network, which is used to measure the link load. The channel assignment process takes into account the principle of load balancing to improve network throughput.

The previous works use mathematical methods and combine other factors to establish a mathematical model to solve the problem of channel assignment. Roh *et al.* [14] study a joint channel assignment, link scheduling, routing, and rate control problem for the WMNs with multiple orthogonal channels and multiple directional antennas. The problem is formulated as a mixed integer nonlinear problem, and authors develop an algorithm to solve the problem by using the generalized Benders decomposition approach. In [15], a multi-objective approach to optimize wireless mesh network design with three conflicting objectives is presented: it minimizes the number of Internet Transit Access Points, maximizes the fairness of bandwidth assignment and maximizes coverage to mesh clients. Instead of distributing the nodes, links or network interfaces to different channels to reduce interference, Xu *et al.* [16] try to assign as many channels as possible to the links. Jiao *et al.* [17] propose a method to estimate the end-to-end delay distribution under the general traffic arrival process and Nakagami-m channel model. The above schemes are all based on the assignment of orthogonal channels, but currently, the limited orthogonal channel assignment is difficult to meet the ever-increasing communication demand.

Wang *et al.* [18] break the current situation that end-to-end channel assignment schemes typically focus on assigning channels in different frequency bands to mesh the access and backbone networks. The backbone network and access network are both based on the IEEE 802.11 technology. Then channel assignment is designed using POCs to implement end-to-end traffic transmission efficiently. The proposed channel assignment scheme in [19] assigns the channels to the link with the goal of minimizing total network interference by using POCs to increase network capacity. The related works in [20] use POCs to design the channel assignment scheme, which improve the spectrum utilization of WMNs and the overall network capacity.

From the above analyses, considering the current network capacity and interference problems of WMN, the channel allocation scheme can greatly improve network performance by using POCs rationally. Therefore, a POCs allocation scheme with effective interference avoidance and load balancing is proposed, which aims to improve network throughput and reduce the packet loss rate.

III. PRELIMINARIES

A. NETWORK MODEL

Basing on IEEE802.11b standard, MRMC-WMNs can be modeled as the undirected graph $G(V, E)$, where V represents the node set of mesh router, mesh gateway and mesh client, and E represents the link set of wireless links between mesh routers. The mesh router is equipped with $k(k \geq 2)$ wireless interfaces. The set C represents the available channel and the number of OCs and POCs is c_n.

TABLE 1. The variable definitions.

Parameter	Definition
$G(V,E)$	Undirected graph
$G_f(V_f,E_f)$	Weighted traffic subgraph
C	Available channel
F	Flows set in the network
p_i	Path of stream f_i
$load(l)$	Weight on the link l
$d_i(l_i,l_j)$	Distance between the link l_i and l_j
$I_R(l_i)$	Potential interference range
$N(l_i)$	Potential interfering link set of link l_i
$R_I(\tau)$	Potential interfering links of link l_i
$\boldsymbol{I_i^j}$	Binary matrix of $c_n \times c_n$
i_{xy}	The x-th row and the y-th column element of the matrix $\boldsymbol{I_i^j}$
$I_r(\tau)$	Reduced interference range ratio
S	Link importance factor
$h(l)$	Minimum hops from link l to gateway
$S(l)$	Link importance factor of link l
d_v	Degree of node $\boldsymbol{V_i}$
M	Number of time slots
$\boldsymbol{V_i}$	Channel allocation vector
c_i^j	Interference-free channel set
$\boldsymbol{M_{CT}}$	Three-dimensional matrix

To calculate the traffic situation, we define F as the flows set in the network. Each flow has a source node s_i and a destination node d_i. The load on the flow f_i is r_i, and the path of stream f_i is represented by p_i. According to the set F of flows in the network, the weighted traffic subgraph $G_f = (V_f, E_f)$ can be extracted from $G(V, E)$, which is defined as follows:

(1) $E_f = \{l | \forall f_i \in F \ and \ l \in p_i\}$.

(2) $V_f = \{v | \forall l \in the \ endpoint \ of \ E_f\}$

(3) $\forall l \in E_f$, the weight $load(l)$ on the link l is the sum of the loads of all flows over link l:

$$load\ (l) = \sum_{f_i \in F} r_i \times t_{f_i}^l \tag{1}$$

where $t_{f_i}^l$ is a binary variable that is used to determine whether there is flow. When the flow $t_{f_i}^l$ passes through the link l, $t_{f_i}^l = 1$, otherwise it is 0.

The assumptions we made in this paper are listed as below:

(1) All mesh routers are stationary and work with the same transmission power and transmission range. Mesh clients are connected to the nearest mesh routers within one-hop distance. As the performance of WMNs is mainly decided by its backbone network, clients are usually ignored and the corresponding access routers are considered instead [21].

(2) Wireless interfaces of mesh router has similar configurations, functions, and transmit power.

(3) Centralized channel assignment scheme is applied, in which channel assignment results are calculated by center controller (i.e., gateway node) and then spread to the whole network.

(4) Routing paths are pre-determined by AODV routing protocol.

Finally, for the reader's convenience, the variable definitions used in the paper are listed in TABLE 1.

B. INTERFERENCE MODEL

In this paper, sender and receiver contention avoidance interference model proposed in [10] is used to model interference. The distance $d(l_i, l_j)$ between the link $l_i = (u_i, v_i)$ and $l_j = (u_j, v_j)$ is defined as the minimum distance between the sending node of one link and the receiving node of the other link in Equation (2).

$$d_i\left(l_i, l_j\right) = \min\left(d\left(u_i, u_j\right), d\left(v_i, u_j\right)\right) \tag{2}$$

The interference range $R_I(\tau)$ is related to the channel spacing for POCs due to the different degree of spectrum overlap between two different channels.

In [10], the two-ray ground propagation model is established, and the co-channel interference range $R_I(0)$ is derived from the power and antenna gain of the transmitting node. Co-channel interference range can be calculated in Equation (3).

$$R_I(0) = d\left(l_i, l_j\right) = \sqrt[k]{\frac{P_t \times G_r \times h_t^2 \times h_r^2}{CS_{th}}} \tag{3}$$

Thus the node interference range $R_I(\tau)$ with the channel interval can be calculated in Equation (4).

$$R_I(\tau) = I_r(\tau) \times R_I(0) \tag{4}$$

We define $I_R(\tau) = \sqrt[k]{od\left(c_i, c_j\right)}$ as the reduced interference range ratio, which is normalized to a scale of [0, 1]. $I_r(\tau)$ is related to the degree of overlap $od\left(c_i, c_j\right)$ of the channels c_i, c_j where the two nodes are located. It is used to describe the reduction in interference range observed on adjacent channels due to the utilization of POCs. From equations (3) and (4), when the values such as node transmit power P_t, carrier sensing threshold CS_{th}, path loss factor k and antenna gain G_r, G_t, antenna height H_r, H_t are sure, the value of the node interference range $R_I(\tau)$ is only related to the channel interval. The larger is, the smaller the channel overlap degree $od\left(c_i, c_j\right)$ is, and the smaller the interference range of the node is. When $d_i\left(l_i, l_j\right)$ is no more than the corresponding interference range $R_I(\tau)$, the two links interfere with each other, and otherwise not. The minimum channel spacing Ï"$_{min}$ for interference-free transmission between two links can be expressed by Equation (5).

$$R_I(\tau_{\min}) < d\left(l_i, l_j\right) \le R_I(\tau_{\min} - 1) \tag{5}$$

In the protocol interference model, the receiving node can successfully receive the data from the sending node under the condition that no other node is transmitting within the interference range of the receiving node. When using the RTS/CTS mode of IEEE 802.11, for any link l_i in the network, after the node u_i sends data to the node v_i, the node v_i needs to reply the Acknowledgement to the node u_i to confirm the received data. According to the interference model of the protocol, the interference range of the link is the union of the interference ranges of the endpoints of the link to ensure the two-way reliability of the link. The interference range of the link at different channel intervals is shown in FIGURE 2.

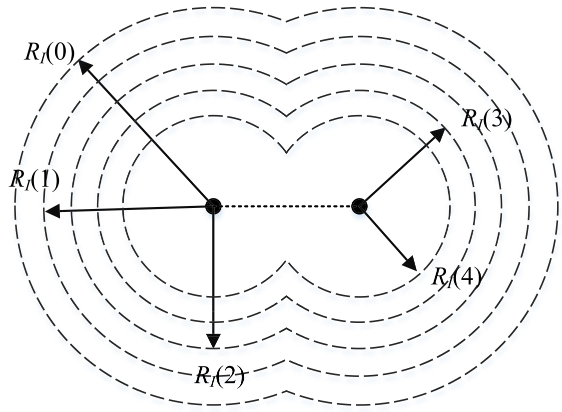


FIGURE 2. Interference range of links at different channel interval.

The potential interference range $I_R(l_i)$ for link l_i is defined in Equation (6).

$$I_R(l_i) = D(u_i, R_I(0)) \cup D(v_i, R_I(0)) \tag{6}$$

where $D(u_i, R_I(0))$ is a circular area with the point u_i as the center and $R_I(0)$ as the radius, ie, the interference range of the node u_i. $D(v_i, R_I(0))$ is the interference range of the node v_i.

From the above, it can be seen that for the link l_i which has been assigned a channel, the remaining links may be potentially interfering links of link l_i if one or both of its endpoints are within $I_R(l_i)$. These links for m the potentially interfering link set $N(l_i)$ of link l_i. $l_j \in N(l_i)$is a potential interfering link of link l_i. A binary matrix $\boldsymbol{I}_i^j$ of $c_n \times c_n$ is defined to indicate the mutual interference when the links l_i and l_j use different channels. If the link l_i uses the channel c_x and the link l_j uses the channel c_y, the distance of links is $d_i\left(l_i, l_j\right)$, then the x-th row and the y-th column element i_{xy} of the matrix i_{xy} can be represented by Equation (7). i_{xy} is 1 indicates that there is interference between the two links; otherwise not.

$$i_{xy} \begin{cases} 1, & d(l_i, l_j) \le R_I\left(\left||c_x - c_y\right|\right) \\ 0, & d(l_i, l_j) > R_I\left(\left|c_x - c_y\right|\right) \end{cases} \tag{7}$$

IV. LBIA-POCA SCHEME

The scheme proposed in this paper mainly consists of two stages. The first stage is the assignment of communication interfaces between nodes, determining the connection relationship between node interfaces, that is, which interface will be assign to communicate with each neighbor. The second stage is the interference-free channel assignment stage. The LBIA-POCA uses the heuristic algorithm to perform multiple rounds of POCs assignment for links in which there are flows and further optimizes the link scheduling. Then more time slots that will not cause interference are assignd to more important links. The flow of the algorithm is shown in FIGURE 3.

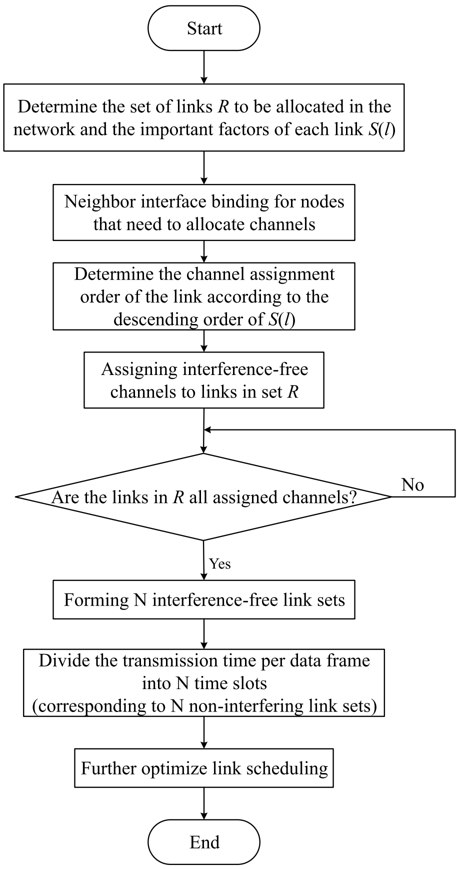


FIGURE 3. **The flow of the LBIA-POCA algorithm.**

A. COMMUNICATION INTERFACE ASSIGNMENT BETWEEN NODES

Since each node of the MRMC-WMNs is equipped with multiple radio interfaces, the determination of the connection relationship between the interfaces of the nodes before the channel assignment becomes a key step in determining the rationality of the channel assignment. Assume that the degree of node v_i is d, which has k interfaces, and the set of neighbor nodes is $N = \{n_1, n_2, \ldots, n_n\}$. Each neighbor selects one interface to transmit data packets to node v_i, and it is preferable that the neighbor nodes should be equally associated to the k interfaces of node v_i, ie, the load assignd on each interface is balanced. When the number of neighbor nodes is greater than the number of node interfaces, the one-to-one matching between the interface and neighbor nodes cannot be implemented. In order to achieve load balancing among node interfaces, we use a combination algorithm based on Huffman tree to combine neighbor nodes. Defining the load between node v_i and its neighbors is $r_1, r_2, \ldots, r_n$. The algorithm should ensure that the variance with all possible combinations is as small as possible to achieve load balancing. The composed neighbor nodes match one of the interfaces of the node v_i and are considered overall when allocating the channels, allocating the same channel. The communication interface between nodes is assigned as Algorithm 1 below.

Algorithm 1 Neighbor Node Interface Assignment

Require:
$G_f = (V_f, E_f)$, neighbor node set N of all nodes, with the load $r_1, r_2, \ldots, r_n$
Ensure:
The distribution result of the communication interface between nodes
for $v \in v_f$ **do**
  if $n > d_v$ //n is the number of neighbor nodes **then**
    select two neighbor nodes n_i and n_j with the lowest two loads r_i, r_j
    consider n_i and n_j as a combination with the load $r_{i+j} = r_i + r_j$
    delete the two neighbor nodes n_i and n_j
    $n--$
  else
    bind each neighbor with an interface
  end if
end for

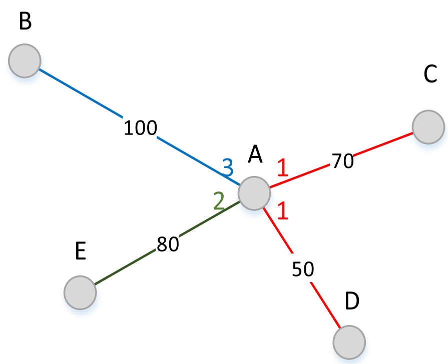


FIGURE 4. **Neighbor node interface assignment.**

FIGURE 4 shows an example of neighbor node interface assignment. Assume node A is equipped with 3 interfaces and can communicate with nodes B, C, D, E nodes via wireless links AB, AC, AD, and AE. The number on each link represents the link load. Since the number of available interfaces is less than the number of neighbors, the two links in AB, AC, AD, and AE have to share the same interface. According to the Huffman tree-based allocation algorithm, interface 1 is assignd to the two links AC and AD with the lowest load firstly. Next, links AE, AB are assigned to interfaces 2, 3, respectively. At this point, the neighbor interface assignment of node A is complete. The process of neighbor-interface assignment for other nodes is similar.

B. INTERFERENCE-FREE CHANNEL ASSIGNMENT

We adopt the centralized channel assignment algorithm. The network centralized server can search flows, and periodically run and update the channel assignment. Due to the limited channel resources, channels without interference are even more scarce. Thus the links are ranked in descending order according to the link importance factor $S(l)$, and all the links are divided into M interference-free link sets. Correspondingly, the transmission time of each data frame is also divided into M time slots, which correspond to each set of interference-free links, and only the links in the corresponding interference-free link set are scheduled in each time slot. The three-dimensional matrix $\boldsymbol{M_{CT}}$ is defined as an information matrix containing link, slot, and channel assignment information.

A channel allocation vector $\boldsymbol{V_i}$ of $|C| \times 1$ is defined for each link l_i, then the m-th element of $\boldsymbol{V_i}$ is 1 if l_i uses the channel c_m. If the link l_j is the potential interfering link of l_i, l_j has been assigned a channel according to the interference model in Section 3.2, and both the channel allocation vector $\boldsymbol{V_i}$ and the link mutual interference moment $\boldsymbol{I_i^j}$ are known. Then the interference-free channel set C_i^j of l_i relative to its potentially interfering link l_j can be denoted as Equation (8).

$$C_i^j = \{c|\boldsymbol{I_i^j} \cdot \boldsymbol{V_i} = 0\} \tag{8}$$

After traversing all the links in $N(l_i)$, the interference-free channel set C_i of l_i is defined as the intersection of interference-free channel set of all links in $N(l_i)$ as Equation (9).

$$C_i = C_i^1 \cap C_i^2 \cap \ldots \cap C_i^j l_1, l_2, \ldots, l_j \in N(l_i) \tag{9}$$

Define the link importance factor S to determine the channel assignment order of the links in Equation (10).

$$S(l) = \frac{load(l)}{h(l)} \tag{10}$$

In order to maximize the fairness of the network, the link load value is used as an important indicator to measure the importance of the link. $load(l)$ is the load value of link l, defined by equation(1). At present, the main business of WMNs is to provide Internet access and obtain network services for users. Therefore, nodes closer to the gateway are subject to more network pressure. Define the minimum hops from link l to gateway as $h(l)$. From the definition of S, we can see that the critical factor of the link is related to the link load and the minimum hops from the gateway. The larger S is, the more important the link is. So the channels are assigned to the links in descending order of S.

We adopt a heuristic algorithm to optimize the link scheduling according to the descending order of the link $S(l)$ and assign more time slots that satisfy the interference-free constraint for links with higher degrees of importance. Assuming that the candidate link l_k is in the slot s_i, determine whether the link l_k and the links in any time slots s_j $(j \neq i)$ interfere with each other. If there is interference, the link l_k cannot be scheduled within the time slot s_j; otherwise, a scheduling time slot is added to the link l_k, that is, the link can be scheduled within the time slot s_j. The interference-free channel assignment is described as Algorithm 2.

Algorithm 2 Interference-Free Channel Assignment

Require:
  $G_f = (V_f, E_f)$
Ensure:
  channel assignment results
  Initialization: $M = 0$, $i = 1$, $\boldsymbol{M_{CT}} = 0$
  R = l //sort all links($\forall l \in E_f$) in descending order of $S(l)$
  P = R //P is the set of links for which channels have not been assigned
  while $P \neq \emptyset$ **do**
    $L_i = \emptyset$
    for $l_i \in P$ **do**
      calculate the interference-free channel set C_i for link l_i
      if $P \neq \emptyset$ **then**
        assign the channel c with the largest number of channel to the link l_i
        $L_i = L_i \cup \{l_i\}$
      end if
    end for
    $P = P - L_i$
    $M = i$
    $i = i + 1$
    update $\boldsymbol{M_{CT}}$
  end while
  for $l_k \in R$ **do**
    get the slot s_i where l_k is located from $\boldsymbol{M_{CT}}$
    while $1 \ll j \ll N$ and $j \neq i$ **do**
      if there is no interference between l_k and the links in s_j assign slot s_j to l_k **then**
        update $\boldsymbol{M_{CT}}$
      end if
    end while
  end for

V. PERFORMANCE EVALUATION

A. SIMULATION SETTINGS AND PERFORMANCE METRICS

In order to verify our proposed schemes in IEEE 802.11b WMNs, we evaluate the performance of the proposed scheme by discrete event network simulator (NS, NS-3.19). We also modify NS to support MRMC technology and POCs. Grid topology of NÃ-N squared grids is used, that is, each vertex is deployed with a mesh router, and each edge denotes a wireless link. The grid step is set to 250 m [22]. The gateway is located in the bottom right corner. A mesh router can communicate with its neighbors except the diagonal nodes. The simulations are based on IEEE 802.11b standard which has 3 OCs out of 11 available POCs, and the data transmission rate at the physical layer is 2 Mbps. Each node is configured with 3 radios. For all interfaces, the transmission range is 250 m and the carrier sense range is 550 m. CBR (Constant bit rate) source is used to generate data packets, and the packet sending rate is 200 kbps with a fixed packet

TABLE 2. Simulation parameters.

Simulation Parameters	Values
Network topology	5 × 5 grid topology
PHY/MAC standards	IEEE 802.11b
channels	11
No. of radio of each node	3
Traffic type	CBR(UDP)
Transmission range	250m
Co-channel interference range	550m
Packet size	512Bytes
Physical transmission	2Mbps
Simulation time	1000s

size of 512 Bytes. In order to simulate the hybrid traffic scenario, we simulate two types of services, point-to-point traffic and Internet-oriented traffic respectively, by setting up flows from the Internet and mesh routers which connected to mesh client directly. The concrete simulation settings are listed in TABLE 2.

Performance comparison is presented according to the performance metrics whose definitions are given below.

(1) Network throughput. Network throughput is defined as the total amount of data bits actually received by receivers divided by the time between receiving the first packet and the last packet.

(2) Average end-to-end delay. End-to-end delay is defined as the time it takes a packet to reach the destination after it leaves the source. The average taken over all received packets is average end-to-end delay.

(3) Average packet loss ratio. It is defined as the ratio between the number of data packets received unsuccessfully and the number of packets supposed to be received by all receivers.

For validation of the proposed approaches, the simulation results are compared with end-to-end load-aware partially over-lapped channel assignment (ELIA) [18] and load balance link layer protocol (LBLP) [12]. ELIA explore how to exploit partially overlapped channels to perform end-to-end channel assignment in order to achieve effective end-to-end flow transmissions. After a round of non-interfering channel allocation for all links, Complementary Channel Assignment is performed for the link that has not been assigned with the principle that selecting the channel with the least interference. In LBLP, an interface can work in a sending or receiving mode. For the receiving interfaces, the channel assignment is proposed considering the number, position and status of the interfaces, and a task allocation algorithm based on the Huffman tree is developed to minimize the mutual interference. A dynamic link scheduling algorithm is designed for the sending interfaces, making the tradeoff between the end-to-end delay and the interface utilization. A portion of the interfaces can adjust their modes for load balancing according to the link status and the interface load. Load balancing among interfaces of nodes is considered in both ELIA-POCA and LBLP. We also compared the performance of the proposed scheme only using the OC channels. The performance of the proposed approach is evaluated by conducting two sets of simulation experiments. In the first set of experiments, we fix the grid size as 5×5 and vary the number of concurrent flows from 4 to 24 to examine the impact of different flows on the throughput, average end-to-end delay and average packet loss ratio in the hybrid traffic environment. In the second scenario, we vary the grid size from 5×5 to 10×10 and impose a certain number of CBR flows concurrently on the network to observe the impact of network size on performance. To reduce the effects of errors and random results, the consistency and reproducibility are determined through repetitive analyses of traces obtained through ten runs of each scenario.

B. PERFORMANCE EVALUATION

1) SIMULATION RESULTS FOR THE IMPACT OF THE NUMBER OF FLOWS ON PERFORMANCE

In 5×5 grid topologyïijŇwe change the number of concurrent flows from 4 to 25, and observe the network performance. Packet sending rate is 200 kbps. Network throughput, average end-to-end delay and average packet loss ratio of various schemes as the number of flows increases are shown in FIGURE 5.

From above observations, we can see that the order of performance is: LBIA-POCA is the best, LBLP is the second, ELIA is the third, and LBIA-OCA is the worst. FIGURE 5(a) shows the comparison graph of average throughput of the network topology for all schemes. We can see that the network throughput almost linearly increases as the number of flows grows larger in four schemes, but the improvement slope gets smaller gradually. Performance of three schemes using POCs is significantly better than LBIA-OCA. When the number of data flows in the network is 4 and 5, the network load is light. The network throughput generated by the four schemes is almost the same. This is because the network is divided into several sub- networks that do not interfere with each other, and OCs are sufficient to realize non-interfering data transmission. As LBIA-OCA only uses 3 OCs, there is a high probability of assigning the same channel for adjacent links when the number of flows increases. The resulting co-channel interference prevents these links from parallel transmissions, and they have to compete for transmission chance. Packets have to wait for a long time in the buffer queue before being transmitted, and more collisions may happen, which contribute to poor network performance. POCs can be used appropriately to reduce interference between adjacent links and increase spectral efficiency to achieve more parallel transmissions, thus they can help improve network performance. As the network load increases, the LBIA-POCA can achieve higher network throughput than LBLP and ELIA. For example, when the number of data flows in the network is 7, the network throughput of LBIA-POCA, LBLP, and ELIA schemes are 3894.96 kbps, 3221.41 kbps, and 2499.19 kbps, respectively. Compared to ELIA, LBLP interface allocation is relatively simple. The interface allocation of ELIA can be adjusted adaptively according to the

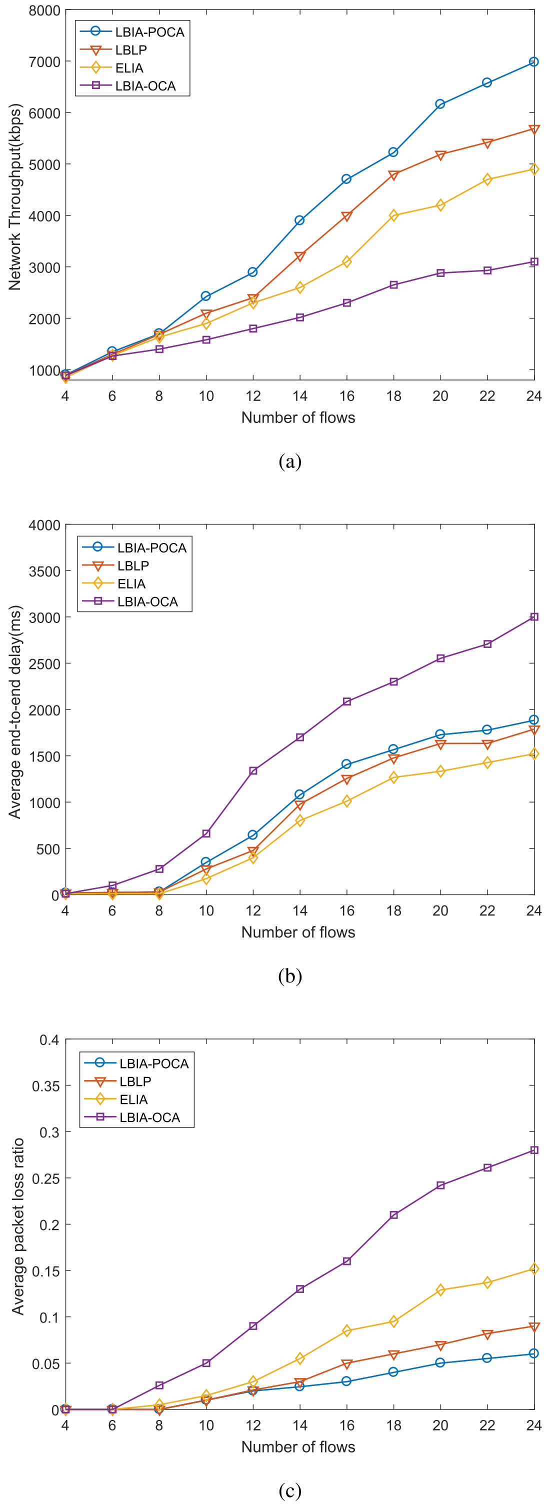


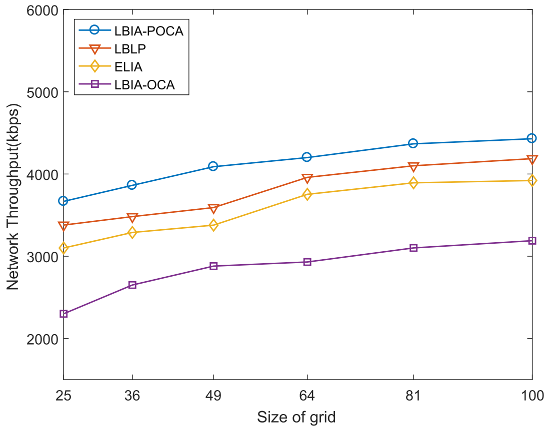
FIGURE 5. Performance comparison as the number of flows increases. (a) Network throughput comparison. (b) Average end-to-end delay comparison. (c) Average packet loss ratio comparison.

load condition of the node, so the performance is better. LBLP does not take the characteristics of POC into account, thus the interference model is not suitable than LBIA-POCA. Due to reasonable neighbor interface binding and division of time slots for interference-free transmission, the LBIA-POCA achieves better network performance. As more data streams are injected into the network, the network becomes denser and it is difficult to eliminate interference between adjacent links even with POCs. Therefore, the performance improvement of the network becomes slower. FIGURE 5(b) shows the comparison graph of average end-to-end delay for all schemes. Since multiple rounds of interference-free channel assignment are executed for links that need to be assigned channels and static link scheduling is used, the LBIA-POCA is transmitted in time slots in sequence, the average end-to-end delay performance is no better than the other two schemes. In other words, the LBIA-POCA sacrifices the average end-to-end delay in exchange for network throughput improvement, and the effect is obvious. FIGURE 5(c) shows the comparison graph of average packet loss ratio for all schemes. The average packet loss rate and network throughput are complementary, that is, the more packet loss, the lower the network throughput.

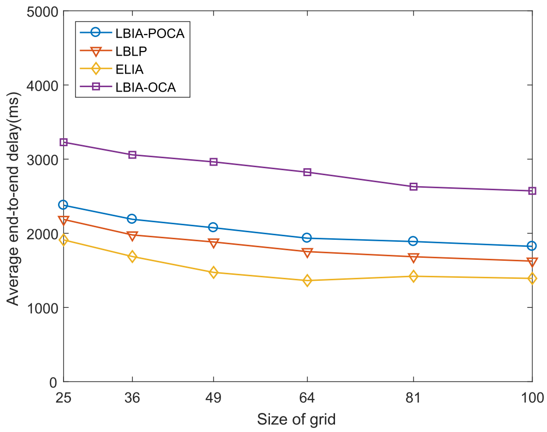
2) SIMULATION RESULTS FOR THE IMPACT OF THE SIZE OF GRID ON PERFORMANCE

In the second scenario, we vary the grid size from 5×5 to 10×10 and impose a certain number of CBR flows concurrently on the network to observe the impact of network size on performance. Packet sending rate is 200kbps. Network throughput, average end-to-end delay and average packet loss ratio of various schemes as the size of grid increases are shown in FIGURE 6.

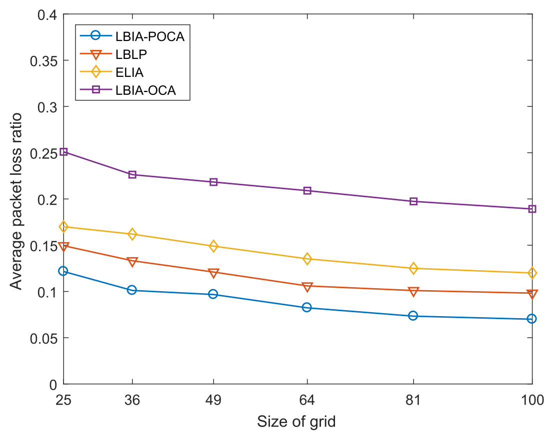
FIGURE 6(a) shows the comparison graph of average throughput of the network topology for all schemes. We can see that the network throughput increases as the number of flows grows larger in four schemes. FIGURE 6(b) and (c) show the comparison graph of average end-to-end delay and packet loss ratio for all schemes respectively. Average end-to-end delay and packet loss ratio have a certain degree of decline as the size of grid increases. When the network topology is small, the OCs scheme has a high average packet loss rate, low network throughput and bad average end-to-end delay. The reason is that the OCs solution cannot assign different channels to these data streams, introducing more serious interference to the network. It takes a long time for the packet to reach the destination node. As the network scale expands, the network throughput and average end-to-end delay performance of the OCs and POCs solutions have been improved. The reason is that larger networks allow for more parallel transmissions, giving OCs and POCs solutions more room to reduce average end-to-end delay and increase network throughput. Take advantage of all available channel resources compared to OCs schemes that use OCs only, packets can reach the destination node faster, which is important for delay-sensitive services. Similar to the first scenario, average end-to-end delay performance of LBIA-POCA is not as good as the other two POCs schemes, but it also achieves better network throughput and average packet loss rate.



(a)

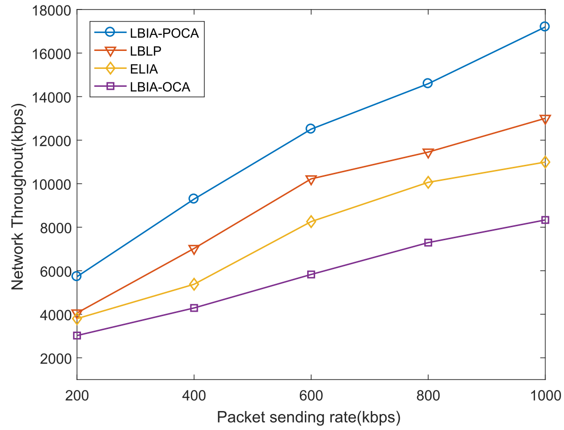


(b)

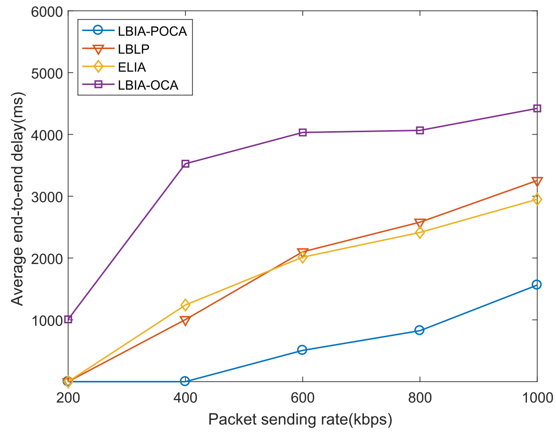


(c)

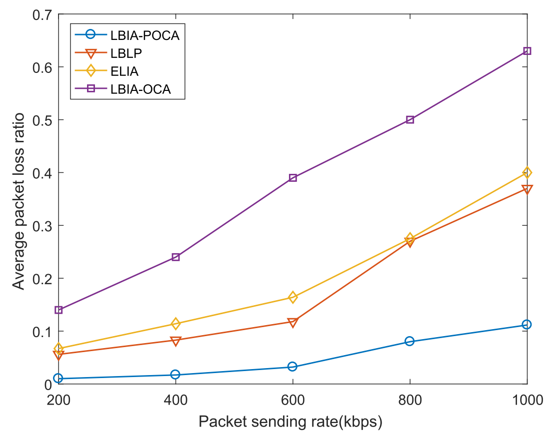
FIGURE 6. Performance comparison as the size of grid increases. (a) Network throughput comparison. (b) Average end-to-end delay comparison. (c) Average packet loss ratio comparison.



(a)



(b)



(c)

FIGURE 7. Performance comparison packet sending rate. (a) Network throughput comparison. (b) Average end-to-end delay comparison. (c) Average packet loss ratio comparison.

3) SIMULATION RESULTS FOR THE IMPACT OF THE PACKET SENDING RATE ON PERFORMANCE

In the third scenario, the random topology of 100 nodes is used. we vary the packet sending rate from 200kbps to 1000kbps and impose 15 number of CBR flows concurrently on the network to observe the impact of the packet sending rate on performance. Network throughput, average end-to-end delay and packet loss ratio of different schemes as the packet sending rate increases are shown in FIGURE 7.

FIGURE 7(a) shows that the network throughput increases almost linearly as the node's packet sending rate increases. The network throughput of LBIA-POCA, is always higher than that of LBLP and ELIA. For example, when the node packet transmission rate reaches 600 kbps, the network throughput of LBIA-POCA, LBLP, and ELIA schemes are 12506.24kbps, 10222.41kbps, and 8258.29kbps, respectively. It can be seen from FIGURE 7(a) and (b), the average packet loss ratio and the average end-to-end delay increase as the node packet sending rate increases. This is because when the node packet transmission rate increases, the longer the node cache queue length, the more collisions there are, so the average packet loss ratio and the average end-to-end delay will increase; the average of LBIA-POCA The packet loss rate and average end-to-end delay are always lower than LBLP and ELIA. For example, when the node packet transmission rate is 600 kbps, the average packet loss ratio and average end-to-end delay of LBIA-POCA are 3.20% and 506.14ms, respectively. The average packet loss ratio and average end-to-end delay of LBLP are 11.83% and 2101.58ms, respectively. The average packet loss ratio and average end-to-end delay of ELIA are 16.47% and 2014.62ms, respectively. The above simulation results also demonstrate the advantages of LBIA-POCA in improving network performance. Overall, the grid size has a certain impact on the performance of WMNs, but its impact is not as significant as the number of concurrent streams in the network.

VI. CONCLUSION

Aiming at the existing network capacity and interference of WMNs, combining the characteristics of MRMC and POCs, we designed a POC assignment scheme with effective interference avoidance and load balancing for WMNs with hybrid traffic. This scheme first assigns interfaces of neighbor nodes and balances loads between interfaces by the Huffman tree-based assignment algorithm. Then perform N round of interference-free channel assignment on the links, so that the link in each time slot of N time slots can be scheduled without interference. Simulation results show that we have demonstrated that the usage of POCs can really improve network throughput. The proposed scheme effectively avoids network interference, improves network throughput and reduces average end-to-end delay and packet loss rate. In future works, we will study how to solve the multicast channel assignment problem since multicast can effectively save channel resources compared with unicast communication. Furthermore, we will also research on joint multicast routing and channel assignment for WMNs with hybrid traffic.

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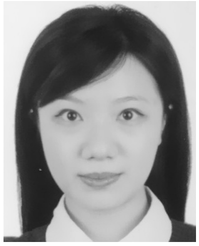

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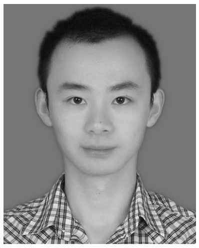

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