

Power-Efficient Spatial Reusable Channel Assignment Scheme in WLAN Mesh Networks

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Abstract Interference has strong effect on the available bandwidth of wireless local area network (WLAN) based mesh networks. The channel assignment problem for multi-radio multi-channel multihop WLAN mesh networks is complex NP-hard, and channel assignment, routing and power control are tightly coupled. To mitigate the co-channel interference and improve capacity in multi-channel and multi-interface WLAN mesh networks, a power-efficient spatial reusable channel assignment scheme is proposed, which considers both channel diversity and spatial reusability to reduce co-channel interference by joint adjusting channel, transmission power and routing. In order to assign channel appropriately, an efficient power control scheme and a simple heuristic algorithm is introduced to achieve this objective, which adjust the channel and power level of each radio according to the current channel conditions so as to increase the opportunity of channel spatial reusability. The proposed channel assignment scheme also takes load, capacity and interference of links into consideration. Simulation results show the effectiveness of our approach and demonstrate that the proposed scheme can get better performance than other approaches in terms of throughput, blocking ratio, energy consumption and end-to-end delay.

Keywords channel assignment · spatial reuse · power control · wireless mesh networks

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1 Introduction

The recent advance of wireless communication technologies has prompted the flourish of wireless mesh networks (WMNs) [1]. IEEE 802.11 wireless local area networks (WLANs) [2, 3] have been considered as potential solutions for constructing infrastructures of WMNs. A WLAN mesh network can be set up in locations with very limited infrastructure to provide ubiquitous connectivity [4], which is composed of mesh points (MPs), mesh access points (MAPs) and mesh gateways (MGs) which provide multi-hop connectivity through the wireless network interface. Since 2004, the IEEE 802.11 [3] working group has started working on mesh network in the task group identified as TGs [2, 4], which will produce the 802.11s standard for mesh networks. The main target of TGs [2] is to investigate and design mesh networks consisting of different WLAN devices performing routing at link layer.

Since IEEE 802.11 WLAN is designed for single hop case, many research results show that it performs poorly on heavy traffic and multihop case [5], in particular for real-time flows subject to multiple hops [6]. In addition, the protocol fails to dispense the available bandwidth fairly to the requesting nodes in multi-hop and single channel case, where interference and heavy traffic will degrade the available bandwidth and system performance greatly. In the WLAN extended service set (ESS) mesh networking, designing the power efficiency and high capacity schemes for interconnecting access points to form an efficient multihop network supporting quality of service (QoS) is a challenge [7], especially for multihop WLAN mesh networks. However, supporting delay sensitive real-time applications over WLAN mesh networks is attractive and necessary.

In order to improve the performance of WLAN mesh networks, existed work tries to utilize multiple channels substantially to increase the effective bandwidth available to wireless network nodes [8]. According to the IEEE 802.11 standard [3], it offers multiple orthogonal channels, that can work simultaneously within a neighborhood. Meanwhile, the price for commodity 802.11 radios is rapidly diminishing. These make it natural to consider the use of multiple inexpensive radios at a single node, where each radio is designed to be capable of switching over multiple orthogonal channels [9]. By allowing multiple simultaneous transmissions within a neighborhood, the co-channel interference is alleviated. Consequently, it is expected that higher system throughput can be achieved.

Multi-radio can also improve system performance, and much research has been conducted in channel assignment problem of multi-radio WLAN mesh networks to achieve high throughput. This is because of its potential of overcoming the inherent wireless multi-hop throughput, scalability and latency problems caused by the half-duplex nature of the IEEE 802.11. In [10], a minimum interference channel assignment (MICA) algorithm was proposed for multicast in multi-channel multi-radio WMNs, which enables the nodes in a multicast tree to operate with minimum interference. However MICA assumes a multicast tree has been constructed before the algorithm is applied, and the goal of MICA algorithm is merely to minimize the interference between nodes in the tree. However the channel assignment problem for multi-radio multi-channel multihop networks is complex NP-hard [11], and channel assignment [12, 13], routing and power control are tightly coupled [14]. However the co-channel interference can only be reduced to a certain degree due to the limited number of available channels [15].

In WLAN mesh networks, channel assignment and power control determine the connectivity between nodes since two nodes can communicate with each other only when they are on a common channel and within the transmission range of each other. Routing decisions are made based on the number of network interface cards (NICs) and channels. Thus, channel assignment and power control have a direct impact on routing. In order to achieve better performance, channel and transmission power should be dynamically adjusted according to the traffic status. Therefore, routing, channel assignment and power control are tightly coupled and should be jointly optimized. Although many approaches have been investigated to resolve channel assignment problem to improve the

performance of the WLAN mesh networks, the existed schemes did not consider the channel assignment problem with routing and power control problems at the same time, especially take the both channel diversity and power-efficient spatial reusable scheme into consideration.

In this paper, we focus on the scenario that all MAPs and MPs operate on multi-channel and multi-radio, and resolve channel assignment problem with routing and power control problems at the same time. The proposed scheme considers both channel diversity and spatial reusability to reduce co-channel interference by joint adjusting channel, transmission power and routing. The motivation of the proposed scheme is to mitigate the co-channel interference, and adjust the channel and power level of each radio according to the current channel conditions so as to increase the opportunity of channel spatial reusability. To mitigate the co-channel interference and improve capacity, power control advantage is applied to reduce the interference and improve the traffic throughput in such networks. In order to appropriately assign channel, an efficient power control scheme and a network model are employed to describe the WLAN mesh network. Then the proposed heuristic algorithm is introduced to achieve channel assignment, which takes load, capacity and interference of links into consideration.

The rest of this paper is organized as follows. The presented power-efficient spatial reusable channel assignment scheme is proposed in detail in Section 2. Section 3 validates the efficiency of the proposed scheme by simulations. Finally, Section 4 concludes the paper.

2 Proposed scheme

2.1 System model

The WLAN mesh network is assumed herein to be composed of many MPs, MAPs and MGs. And the WLAN mesh network architecture as shown in Fig. 1. All of MPs, MGs and MAPs are equipped with backhaul interfaces which are used for backbone communication. Each MAP is equipped with client interfaces which are used for providing network access for MPs within their coverage area. MG is equipped with gateway functionality to enable connectivity to the wired Internet via wired link.

In the network, each mesh node (MP, MAP or MG) can communicate with another node if and only if both are within the communication range of each other and

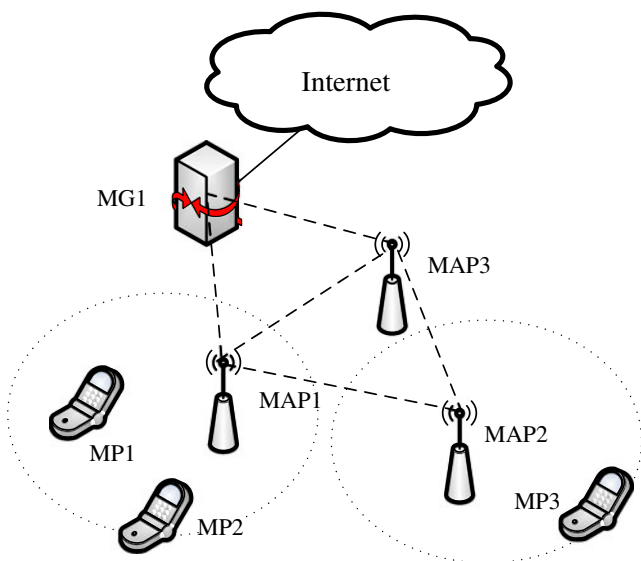


Fig. 1 The WLAN mesh network architecture

a common channel is assigned to their interfaces. A pair of nodes that use a single channel and are within interference range may interfere with each other’s communication, even if they cannot communicate with each other directly. Node pairs that use different channels can simultaneously transmit data without interference. Each node has been defined as having an interference disk with the node at the center. In order to guarantee basic network connectivity, there is a common channel shared for all nodes. On the other hand, to reduce interference, a node should not have too many common channels with any single neighbor.

In the system, there are N orthogonal channels in the WLAN mesh network, and each mesh node i has k_i NICs. The WLAN mesh network is represented by a directed graph $G(V, E)$, where V denotes the set of mesh nodes and E denotes the set of wireless links with which nodes can send packets directly. The links are assumed to be bi-directional. A link $l(i, j)$ is a single-direction connection from node i to node j . Let $C(i, j)$ denote the link capacity of $l(i, j)$. $I(i, j)$ denotes interference link set of $l(i, j)$ and $NI(i, j)$ denotes the interference node set of $l(i, j)$. The power-efficient spatial reusable channel assignment problem is now formally stated as: Given a WLAN mesh network $G(V, E)$, the interference link set $NI(i, j)$ of each link, the number N of non-overlapping channels, the number k_i of NICs with which each mesh node i is equipped, the goal is to assign channels to the links and build corresponding routes to maximize the traffic throughput of a given traffic profile.

2.2 Power-efficient spatial reusable scheme

The interference between nodes with the same channel will degrade the system performance greatly. Meanwhile, the number of channel and NICs equipped by nodes are limited. Hence, improving the spatial reusability is the basic and key issue, even in multi-radio multi-channel multihop WLAN mesh networks.

In order to solve the hidden terminal problem, the request to send/clear to send (RTS/CTS) scheme is introduced in IEEE 802.11. The source node sends a short RTS frame before each data frame transmission, and the receiver node replies with a CTS frame if it is ready to receive. After the source node receives the CTS frame, it starts transmitting its frame. So, all other nodes hearing an RTS, a CTS or a data frame can update their network allocation vectors (NAVs), and will not start transmissions before the updated NAV timers reach zero, if the nodes are using the same channel. In IEEE 802.11 protocol, nodes use fixed and maximum power P_{max} to transmit the control messages (RTS/CTS) as well as data messages. However such scheme lead to two disadvantages: one is that the spatial is not used adequately thus reduce the probability of concurrent transmission; the other one is that a lot of energy is wasted for using maximum power to transmit messages without considering their actual distance.

Let’s consider the case in Fig. 2. Node A uses fixed and maximum power P_{max} to transmit the data messages to node B. When node D hears RTS sent by node A, it will delay to send data to avoid collision,

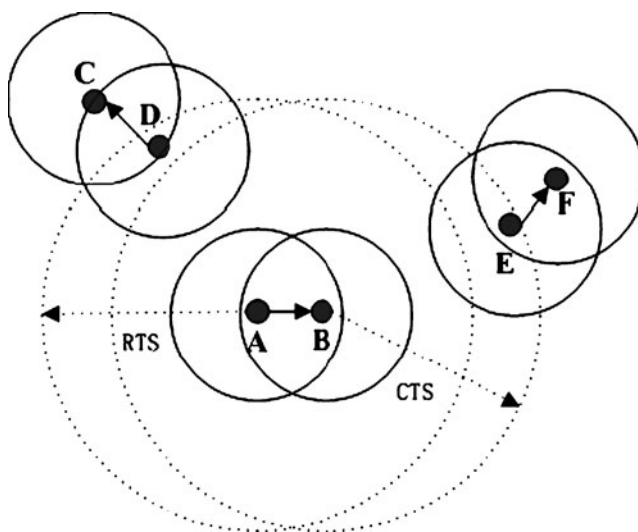


Fig. 2 Inefficiency of the classic RTS/CTS approach

which leads to expose node problem. Node D cannot receive the data from node C to avoid interfering with the ongoing transmission A→B. Node E will delay its transmission to node F, or else the data will collide with the data from node A to node B. Node E is a hidden node. Node E cannot receive the data from node F too, or else the data will collide with the acknowledgement (ACK) from node B to node A.

However, if nodes select their transmission power appropriately according to the distances between them, it is possible the transmissions A→B, C→D and E→F can overlap in time, which not only decreases the interference and improves throughput, but also decreases energy consumption. The essential reason is that IEEE 802.11 protocol magnifies the definition of collision. In addition, fixed and maximum transmission power leads to decreasing channel utility and increasing interference and power consumption. Considering that all nodes using fixed transmission power in a network, P_i denotes the transmission power of node i , G_{ij} is the channel gain from node i to node j . Then the signal-to-interference-and-noise ratio (SINR) $SINR(i, j)$ of node j is:

$$SINR(i, j) = \frac{P_i G_{ij}}{\sum_{n \neq j} P_n G_{nj} + P_{\text{noise}}} \quad (1)$$

where P_{noise} is noise. When the transmission power is fixed and same for all nodes, the SINR only is the function of channel gain. If at node j , the $SINR(i, j)$ of data sent by node i is higher than threshold $SINR_{\text{th}}$, node j can receive the data successfully. So even there is an interference when node j is receiving data from node i , for example, the node v which is in the range of node j , is sending data. Node j also can receive data successfully. So select transmission power appropriately, it will obviously mitigate the co-channel interference for the nodes using the same channel, and improve spatial reuse and capacity in multi-channel and multi-interface WLAN mesh networks.

In order to select power appropriately, a load factor η is introduced to measure system load, namely node's interference:

$$\eta = 1 - \frac{P_{\text{noise}}}{\sum_{n \neq j} P_n G_{nj} + P_{pi}} \quad (2)$$

where P_{pi} is potential interference, $\sum_{n \neq j} P_n G_{nj} + P_{pi}$ is the sum of all received interferences of other nodes and

maximal extra endurable power. It is clear that η will increase if $\sum_{n \neq j} P_n G_{nj} + P_{pi}$ increasing. We can get:

$$SINR_{\text{th}} = \frac{P_i G_{ij}}{\sum_{n \neq j} P_n G_{nj} + P_{pi} + P_{\text{noise}}} \quad (3)$$

Hence the transmission power of node i is:

$$P_i = \frac{\left(\sum_{n \neq j} P_n G_{nj} + P_{pi} + P_{\text{noise}} \right) SINR_{\text{th}}}{G_{ij}} \quad (4)$$

Now the task is to exchange information of nodes to make transmitter select appropriately power. In order to select power appropriately, all nodes exchange information in negotiation period at the beginning of each beacon interval. After negotiation period, nodes can calculate its transmission power and send data to receiver. The node works as follows:

- (1) At the beginning of negotiation period, all nodes with data contend the channel to transmit negotiation message (NEGO) with the maximum transmission power P_{max} . Assumption that node A gets the channel and transmits NEGO successful. When target node B received the NEGO message from node A, it will estimate the channel gain G_{AB} between A and B by the received signal power P_{rev} and transmission power P_{max} in NEGO sent by node A:

$$G_{AB} = \frac{P_{\text{rev}}}{P_{\text{max}}} \quad (5)$$

Then node B calculates transmission power of node A with expression 4, and its extra endurable power:

$$P_{pi} = P_{\text{sum}} - \sum_{j \neq B} p_j G_{jB} \quad (6)$$

where $\sum_{j \neq B} p_j G_{jB}$ can be measured. Now the task is to distribute the potential interference P_{pi} to all nodes in average. For n nodes in $NI(A, B)$ in the range of potential interference, the assigned power P_{sib} is $\frac{P_{pi}}{n}$. Then node B puts the P_A and $P_{\text{sib}}(B)$ into the acknowledge frame ACK (P_A , $P_{\text{sib}}(B)$), and sends it to no node A with maximum power P_{max} .

- (2) For node i in the range of hearing ACK, it can estimate channel gain of node A G_{Ai} , and calculates channel gain from node B to node i G_{Bi} , the transmission power P_A , and $P_{\text{sib}}(B)$. With P_A and G_{Ai} , node i can calculate the transmission interference

of node A. With $P_{sib}(B)$ and G_{Bi} , node i calculate the maximum transmission power.

- (3) Assumption that node C will send data node D. Node C also transmits NEGO message to D with P_{max} . Then it can calculate P_C with expression 5. If $P_C \geq P_{max}$, node D will transmit a NACK message to notify node C to not transmit; else node D calculates P_{pi} and $P_{sib}(D)$, and send ACK message to node C. After receiving ACK from node D, node C compares P_C with $P_{max_int}(C) = \min_{j \in Nei(C)} \left\{ \frac{P_{sib}(j)}{G_{jC}} \right\}$, where $Nei(C)$ denotes the set of neighbor nodes. If $P_C < P_{max_int}(C)$, node C can send data to D with P_C , else it cannot transmit.
- (4) After negotiation period, all nodes will send data with the corresponding power. If there is no data, they can enter in power saving mode to save power.

After negotiation period, nodes B calculates the actual received interference $P_{sum} = \sum_{j \neq B} P_{jB} G_{jB}$. If P_{sum} is larger than the maximum tolerant interference power, which demonstrates that the estimated value is smaller than its actual value. In this case, node B should increase n to decrease potential interference. If $P_{sum} < 2.5P_{noise}$, it means that the extra power of node B is not fully used. In this case, node B should decrease n . Otherwise, the estimated n value is reasonable.

In fact, when the nodes operate in power saving mode (PSM) to decrease power consumption, the ad hoc traffic indication message (ATIM) window can be used as negotiation period. All nodes can exchange information at ATIM window of each beacon interval. Algorithms 1 and 2 show the control flow of sender and receiver in multihop topology.

Algorithm 1: Sender in multihop

```

Input: A, B, Message
1 if within the negotiation period then
2   while not win the channel do
3     contend the channel;
4   end
5   send NEGO with  $P_{max}$ ;
6   while receive ACK do
7     if it is the intended ACK then
8        $P_A = ACK.P_A$ ;
9       if  $(P_A < P_{max}) \wedge (P_A < P_{max\_int}(A))$ 
10        then
11          send TONE( $P_A$ ) with  $P_A$ ;
12          send the data with  $P_A$  after NEGO;
13        end
14      end
15    end

```

Algorithm 2: Receiver in multihop

```

Input: A, Message
1 if within the negotiation period then
2   if receive NEGO message to the node then
3     compute corresponding  $G_{AB}$  using Eq. (5);
4     compute  $P_{AB}$  using Eq. (4);
5     if  $P_A > P_{max}$  then
6       send NACK with  $P_{max}$ ;
7       hold until the end of the negotiation
8       period;
9     end
10    else
11      compute  $P_{ini\_bound}$ ;
12      send ACK( $P_A, P_{ini\_bound}$ ) to node A
13      with  $P_{max}$ ;
14      hold until the end of the negotiation
15      period;
16      receive data;
17    end
18  else if receive message from node j to other
19  nodes then
20    compute corresponding  $G_{jB}$  using Eq. (5);
21    hold until the end of the negotiation period;
22  end
23  else if receive TONE from node j to other node
24  then
25     $P_j = TONE.P_j$ ;
26  end
27 end

```

2.3 Channel assignment scheme

The goal of the proposed channel assignment scheme in a multi-channel WLAN mesh network is to bind each network interface to a radio channel in such a way that the available bandwidth on each link is proportional to its expected load. And the proposed scheme will maximize the number of accepted traffic requests and assign the channel and route for each link and node pair, respectively. Considering the connectivity of the network and power control scheme, the first channel is used as the control channel fixed on the control interface for exchanging control packets. The other $N - 1$ channels are the data channels used by the data interface for data transmission and reception. In order to guarantee the connectivity and channel utility, the control channel can also send packets only if the control channel is available. Let $C(i)(i \in [1, N])$ denote raw capacity of each channel, E denote the set of wireless links $l(i, j)$ with which nodes can send packets directly, k_i is the number of NICs with which node i is equipped, L_i

denotes traffic load of each node i . In order to keep the channel information, each node i maintains a table to record the latest channel statuses of its neighbor nodes. And each node i will notify its neighbor nodes with the simple control message if it changes its channel.

In order to receive packets successfully, the channel assignment scheme is constrained by the interference and power control scheme:

$$SINR_{l(i,j)} \geq SINR_{th} \quad (7)$$

In addition to the application of the interference model, the use of channels and NICs must be restricted to a rational number, meaning that the number of channels and NICs used by a node or a link cannot exceed the respective upper bounds. Considering the constraint of the number of NICs, each node i can only have k_i NICs available, so we have:

$$NICNum(i) \leq k_i \quad (8)$$

At the same time, considering the channel constraint, the available channel for wireless links $l(i, j)$ depends on the assigned channels $NICNum(NL_i)$ for the neighbor links, so we can get:

$$NICNum(i) \leq N - NICNum(NL_i) \quad (9)$$

Furthermore, we should consider the multilinks between two nodes and interference between nodes. Let $NIC_{i,c}$ be a binary variable, which should be unity if a NIC of node i employs channel c . Otherwise, it should be zero. If node k interferes with link $l(i, j)$ on channel c , we employ binary variable $\sigma_{k,l(i,j),c}$ to denote the case and set its value as 1. Otherwise $\sigma_{k,l(i,j),c}$ should be zero. Let $\theta_{l(i,j),c}$ denote a binary variable, which should be unity if traffic passes it on channel c . Otherwise, it is zero. The channel assignment is also constrained by following conditions:

$$L_i \leq \sum_{m \in NICNum(i) \cap NICNum(j)} C_m - \sum_{c \in [1, N]} \sigma_{k,l(i,j),c} C_m \quad (10)$$

Equation 10 constrains the summation of the loads of links in $l(i, j)$ on channel c not to exceed the raw capacity of channel c . Similarly, if link $l(i, j)$ is unloaded, then the summation of load of links can be as large as the raw capacity multiplied by the number of links in $l(i, j)$:

$$1 \geq \sum_{c \in [1, N]} \theta_{l(i,j),c} \geq 0, \quad \forall l_{uv} \in E \quad (11)$$

Equation 11 allows only one channel to be assigned to an arc. That is, link $l(i, j)$ has two arcs with different channels to transmit the traffic.

In order to maximize system throughput, the channel assign scheme should also take more traffic request R_i into consideration. Let ψ^i be a binary variable, which is unity if request R_i is accepted. Otherwise, it is zero. Notably, ψ^i is set to unity if each MAP from source to destination has sufficient bandwidth for request R_i . Otherwise, ψ^i will set to zero. Then we have:

$$\sum_{v \in V} \sum_{c \in [1, N]} \theta_{l(i,j),c} = \psi^i \quad (12)$$

$$\frac{1}{N} \sum_{c \in [1, N]} \theta_{l(i,j),c} \leq \theta_{l(i,j)} \quad (13)$$

$$\theta_{l(i,j)} \leq \sum_{c \in [1, N]} \theta_{l(i,j),c} \quad (14)$$

$$\sum L_i + \sum R_i \leq \sum_n C_n(i, j), n \in [1, N], i \in V, j \in V \quad (15)$$

The objective is to accommodate maximum traffic throughput with the constraints mentioned above, as:

$$\max \sum_n C_n(i, j), n \in [1, N], i \in V, j \in V, l(i, j) \in E \quad (16)$$

Many existed schemes show that routing and channel assignment problems are both NP-complete, and considering both routing and channel assignment simultaneously is impossible. Although linear programming scheme was introduced to solve the routing and channel assignment problem in WLAN mesh networks, the computation time of linear programming is too high to be acceptable. Some heuristic strategy is required since it has less computation time and yields an acceptable solution. Therefore, the two problems are considered individually. The heuristic algorithm employs a routing algorithm to determine the routing for each request. The routing scheme will estimate the approximate load of each link and the most suitable channel is assigned to each link.

The proposed heuristic algorithm comprises expected load estimation phase and channel assignment phase. In expected load estimation phase, the system will construct the routing for each request with computing the expected load, the expected wide band available load and the expected reduction in load of each link in the network. Each node i will record its existed traffic T_i , and its new generated traffic request R_i . The new

generated traffic request R_i can be estimated by some distributions. Then the expected traffic load E_i of node i can be estimated.

In channel assignment phase, the system selects the eligible wide band available nodes and assigns the most suitable channel to them and their related wide band available links. Finally, a channel is assigned to the rest of links. In order to estimate and alleviate interference of nodes, the system must check the conflict links in the graph $G(V, E)$.

For each link $l(i, j)$, find the all links (denoted as set S) within two-hop distance. Then the system will calculate the $SINR(i, j)$ with expression (1). Then if $SINR(i, j)$ or $SINR(j, i)$ is less than $SINR_{th}$, which means that the links set S will interference the communication. If $s_k \in S$ interference link $l(i, j)$, then we set the weight value $w_{s_k, l(i, j)}$ to 1, otherwise, set $w_{s_k, l(i, j)}$ to 0. After checking all links, we connect vertex s_k to vertex $l(i, j)$ if $w_{s_k, l(i, j)}$ equals to 1. Then we can get the number $|NI(i, j)|$ and set $NI(i, j)$ of interference links for each link. And the graph $G(V, E)$ can be denoted as interference graph $G(V_{l(i, j)}, E_{l(i, j)})(l(i, j) \in E)$. Then the system will performance channel assignment scheme as shown in Algorithm 3.

Algorithm 3: Channel assignment algorithm

```

Input:  $G(V, E), k_i, N$ 
Output: links with scheduled channels  $L_C$ 
1 for each link  $l(i, j)$  do
2   calculate interference graph  $G(V_{l(i, j)}, E_{l(i, j)})$ ,
    $NI(i, j)$ ;
3   Sort the links of  $NI(i, j)$  according to the
   interference number in descending order;
4   for each link  $l_m(i, j) \in l_m(i, j)$  do
5     Assign the largest capacity channel
      $n(n \in [1, N])$  to  $l_m(i, j)$  with the constraints
     (7) to (15);
6   end
7 end
8 return  $L_C$ ;

```

According to the proposed the channel assignment algorithm, it will give higher priority to the links with greater interference number for it sorts the links of $NI(i, j)$ according to the interference number in descending order. The channel assignment means that the greatest interference number is assigned to the higher capacity channel with the smallest interference, which will avoid and decrease interference between nodes. At the same time, the channel assignment scheme also considers the other constrain conditions, which will guarantee power control, number of NICs, channel capacity and the spatial reuse.

3 Simulation results

3.1 Simulation setup

In this section, experiments are carried out for performance evaluation of the proposed algorithm described in above section. The simulation tool NS-2 [16] is modified to validate the proposed scheme. In order to fairly compare all testing schemes, we enable the RTS/CTS exchange for all simulation runs. The background noise level is set to -93 dBm. We use a log-distance path-loss model with the path-loss exponent of four in additive white Gaussian noise (AWGN) channel to simulate the indoor mesh environment. A grid topology connecting MPs is used for evaluation. Adjacent MPs are 100m apart from each other. The transmission range of medium access control (MAC) protocol data unit (MPDU) is 120 m, and the carrier sense range of MPDUs is about 280 m. The 802.11a protocol suite is employed, and the MPDU length is fixed at 1,024 bytes. We evaluate the performance of the proposed scheme with wide band available by simulation and compare it with the MICA channel assignment approach [10] and the standard IEEE 802.11 to validate the effectiveness. We conduct the simulations under various mesh topologies. In the network are 12 available orthogonal channels, and each link in the network can be assigned one or two channels. Each node has up to four neighbors. The simulation results are the average value of 100 runs. Simulation parameters are shown as in Table 1.

In the simulations, the traffic requests will generate randomly to increase network load gradually. The valuation metric for the experiments is the throughput, energy consumption, end-to-end delay and the blocking ratio which is the number of rejected requests divided by the number of total requests. A request is accepted if routes exist between the source node and each destination node, and each link on these routes

Table 1 System parameters

Parameter	Value
Transmission range	120 m
Carrier sensing range	280 m
Interference range	240 m
Number of channels	12
Number of NICs	2~4
Rate of control channel	11 Mbps
Rate of data channel	0.5~11Mbps
Data frame size	1,024
SINR threshold	10 dB
Background noise	-93 dB

has sufficient available capacity. Otherwise, the request will be rejected.

3.2 Performance comparisons

In the first scenario we now consider the multi-hop grid topology networks with varying load. A 10×10 grid topology with 10 horizontal flows and the other 10 vertical flows was tested. Each node has 3 NICs. With the given grid topology, each source node will generate new traffic request randomly. We use constant bit rate (CBR) multimedia traffic with 200 Kbps. And the traffic profile is randomly chosen 100 call request pairs and the amount of each call request between source and destination pair was chosen at random range. The overall call request is the total arrival call requests during a unit time.

Figure 3 shows the comparison of blocking ratio using three algorithms that each node equipped with varying NICs. We can see that the blocking ratio of IEEE 802.11 almost keeps constant whatever the number of NICs is. The blocking ratio just decreases from 0.7 (2 NICs) to 0.63 (4 NICs), which means that the number of NICs has little advantage to accept new traffic requests. On the other hand, for MICA and the proposed scheme, a huge performance gain is obtained the number of NICs on each node is increased from two to three. The blocking ratio of the proposed scheme significantly decrease from 0.41 (2 NICs) to 0.21 (3 NICs), which is also obviously lower than that of MIC about 0.13 (2 NICs) and 0.1, respectively. However, the performance gain does not increase greatly as the number of NICs on each node is increased from three to four. The results reveal that the larger number of

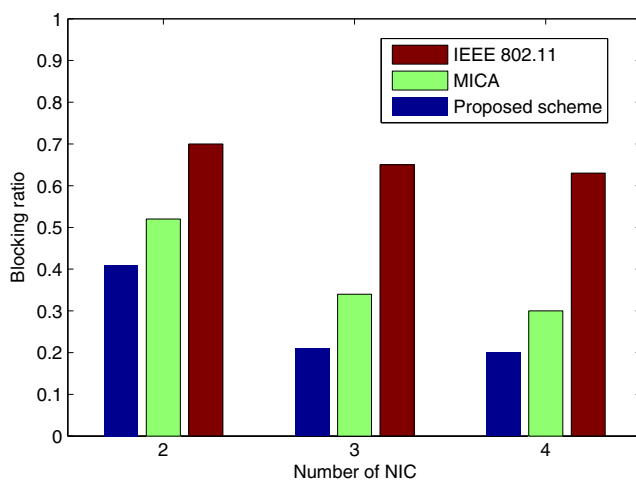


Fig. 3 Blocking ratio in grid topology with varying number of NICs

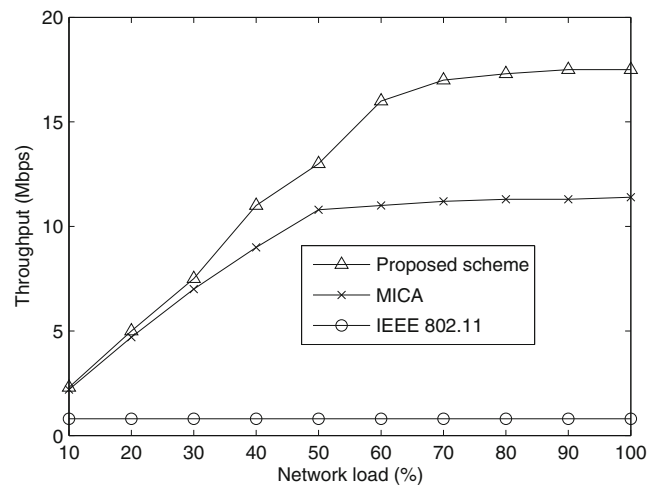


Fig. 4 Aggregate throughput in grid topology with varying network load

orthogonal channels that are available for WLAN mesh networks improves performance. Considering the cost, three NICs are enough for each node. In the following scenarios, we set k_i to 3.

Figure 4 shows the aggregate throughput in grid topology with varying network load. It's clear that the aggregate throughput of IEEE 802.11 almost keeps constant as 0.8Mbps. The reason is the fixed maximum power increase the interference between nodes. For the proposed scheme, the aggregate throughput increases more quickly than that of MICA. Because the proposed scheme can make full use of both channel diversity and spatial reusability to reduce co-channel interference by joint adjusting channel, transmission power and routing. The results show that proposed scheme has higher throughput and can achieve higher utilization of channels.

The energy consumptions of three schemes are shown in Fig. 5. The energy consumption of IEEE 802.11 keeps almost 1.8×10^{-3} Joules/Packet since it almost uses the constant transmission power. For proposed scheme, the energy consumption is lower than that of MICA and IEEE 802.11 at any network load. With load increasing, for the proposed scheme, the energy consumption decreases slowly from 0.8×10^{-3} Joules/packet to 0.6×10^{-3} Joules/Packet. However, for MICA, the energy consumption is about 1.5×10^{-3} Joules/Packet with 10% load, and it gets the smallest value at 60% load. Then it increases to 1.2×10^{-3} Joules/Packet too. The energy consumption error of two schemes is larger than 0.2×10^{-3} Joules/Packet. The reason is that the proposed scheme can change the transmission power adaptively, which saves power consumption. The efficient channel assignment scheme

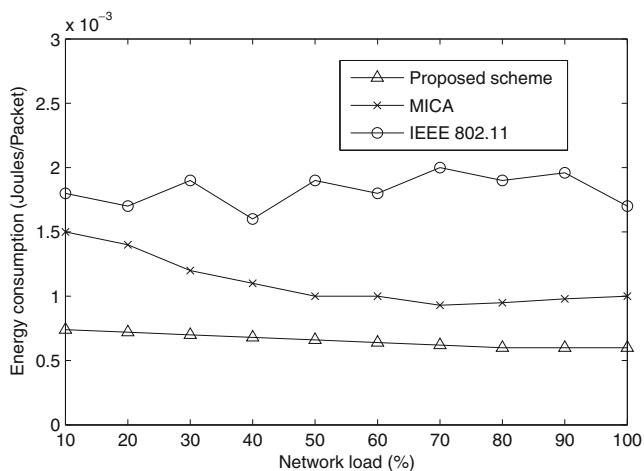


Fig. 5 Energy consumption in grid topology with varying network load

also increases the throughput, which will decrease packet collisions and save energy consumption. So the proposed scheme can save more power than those schemes. But MICA uses fixed transmission power at any case. With load increasing, the packet collisions also increases, which leads to more RTS/CTS collisions. Compared with frame collisions, RTS/CTS collisions decrease power consumption. So the energy consumption of MICA and the proposed scheme will slightly decrease with network load increasing. However IEEE 802.11 always uses the fixed maximum power to transmit control message. Hence the energy consumption almost keeps the same.

In the second scenario we evaluate and compare the performances of the proposed scheme and MICA in randomly generated network topologies. Within a 800×800 m² area, 100 mesh nodes are randomly placed. A gateway node is located in the right upper corner of the area. In each scenario, all mesh nodes (except the gateway) generate traffic randomly. We simulate 40 different scenarios.

Figure 6 shows the aggregate throughput in random topology with varying network load. The results are similar to Fig. 4. Compared with Fig. 4, the throughput of three schemes in random topology is slightly higher than that in grid topology. The possible reason is that the node density in the grid networks is more uniform than the density in the random networks. Therefore, each node in the grid topology confronts much more contention than the random topology. The more contention will lead to more interference. With network load increasing, the aggregate throughput of the proposed scheme and MICA also increases. But for IEEE 802.11, the aggregate throughput almost

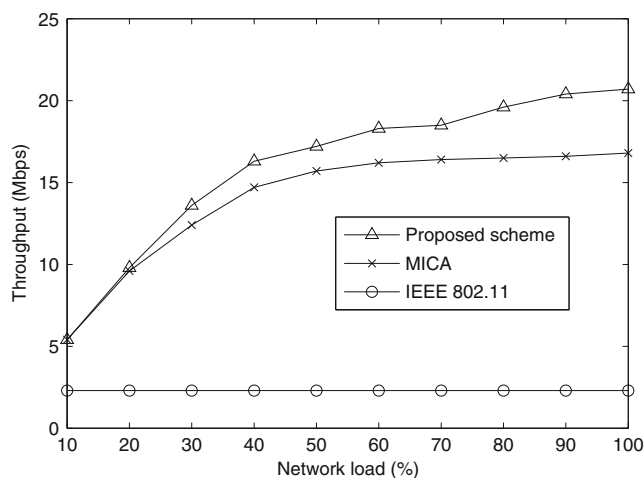


Fig. 6 Aggregate throughput in random topology with varying network load

keeps constant as 2.3 Mbps, since the fixed maximum power increase the interference between nodes. For the proposed scheme, the aggregate throughput increases more quickly than that of MICA. As network load increasing, the error between the proposed scheme and MICA increases obviously. The reason is that the proposed scheme can make full use of both channel diversity and spatial reusability to reduce co-channel interference by joint adjusting channel, transmission power and routing. Especially in random topology, the control channel can guarantee the network connectivity and channel utility.

From Fig. 7, we can see the similar results as shown in Fig. 5. Since there are more collisions in the random topology, the energy consumption of three schemes is

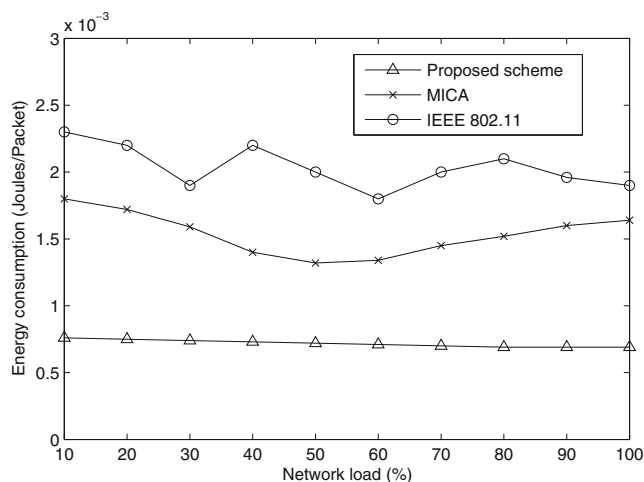


Fig. 7 Energy consumption in random topology with varying network load

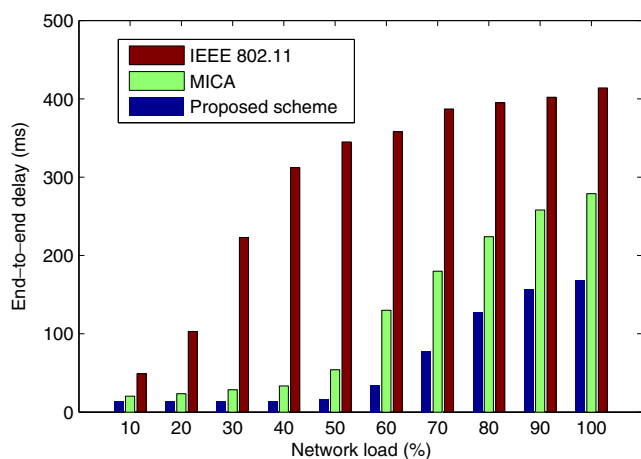


Fig. 8 End-to-end delay in random topology with varying load

a little higher than that of chain topology. For IEEE 802.11, the energy consumption increase to 2.2×10^{-3} Joules/Packet on average. It is clear that, for proposed scheme, the energy consumption is slower than those of MICA and IEEE 802.11 at any network load, which almost keeps constant about 0.8×10^{-3} Joules/Packet. However, for MICA, the energy consumption is about 1.8×10^{-3} Joules/Packet with 10% load, and it gets the smallest value at 50% load. Then the energy consumption increases to 1.52 Joules/Packet too. The energy consumption error of two schemes is larger than 0.5×10^{-3} Joules/Packet. Compared with Fig. 5, we can see that with random topology, the energy consumption is clearly high than that with chain topology for MICA. The reason is that MICA can't control transmission power and assign channel efficiently, which will lead to more frame collisions, and the power interference also limits the nodes can hearing RTS and CTS messages. With load increasing, such scheme decreases throughput and increase energy consumption. For the proposed scheme, it improves spatial reuse by adjusting transmission power, and saves power greatly.

Figure 8 shows the average end-to-end delay of different schemes. As shown in Fig. 8, for the proposed scheme, the end-to-end delay of nodes random selected with different connections and different hops, is clearly lower than those of MICA and IEEE 802.11. It is obviously the end-to-end delay of IEEE 802.11 is the highest in the schemes. In particular when the load increases to 30%, the end-to-end delay of IEEE 802.11 will abruptly increase to 223 ms. The delay will still increase slowly to 414 ms with the load increasing, which is obviously higher than the proposed scheme about 246 ms. This is because the power selection and transmission scheme of IEEE 802.11 can't make full use of space and channel diversity. With load increasing, for

the proposed scheme, the end-to-end delay increases slightly. Especially when the load is less than 50%, the delay keeps almost constant 14ms. However, for MICA, the end-to-end delay is slightly higher than that of the proposed scheme. The error between MICA and the proposed scheme will increase as network load increasing. The results demonstrate that proposed scheme can decrease end-to-end delay by adjusting transmission power to increase spatial utility.

4 Conclusions and future work

This paper studies the problem of power control, routing and channel assignment in multi-channel and multi-interface WLAN mesh networks. In order to improve power efficiency and capacity of WLAN mesh networks, especially to improve channel assignment, an efficient power control scheme is proposed which adjusts nodes' transmission power appropriately according to the distances between them. The problem of routing and channel assignment in a multi-channel and multi-interface WLAN mesh network is resolved by a simple heuristic algorithm. Detailed simulation results and comparisons with related work show that the proposed scheme is effective in multihop WLAN mesh networks, especially for real-time traffic at heavy traffic load, which makes the system achieve better channel utilization, decrease end-to-end transmission delay and energy consumption because the scheme can get the load status and interference between nodes.

Although WLAN mesh networks can be built up based on existing technologies, field trials and experiments with existing WLAN mesh networks prove that the performance of WLAN mesh networks is still far below expectations. We will keep track of standardization activities of 802.11s and improve the WLAN mesh network performance with the new features.

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