INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. 2012; **25**:1122–1138
Published online 28 June 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/dac.2385

A dynamic channel assignment strategy based on cross-layer design for wireless mesh networks

Weifeng Sun, Tong Fu, Feng Xia*,†, Zhenquan Qin and Rong Cong

School of Software, Dalian University of Technology, Dalian 116620, China

SUMMARY

In wireless mesh networks (WMNs), if nonoverlapped channels or partially overlapped channels are used properly, the throughput can be improved drastically. However, the number of nonoverlapped channels is limited in wireless communication standards. An effective channel assignment algorithm for a WMN is necessary to increase the utilization rate of space and nonoverlapped channels. Static channel assignment algorithms can improve network throughput, but their accuracies are not satisfactory in common scenarios. Dynamic channel assignment algorithms can allocate channels according to the status of adjacent links in WMNs. A dynamic channel assignment algorithm needs cross-layer design to get the information of routing. A routing-information-aware channel assignment algorithm based on a cross-layer design is proposed, which is named R-CA. The proposed method can dynamically allocate channels for wireless nodes when they need communication and release channels after data transmission. In R-CA, limited channel resources can be used efficiently by more wireless nodes, and hence the communication throughput can be improved. Simulation results show that our channel allocation strategy can effectively ensure and enhance the network throughput and packet delivery rate in WMNs. Copyright © 2012 John Wiley & Sons, Ltd.

Received 16 August 2011; Revised 18 May 2012; Accepted 22 May 2012

KEY WORDS: dynamic channel assignment; wireless mesh network; cross-layer design; routing

1. INTRODUCTION

The wireless mesh network (WMN), different from the mobile ad hoc network, is emerging as a promising technology for low-cost, high-capacity, flexible, and ubiquitous broadband Internet access [1]. It combines the advantages of wireless local area networkimg and ad hoc networks. In a WMN, a collection of wireless access routers provides connectivity for mobile clients acting as access points in a traditional wireless local area network, and access routers communicate with each other wirelessly and potentially over multiple hops. A small fraction of those access routers are wired to the Internet and serve as Internet gateways for the rest of the network. Wireless mesh networks based on commodity IEEE 802.11 hardware and employing self-configuring ad hoc networking techniques can offer wider coverage with less expense and easier deployment. Consequently, WMN can be put into a number of new application scenarios, including community wireless networking to provide affordable Internet access, especially beneficial for low-income neighborhoods and scarcely populated areas.

IEEE 802.11-based wireless mesh access points can possess many multiple radio interfaces. Every interface uses an available nonoverlapped or partially overlapped channel (IEEE 802.11b/g standards have three nonoverlapped channels in 2.4 GHz band, and the original IEEE 802.11a standard has 12 nonoverlapped channels in 5.15–5.35 GHz and 5.725–5.825 GHz bands mostly in synchronous). Wireless mesh access points can communicate with many other neighbor points at

*Correspondence to: Feng Xia, School of Software, Dalian University of Technology, Dalian 116620, China.
†E-mail: f.xia@ieee.org

the same time with multiple radios and multiple nonoverlapped channels. However, for propagation characteristics of wireless signals, a node can receive all signals within its receiving range and send data in all directions equally in theory. It has a serious drawback, namely channel interference. Interference arises whenever two or more nodes try to communicate on the same or adjacent channels within each other's receiving range at the same time. It results in high packet loss rate, high delay, and low network throughput. Channel assignment algorithms are proposed for solving this problem [2]. The goals of channel assignment algorithms are to minimize the interference between wireless communicating links, and improve the quality of communications.

This paper addresses the channel assignment problem and specifically investigates the dynamic cross-layer channel assignment methods in wireless mesh networks. The contributions of this paper are outlined below.

- A novel routing-based dynamic channel assignment algorithm is presented. The method can employ multiple channels simultaneously by equipping each node with multiple interfaces. It is a cross-layer design between the network layer and media access control (MAC) layer.
- The algorithm can flexibly select channels for the network interface radios of mesh nodes. The routing-based channel assignment algorithm (R-CA), which includes distribution algorithm and response management algorithm, can minimize the interference within the communications in wireless mesh networks.
- Examples are presented and simulations are carried out to show the efficiency of our algorithm. The algorithm can get higher performance with the increasing of nonoverlapped or partially overlapped channels. Analyses also show the usability and effectiveness of the channel assignment method.

The remainder of the paper is organized as follows. Section 2 lists some channel assignment and wireless spectrum algorithms. Section 3 proposes routing based on dynamic channel allocation strategy named R-CA. Section 4 describes the simulation and performance evaluation. Section 5 concludes the paper.

2. RELATED WORK

Many researchers have studied channel assignment and spectrum allocation algorithms in wireless multihop networks. The channel assignment mechanism involves allocating channels to each link efficiently and satisfying the electromagnetic compatibility constraints. Channel assignment algorithms are generally classified into fixed and dynamic algorithms. The fixed channel assignment algorithm is simplified, and it is designed based on long-term traffic demands. However, it cannot adapt to traffic variation. Therefore, it will result in poor bandwidth utilization.

Dynamic channel assignment algorithms can be regarded as centralized or distributed algorithms. Channels are pooled together and then assigned and modified in real time. This kind of assignment scheme has the potential to achieve significantly improved bandwidth utilization, especially when there are many temporal or spatial traffic variations.

Wu *et al*. [3] studied the problem of channel assignment in multiradio and multichannel wireless mesh networks, considering the support of opportunistic routing technique. The channel assignment problem is modeled, and an opportunistic routing protocol and workload-aware channel assignment and routing algorithms are proposed.

Li *et al*. [4] proposed a remap method, which is a simple, novel paradigm that uses retransmission permutation for decoding collisions in overlapping OFDM channels. The method is implemented in IEEE 802.11g, and the experiment results show that the diversity created by remapped frames can substantially improve decoding efficiency and increase wireless communication throughput.

Marina *et al*. [5] proposed the CLICA (connected low interference channel assignment) algorithm. It translates the channel assignment problem into a coloring problem. In CLICA, the authors create a weighted conflict graph according to the protocol model and use this graph to show the status of conflict channels. CLICA minimizes the maximum interference of each link, but reduces the expansibility of channel assignment. It is a theoretic channel assignment algorithm and it cannot be used in practice.

DOI: 10.1002/dac

Subramanian *et al.* [6] proposed that the channel assignment problem is minimizing the maximum network interference when the number of radio frequencies is limited. The algorithm uses tabu search technique to color the nodes of the conflict graph. However, it may create network shock, so it can only be used in a static network.

The channel allocating information should be shared between different nodes. Gong and Midkiff [7, 8] proposed that nodes use common channels to send and receive route information and control information. Some algorithms [9, 10] are based on packets to communicate information. They may reduce throughput and increase delay because of frequent channel switching. Some other algorithms (e.g., [11]) are based on flows. This kind of algorithm needs a complex iterative process, and it will make the switching channel frequent when network traffic is changed.

Raniwala and Chiueh [12] proposed a centralized interference-aware channel allocation called breadth first search channel assignment. Essentially, the algorithm is a greedy algorithm. In [12], the authors considered that current data flows will interrupt when the communicating nodes switch their channels. In the breadth first search channel assignment algorithm, the data flows will use default channels to transfer data to avoid loss. However, the algorithm needs every node using a channel to obtain the number of interference radio. Therefore, some channels will be wasted.

Ramachandran *et al.* [13] took into account the stability of the wireless mesh network topology and tree aggregation traffic. Their algorithm uses a gateway as the root of the logical tree topology. The algorithm includes a load-balancing routing algorithm, an adaptive traffic load channel assignment algorithm, and a fault recovery mechanism. Moreover, it summarized how to solve the dependence problems of channel assignment and the principles of distributed channel assignment. Skalli *et al.* [14] proposed a static channel assignment algorithm, called Mestic algorithm. With this algorithm, nodes do not need to switch channels frequently, and the cost is lower. However, it is not applicable to the status wherein the network topology transformations are frequent.

Most of the researches mentioned above used nonoverlapped channels directly in wireless multihop networks, while the nonoverlapped channels are limited in IEEE standards. Mishra *et al.* [15] studied the partially overlapped channels. They modeled partial overlap between channels, and carefully used some partially overlapped channels, which can lead to significant improvements of performance. It is said that the channel assignment algorithm can improve the efficiency of channel utilization than that of the nonoverlapped channels utilization algorithm.

Yang *et al.* [16] found that the traditional 'one-size-fits-all' approach to guardband assignment is ineffective. The guardband values can be set based on network conditions and adapt to changes. The implemented intelligent guardband configuration system Ganache shows that the guardband can be assigned dynamically. The technique can be used in dynamic channel assignment.

Wang [17] proposed two algorithms, called the centralized joint rate regulation and power control algorithm and the distributed joint rate regulation and power control (DJRRPC) algorithm, to maximize the data rate and at the same time to minimize the transmitting power on each hop of the wireless network. However, the proposed DJRRPC algorithm needs to reduce certain transmission link's rate by the parameter Δ in each iteration. Therefore, it will take more execution time than the integrated power and rate control algorithm. Increasing the value of Δ can improve the execution time of the proposed DJRRPC algorithm. Also, this can affect its performance in terms of data rate.

Cho *et al.* [18] considered cooperative power allocation based on partial channel state information in a multicell multiuser dual-hop MIMO relay system. They showed that the end-to-end capacity of the proposed scheme is maximized when the principal eigenvectors of the transmit correlation matrices of the desired and interference channel are orthogonal to each other, and that it notably outperforms the average signal-to-noise ratio-based and correlation-based power allocation schemes in interference-limited environments.

Kao *et al.* [19] presented an analytical model for dedicated control channel protocols using discrete-time Markov chains and an M/M/k model to evaluate the network throughput under saturated and unsaturated conditions. Furthermore, based on the model, the adaptive initial window size tuning scheme was proposed to improve network throughput for dedicated control channel protocols. A novel multichannel MAC protocol is proposed to reduce redundancies and schedule more packets to achieve ideal maximum throughput. However, the proposed model has not been extended for multihop scenarios.

Channel assignment in WMN is addressed jointly along with the problem of routing and balancing of mesh nodes. The proper assignment of channels is crucial to choosing the lowest interference path during routing. In [20], the authors addressed the joint problem by formulating it as a set of linear programming constraints. This problem is divided into three subproblems, which are channel assignment, flow routing, and link flow scheduling. It shows that allocating channels dynamically in a wireless network is available.

Cross-layer design can obtain more information from the network layer, MAC layer or other layers, and it has been widely used in designing protocols and optimizing algorithms for wireless multihop networks. Bononi *et al*. [21, 22] proposed a cross-layer architecture and designed a novel joint multipath routing and channel allocation scheme for multiradio WMN. In this method, channel allocation is performed during the routing setup. They also proposed a load-balancing scheme. The algorithms are performed based on their architecture and model.

This paper deals with assigning adapted channels dynamically during routing and minimizing the interference. This is a cross-layer strategy, which shares the information between the network layer and MAC layer. We researched the disadvantages of existing channel assigned algorithms and propose a new R-CA algorithm to solve the dynamic channel assignment problem [23]. Simulation results show that R-CA achieves a much better performance in reducing interference in an IEEE 802.11-based multichannel mesh network.

3. DYNAMIC CHANNEL ASSIGMENT BASED ON CROSS-LAYER DESIGN

3.1. Problem description

For an allocation method to be successful, it must satisfy the following conditions:

- Consider the channel assignment problem on a static wireless network of N nodes, each of which has K interfaces. Let C denote the number of available nonoverlapped channels; in most cases we have $C > 1$, which means we have more than one nonoverlapped channels in our network topology and the cost of $C \geqslant K$ should also be considered, which means the number of available nonoverlapped channels is more than interfaces of nodes.
- Given an assignment of channels to a communication, nodes i and j can communicate if and only if they share a common channel and they are within the communication range of each other. A link will exist between node i and j under these conditions. This is one of the goals to ensure the network connectivity in the channel assignment.
- Avoid the interference among two or more receiving ranges as much as possible. This is another goal of channel assignment, which ensures the quality of communication.
- Easy to be used in the wireless mesh network and can adapt to the variable transmitting qualities of wireless links, especially in wireless multihop networks.

Moreover, in the multichannel wireless network, some other problems must be considered such as channel coordination problem and network capacity problem.

For ensuring communication between nodes, channel coordination is necessary. It includes three main aspects: channel synchronization, hidden terminals, and broadcast.

Before each communication, the sender must ensure that the receiver is listening on the same channel. If not, a situation might happen wherein node A wants to use Channel 1 to send a packet to node B, which works on Channel 2, and node B cannot receive this packet. After failing to send the packet repeatedly, A will confirm that the link to B is broken and drops it, so the channel must synchronize before being used. The hidden terminal problem is an example of channel synchronization.

In single-channel networks, nodes use the RTS/CTS (request to send/clear to send) mechanism to avoid hidden terminals and expose terminal problems. However, in multichannel networks, the channels that can be used are more than one. Lack of information exchange between adjacent nodes may cause interference and collisions. For instance, node A uses Channel 1 to send packets to node B. Node C, and adjacent nodes of A, do not know this information and use Channel 1 to send packets to B. This will result in a hidden terminal problem wherein B cannot receive data.

DOI: 10.1002/dac

Another problem is the broadcast in multichannel networks. Nodes can only listen to the broadcast in the same channel. A wireless channel is a kind of broadcast medium. In single-channel networks, if a node sends a packet, all nodes in the communication zone will receive it. However, in multichannel networks, adjacent nodes work in different channels, and not all nodes can receive broadcast packets when a node broadcasts. This makes the exchange of information among nodes difficult.

Normally, three methods are used for these problems. One way is that each node switches channels according to a fixed scheduling policy. Channel scheduling can be set up prior to network deployment and generated. Each node in this method uses a fixed and accurate time to switch channels. It needs clock synchronization service algorithms. Another way is that all nodes in the network periodically switch to a public channel and stay in this channel for a period of time. This method needs clock synchronization, and the time which node works on a channel will affect the performance of the network. The last method is that each node uses a common channel to exchange information. In this way, every node must have several network interface cards and one of them binds a settled channel. Nodes use this channel to monitor and exchange channel information. It only needs more network interface cards or a soft-radio as the transceiver described in [24].

In multichannel networks, a node will communicate intensively in certain areas in a period of time. In these areas, using more channels can cause more interference. How to balance the channel resources has become an important issue. It is necessary to reduce interference and improve network performance.

The present studies on channel assignment focus on the static assignment strategy. Static strategy has the drawback of reallocating channels to correct mistakes. The process could change the network topology of nodes besides time consumption. Also, these drawbacks are fatal. To solve the channel assignment problems dynamically, we propose a routing-based channel assignment algorithm called R-CA. Channels assigned on the links are dynamically changed with the next-hop routing information in our algorithm.

3.2. *Algorithm design*

The details of the algorithm are described in this section. R-CA needs additional information and it can assign proper channels to links based on the information.

In R-CA, every node uses a fixed interface to bind a common channel for exchanging routing information and channel information. This method increases the cost of mesh nodes, but it is efficient.

The R-CA needs every node to generate and maintain a table, and the main data (named channel_info) are shown in Table I. Channel_info includes the channel expected to occupy by communication (c_{pre}) initialized to 0, channel occupied by communication (c_{cur}; may have more than one value) initialized to 0, and expected completion time for data transmission (t_{pre}) initialized to 0. c_{pre} is used to mark the channel that will be used. c_{cur} is the channel occupied currently. t_{pre} is calculated by node and used in the response management algorithm to control response information. t_{pre} is computed by expected transmission count $\times S/B$, where S is the packet size and B is the link capacity.

Table I. Channel_info of node.

Channel expected to occupy by communication	c_{pre}
Channel occupied by communication	c_{cur}
Expected completion time for data transmission	t_{pre}

DOI: 10.1002/dac

The algorithm of R-CA includes two sections, distribution algorithm and response management algorithm. Distribution algorithm uses the result of the response management algorithm.

Algorithm 1: distribution algorithm

do {
  if (no channel c_{pre} that is noninterrupting with c_{cur})
    {wait for an available channel; }
else
 {while (c_{pre} is available)
  {node updates its c_{cur} list;
   $c_{\text{cur}} = c_{\text{pre}}$;
   route to next hop node with channel c_{pre}; }
   node calculates t_{pre};
   if (no available channel)
    {use Algorithm 2 to decide the next step;
     if (respond routing to another node)
      {notice last hop to route to another node ; }
     if (respond waiting)
       {store address;
     notice all nodes before to wait for available channel;
        notice next hop to store its address ; }
     }
    else routing ; }
} while (do not find out the destination node and complete channel assignment)

Algorithm 1 is the main algorithm. It allocates channels when a node routes packets and forwards frames to the next hop. When there is no available channel to use, Algorithm 1 uses Algorithm 2 to decide which channel should be allocated.

When a node A routes, its broadcast packet carries c_{pre} besides the routing information. The nodes around it receive the broadcast packet and update c_{cur} if channel c_{cur} is 0. If other nodes route to one of these nodes, they will decide the next step themselves and do not impact node A. Algorithm 2 uses this method to avoid channel interruption between adjacent nodes.

Algorithm 2: response management algorithm

receive routing packet;
if (channel is unavailable)
  {compare receive t_{pre}(named $t_{\text{pre}}{}'$ here) with its own t_{pre};
   if ($t_{\text{pre}}{}' < t_{\text{pre}}$)
    {respond with information that route to another node ; }

DOI: 10.1002/dac

else {respond to wait for a available channel;
compute t_{pre} and update channel_info;
notice its address to next hop node ; }
}
else
{respond with information that channel is available and keep on routing ; }

Algorithm 2 is designed to deal with response information. It is used when a node needs to change routing paths or wait for available channels.

In response management algorithm, there may be several nodes that are waiting for one node, called waited-node, to give up the channel at the same time. Then, when waited-nodes give up the channel, which node first uses this node and this channel is an important problem. For this question, we define a queue to store the addresses of nodes that wait for the channel (this kind of node is called waiting-node.). The waited-node uses queuing to store addresses of the waiting-nodes. After the waited-node gives up the channel, the first node in the queue can use this channel to route to waited-node. When the queue is full, waited-node refuses to store addresses of other nodes and notices the node that wants to store the address. The length of the queue cannot be too large, which will cause the node to wait for too much time and decrease the performance of the network.

The R-CA uses expected completion time for data transmission t_{pre} and the length of the queue as routing metric. When the queue of a node is full, the load of this node is too much. Other nodes cannot communicate with it. This method limits the number of flows that go through a node. It avoids the loads of one node being too much but others are less.

3.3. Routing protocol

In R-CA, channel information is carried by routing packets. A node allocates a channel for communication according to received data and its own data in the channel info. However, the present routing protocol cannot carry MAC information. A routing protocol based on cross-layer method is proposed. The process of this protocol includes two interaction sections such as routing start-up and reply. The packets of routing start-up include c_{pre}, c_{cur}, t_{pre}, and data size besides routing information. The packets of reply include c_{cur}, t_{pre}, and response information besides routing information.

The process of routing start-up and reply is as follows. Figure 1 shows the process of routing start-up. A, B, and C are mesh nodes, C1 is common channel, C2 and C3 are used to transfer data. Three nodes work on channel C1 to transfer routing information. Every node updates its channel_info when it receives routing packet.

Figure 2 shows that nodes reply routing information. In Figure 2(a), if the channel is coordinated between B and C, C replies to B with channel C3, and the same as B and A. In Figure 2(b), if channel C1 is available to occupy, B will notice its channel information and change channel message to

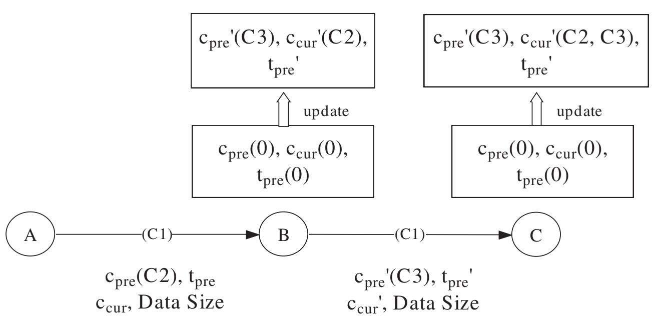
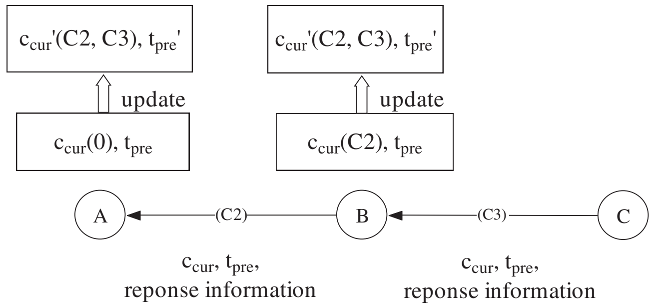
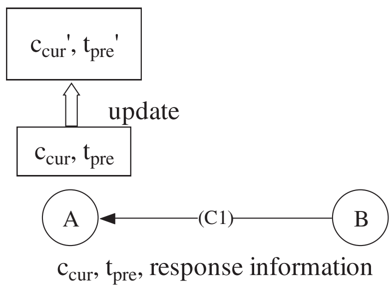


Figure 1. Process of routing start-up.



(a) Successful reply



(b) Unsuccessful reply

Figure 2. Process of reply in different conditions.

A. Then node A updates its channel_info and chooses an available channel to coordinate with B. If no channel can be used, A tries to link another node or waits for an available channel.

3.4. *Selection of available channels*

This section discusses the effect of the performance of the algorithm in nonoverlapped channels environment or in partially overlapping channels environment.

In IEEE 802.11b/g, 11 channels are defined in the 2.4 GHz band. The bandwidth of each channel is 22 MHz and the center frequency interval between adjacent channels is 5 MHz. One channel overlaps with the other four adjacent channels partially at least. These channels are called partially overlapping channels. Interference appears between adjacent channels. IEEE 802.11b/g provides three nonoverlapped channels, Channel 1, Channel 6, and Channel 11 at most at the same time. Using nonoverlapped channels can avoid interference. However, if communication links around a node are more than three, interference of the same channel will appear. Also, if only three channels can be used, the channel resources will be wasted. Considering partially overlapping channels, the overlaps are only part of the adjacent channels. A channel signal can be interfered only on the part of the signal of adjacent channels. This means the interference zone or interference distance can be reduced.

Feng and Yang [20] proved that using partially overlapping channels can improve the performance of a network compared to only using nonoverlapped channels. Also, they provided a method for calculating the interference zone among different channels, which can be expressed as a function of channel separation Δ, as Formula (1).

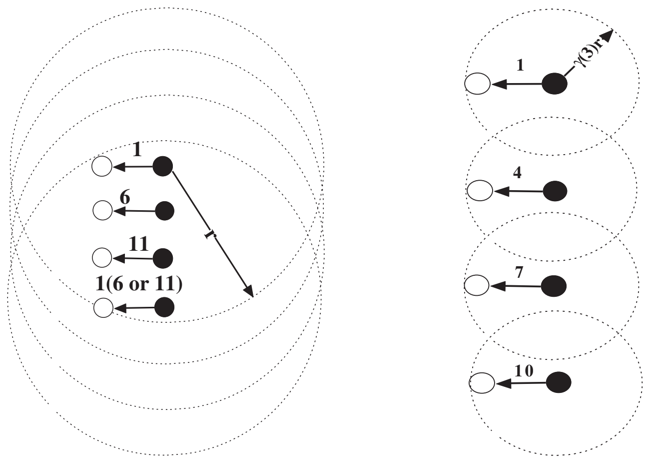
$$r(\Delta) = \sqrt[\alpha]{\beta(\Delta) \times T_{\mathrm{SINR}}} \times d = \gamma(\Delta) r(0)\,. \tag{1}$$

In formula (1), Δ is the channel separation, $r(\Delta)$ is the maximum interference distance when two links work on channels in which the channel separation is Δ. α is the loss factor of the path in free space ($\alpha = 2, 3, 4$). $\beta(\Delta)$ is the power receiving coefficient of different channels; if $\Delta = 0$, $\beta(0) = 1$. d is distance between two nodes; $\gamma(\Delta)$ is channel interference factor.

DOI: 10.1002/dac

Table II. Channel interference factor.

γ (α \ $\triangle$)	0	1	2	3	4	≧5
2	1	0.93	0.75	0.39	0.14	0
3	1	0.84	0.83	0.53	0.26	0
4	1	0.98	0.87	0.61	0.34	0



(a) r = 5 (b) r = 3

Figure 3. Interference zone of different channel separations.

Set $r(0)$ as the interference range of the same channel, that is, the maximum interference distance r.

$$r(0) = \sqrt[\alpha]{T_{\mathrm{SINR}}} \times d \, . \tag{2}$$

Then, according to Formula (2), channel interference factor with respect to the path loss factor α equaling 2, 3, and 4 can be calculated. The corresponding results are shown in Table II. In the table, γ represents $\gamma(\Delta)$, the channel interference factor.

Table II shows that the interference zone of different channels is shorter than that of the same channel. When channel separation is bigger than 3, the interference zone drops down to about 14% to 34%.

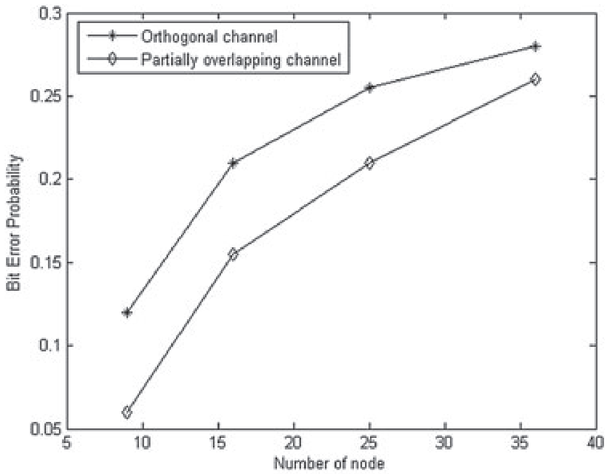
On the basis of the analysis above, we know that the interference range can be reduced largely when channel separation is wide enough.

This means that we do not have to be limited to the nonoverlapped channel. As long as the channel separation is wide enough, partially overlapping channel can also be used, which can increase the spatial reuse of frequency and decrease the interference. Taking the network in Figure 3(a), there are four pairs of 'send-receive' nodes. Solid nodes are defined as sending nodes, while hollow nodes are defined as receiving nodes. A dashed circle indicates the interference zone of each node that uses the same channel. If four links share the same channel, the maximum interference distance is r and data transmission on each link will cause interference to any other link. Any two links cannot share the same channel to transmit data. If nodes in the network use a nonoverlapped channel, there must be two links that are assigned to the same nonoverlapped channel. It will create interference and reduce the performance of the network.

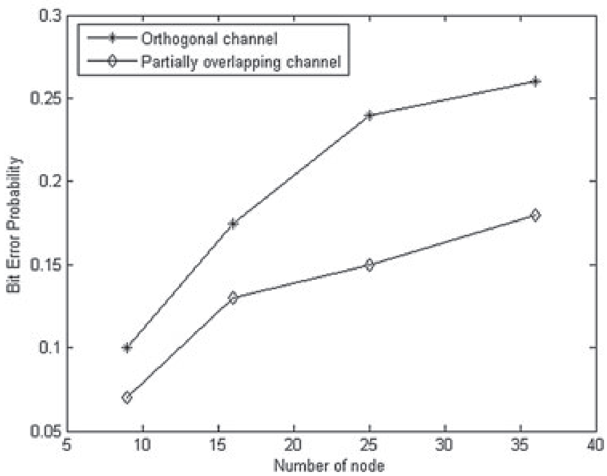
We assign a partially overlapping channel for the network, as shown in Figure 3(b). Dashed circles in the figure indicate the interference zone of the channel when the channel separation is 3. Channel interference factor is about 0.5 when α equals to 3. Interference distance between channels $r(3)$ is about $0.5r$. Each solid node is not in the others' interference zones. As shown in the figure, any two links will not interfere with each other as long as the channel separation is larger than three between two links. These links can transmit data simultaneously without interference and collision.

To show the effectiveness of interference in different channels, simulations are carried out. Figure 4 is one of the results of bit error probability between nonoverlapped channel and partially overlapping channel in different network environments. There are several simple networks in this example. They are based on IEEE 802.11b, and their scales are 3×3, 4×4, 5×5, and 6×6, respectively. Each node has R network interface cards ($R = 2$ or $R = 3$). Simulation time is 40 s. The distance of two nodes is 100 m. Transmission distance is 120 m. The interference distance of the same channel is 250 m. The data packet size is 512 bytes. The interference extent of different separation channels can be showed by the bit error probability. The separation is from 0 to 5.

In Figure 4(a), the number of network interface cards of each node is two. In Figure 4(b), each node has three NICs (network interface controllers). As the figure shows, bit error probability of nodes that use partially overlapping channels is lower than nodes that use nonoverlapped channels obviously. Also, the more NICs used, the more number of nodes bring less bit error probability. It



(a) Each node equipped with two NICs



(b) Each node equipped with three NICs

Figure 4. Bit error probability.

means that interference will decrease by using partially overlapping channels. The increment of the NIC number and the network scale can make interference decrease faster.

Partially overlapping channels are used in R-CA. Its model and the process of choosing channels are as follows:

$e_i = (v_m, v_n)$ is defined as one of the link between node v_m and node v_n, where v_m and v_n are two adjacent nodes in the network and they are two end nodes of link e_i. $d(e_i, e_j)$ is the distance between two links. $\Delta(i, j)$ is minimum channel separation for avoiding interference between adjacent links e_i and e_j. Interference range of nodes that use the same channel is r. Interference range of nodes that use different channels with interval Δ is $\gamma(\Delta)r$.

If the channel separation between two links is large enough, there is no interference. The process of selecting channel c_{pre} can be achieved as follows:

if $d(ei, ej) > r$

$\Delta(i, j) = 0$

else if $d(ei, ej) > \gamma(1)r$

$\Delta(i, j) = 1$

else if $d(ei, ej) > \gamma(2)r$

$\Delta(i, j) = 2$

else if $d(ei, ej) > \gamma(3)r$

$\Delta(i, j) = 3$

else if $d(ei, ej) > \gamma(4)r$

$\Delta(i, j) = 4$

else $\Delta(i, j) = 5$

$c_{pre} = \max\{(c_{cur} + \Delta(i, j)) \bmod 11\}$

if $(c_{pre} - \max\{c_{cur}\} < 5)$

$c_{pre} = 0$ //No channel can be used

Here, when c_{cur} stores more than one channel information, at most n (n is the length of the queue *wait_node*), the value of c_{pre} should be the maximum one. It will obtain the maximum separation of each channel. If the maximum c_{pre} interferes with one channel in the c_{cur}, no available channel can be used and the node waits for a free channel or change links.

3.5. Processes and Interactions of R-CA

This section uses some examples to explain R-CA. In the R-CA, the source node can allocate channels according to the status of adjacent nodes until it finds the destination node. A channel is used only when the node needs to communicate and it will be free after communication to provide more usable nonoverlapped channels for network. Three cases will appear in R-CA:

(1) At least one available channel can be used. Nodes use it directly.
(2) No available channel can be used. Node routes through another node.
(3) No available channel can be used. Node waits for a free channel.

Next, there are some examples to show the whole process of the algorithm.

Figure 5 shows a simple channel assignment process of two nodes. After B receives the channel information of A, B calculates t_{pre} and updates channel_info. Then, B checks its c_{cur} and receives c_{pre}. If channel c_{cur} and c_{pre} are not interrupting, B adds c_{pre} to its c_{cur} and allocates channel c_{cur} between A and B. If they are interferential, B compares received t_{pre} (named $t_{\text{pre}'}$ here) with its own t_{pre}. Then, respond waiting when $t_{\text{pre}'} < t_{\text{pre}}$. Otherwise, the response is routing through another node.

DOI: 10.1002/dac

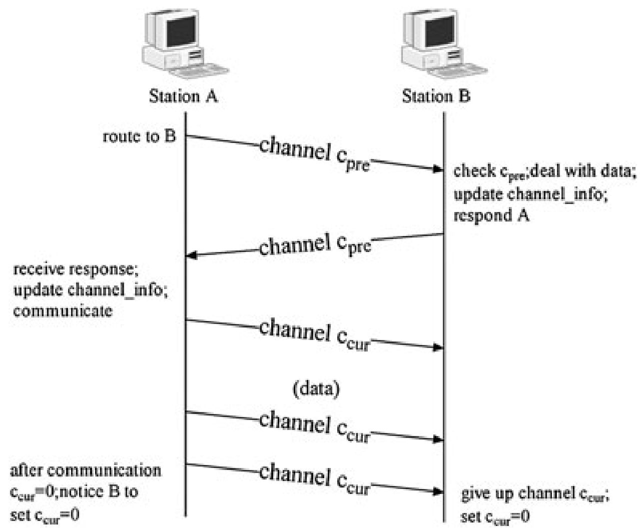


Figure 5. Channel assignment diagram of two nodes.

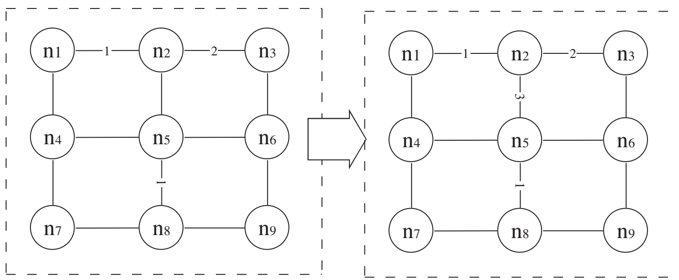


Figure 6. Channel assignment of Case 1.

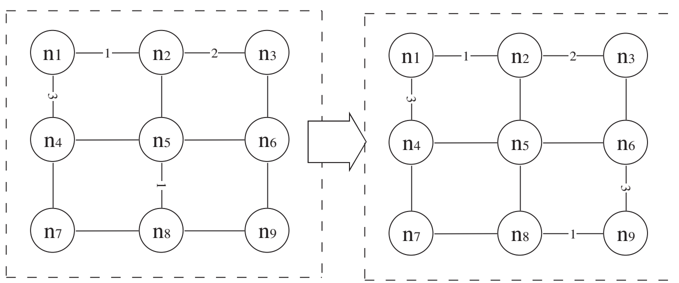


Figure 7. Channel assignment of Case 2.

Figures 6–8 are three simple examples to explain Cases 1–3, respectively. In the examples, nodes can use four channels without interference, such as 1, 2, 3, and 4 (channel 4 is the common channel for the messages transmission). In Figure 6, it is shown that the source node can route to the destination node with noninterfering channel. Figure 7 shows the process where the node routes through another node. Figure 8 shows the process of waiting for an available channel. In the three figures, it is supposed that there is no interference between different channels. Each node can affect adjacent nodes.

In Figure 6, n_2 and n_3 are communicating with Channel 2. Node n_2 updates its channel_info and broadcasts its channel information to its adjacent nodes. Node n_5 changes the value of its c_{cur} to 2 after receiving the broadcast packet. When n_5 receives the channel information of n_8, it checks its c_{cur}. Its c_{cur} is not equal to 1. Nodes n_5 and n_8 can use Channel 1 to communicate. Then, n_5 checks

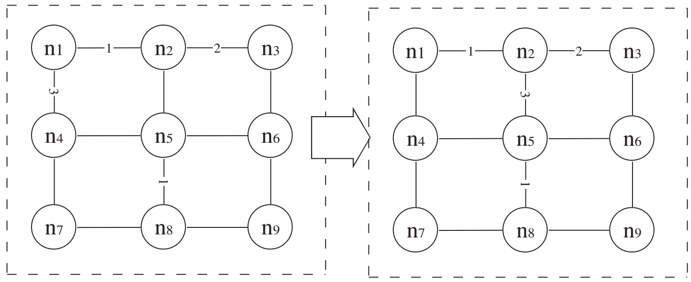


Figure 8. Diagram of Case 3.

its c_{cur}. Channel 3 is available. Therefore, n_4 can route to n_2 directly by channel 3. In Figure 7, n_2 and n_4 notice n_5 that Channel 1, 2, and 3 are not available, and n_5 changes its c_{cur}. Now, n_8 wants to use Channel 1 to connect to n_5. n_5 checks that this channel is not available and goes to Algorithm 2. By computing time cost, n_5 notices n_8 to connect to another node.

In Figure 8, n_2 and n_4 notice n_5 that Channel 1, 2, and 3 are not available. n_5 changes its c_{cur}. Now, n_8 wants to use Channel 1 to connect to n_5. n_5 checks that this channel is not available and goes to Algorithm 2. By comparing time cost, n_5 notices n_8 to wait for a free channel. After the communication of n_1 and n_4, Channel 3 is free, and n_5 keeps on routing.

These examples show that R-CA can assign channels according to different scenarios. R-CA is a cross-layer and dynamic algorithm. The node can change the channel and routing path according to the channel information of its neighbors.

4. PERFORMANCE EVALUATION

In this section, we first describe the simulation environment, then conduct the simulations and analyze the results.

4.1. Simulation settings

The R-CA is simulated in NS-2.33.[‡] Simulation range is 1200×1200 in NS2. Simulation time is 50 s. The number of channels is 4. The number of wireless nodes is 30, which are in a 5×6 grid network. Every multiradio node has five network interface cards. The distance of two nodes is 100 m. Transmission distance is 120 m. The interference distance of the same channel is 250 m. The data packet size is 512 bytes. We define table channel_info. Also, every parameter in the channel_info is initialized to 0. Then, we modify the ad hoc on demand distance vector routing protocol for carrying channel information when nodes route. In the new protocol, route request packets include c_{pre} and t_{pre} except routing information. Route reply packets add response information for the next hop. Because of that, every node can communicate to four nodes at the same time, the length of the waiting node address queue is defined as 4 here.

In the first scenario, the number of sending packets per second is alterable from 5 to 25. Four flows (each going over two hops) in the network are generated randomly. These four flows communicate across one node. The network uses partially overlapping channels. Other parameters are fixed. We compare packet delivery rate of R-CA method against a static multichannel assignment method. The experiments are then repeated for 10 times.

In the second scenario, all parameters are fixed except the number of flow. This number changes from 2 to 10. Each flow goes over two hops. The number of sending packets per second is 20. In the scenario, nodes use nonoverlapped channels and partially overlapping channels; the channel information is also based on IEEE 802.11b. Compare the average throughput of R-CA method against a static multichannel assignment method and a single-radio method. The experiments are then repeated 10 times.

[‡](http://www.isi.edu/nsnam/ns/)

4.2. Simulation results

The simulation results are shown in Figures 9 and 10.

Figure 9 shows the packet delivery rate of different numbers of sending packets per second in a multichannel mesh network with a static channel assignment method (static CA) and in a multichannel mesh network with R-CA method. In Figure 9, at the beginning, two packet delivery rates are similar. With the number of sending packet per second increasing, the packet delivery rates begin to decrease but unnoticeably. In the network using static method, every link is allocated a channel. Because of a common channel used to coordinate channels, three channels are left to transfer data. At least two links across one node must work on the same channel. Interference and collision will appear and decrease the packet delivery rate. In R-CA method, a node can balance the channel resource by waiting for a free channel or changing the routing. Also, the packet delivery rate of R-CA is better than the static channel assignment algorithm.

Figure 10 shows the average throughput of flows in a single-channel mesh network, in a multichannel mesh network with a static assignment method, and in a multichannel mesh network with R-CA method. In Figure 10(a), nodes use nonoverlapped channels. Nodes in a single-channel network use only one channel. Every link of a node in static assignment method is allocated different channels as much as possible. At the beginning, the average throughputs of the three cases are similar. It is because less flows result in less channel disturbances. With the increase of flow, the

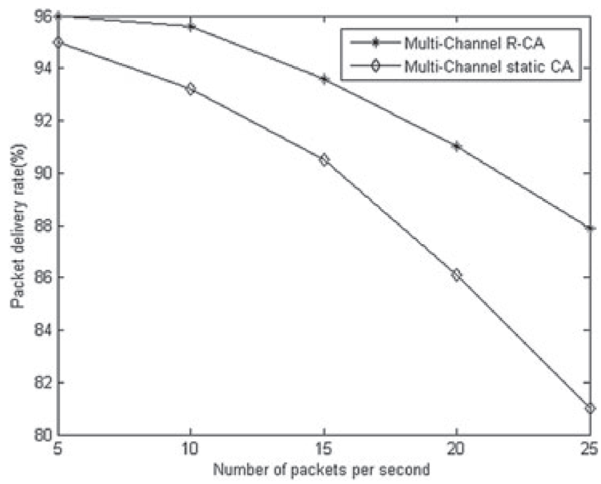
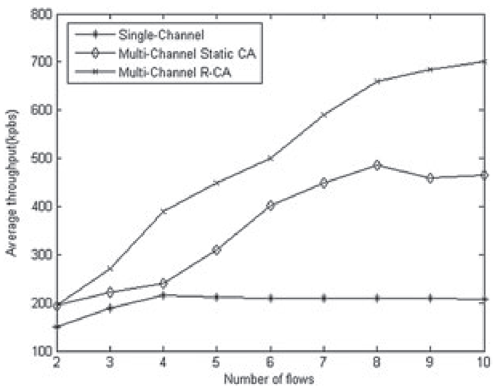
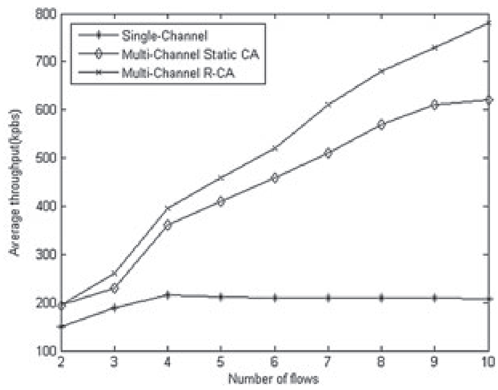


Figure 9. Impact of number of send packet per second.



(a) Nonoverlapped channels



(b) Partially overlapping channels

Figure 10. Impact of number of flows on the topology.

nonoverlapped channels become less relatively. In a single-channel network, using only one channel creates more interference, and hence, its throughput is the lowest. When the number of flows is increasing from 8 to 10, the average throughput with static multichannel assignment method reduces, and the increment of R-CA decreases. The reason behind this is that each node uses static multichannel assignment having a stable number of interface, and every interface is assigned a channel. Too many flows result in unfair loads on a network. Much more packets are transferred in some links and some other links are free. Nodes using R-CA can release the channels after transmission; nodes have more usable channel resource. When the number of flows is more than 8, some nodes put addresses into the waiting node queue to wait for available channels. This results in the increment decreasing. The average throughput of R-CA is more near optimal here. It has better capacity than static multichannel and single-channel although the increment decreases as the number of flows increases.

As Figure 10(b) shows, the average throughputs in the three environments are better than the throughputs in Figure 10(a). The reason is that using partially overlapping channels reduces interference among links. More channels used by nodes achieve the increase of throughput.

In simulation, the result of channel assignment by using R-CA is optimal, and the performance of the network is improved. For example, when using nonoverlapped channels, R-CA outperforms multichannel static channel assignment algorithm about 26%, 45%, 52%, when the number of flows are 4, 8, and 10, respectively.

4.3. Discussion

The dynamic channel assignment algorithm R-CA is a cross-layer algorithm, which combines the information of the network layer (routing algorithm) and MAC layer (channel switching algorithm). R-CA adds channel_info tables' c_{pre}, c_{cur}, t_{pre} to get the channel information of neighbors, and the memory required is in the bound of wireless mesh nodes.

To share the channel information, there are necessary processes, which had been described in Figure 5. The processes can have further interference for wireless communications, but the simulation results show that the addition process is little compared with the performance improvement. The simulations were conducted in the all-around radios and the performance would be higher if we used soft-radio and Sora [24].

The dynamic channel assignment algorithm proposed in [12] is based on static architecture. Another dynamic channel assignment method in common wireless multihop networks the use of channel switching prediction. We can use the Hidden Markov Model to predict each node's traffic load, and the hidden states could be formulated by observation sequences. However, there still needs to be a method to decide the channel collisions if there are more than one link sharing the same channel. This research is one of our future works.

5. CONCLUSION

In this paper, some typical existing studies on channel assignment algorithms have been analyzed and the principles of channel distribution have been formulated. Considering the problem of channel interference in multihop wireless mesh networks, a dynamic channel assignment algorithm called R-CA has been developed. R-CA is a dynamic algorithm based on a cross-layer design that includes a MAC layer and a network layer. It can assign the channel and routing at the same time. Simulation results demonstrate the effectiveness of the R-CA algorithm in exploiting channel assignment diversity for reducing interference and leading to significant performance benefits in an IEEE 802.11-based multihop mesh network.

Our future work will focus on reducing interference, and more comprehensive evaluation of the R-CA algorithm, including theoretical performance characterization and real-world performance in a multihop wireless mesh test bed.

DOI: 10.1002/dac

ACKNOWLEDGEMENTS

This work was supported in part by the Natural Science Foundation of China under grant No. 61103233, 60903153, and 90715037, NSFC-JST under grant No.51021140004, the Fundamental Research Funds for the Central Universities (DUT12JR08, DUT12JR10), the SRF for ROCS, SEM, and DUT Graduate School (JP201006).

REFERENCES

1. Min GY, Wu YL, Li KQ. Performance modelling and optimization of integrated wireless LANs and multi-hop mesh networks. *International Journal of Communication Systems* 2010; **23**(9):1111–1126.
2. Alicherry M, Bhatia R, Li EL. Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks. *Proceedings of ACM Mobicom*, New York, NY, USA, 2005; 58–72.
3. Wu F, Raman V, Vaidya N. Being opportunistic or being concurrent - on designing channel assignment algorithms in multi-Radio, multi-Channel wireless mesh networks. *Proceedings of the IEEE SECON*, Boston, Massachusetts, USA, 2010; 1–3.
4. Li EL, Tan K, Viswanathan H, Xu Y, Yang YR. Retransmission $\neq$ repeat: simple retransmission permutation can resolve overlapping channel collisions. *Proceedings of ACM MOBICOM*, Chicago, Illinois, USA, 2010; 281–292.
5. Marina MK, Das SR, Subramanian AP. A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks. *Computer Networks* 2010; **54**(2):241–256.
6. Subramanian AP, Gupta H, Das SR, Cao J. Minimum interference channel assignment in multiradio wireless mesh networks. *Proceedings of IEEE SECON*, San Diego, CA, USA, 2007; 481–490.
7. Gong MX, Midkiff SF. Distributed channel assignment protocols: a crosslayer approach. *Proceedings of IEEE Wireless Communications and Networking Conference*, New York USA, 2005; 2195–2200.
8. Gong MX, Midkiff SF, Mao S. Design principles for distributed channel assignment in wireless Ad Hoc networks. *Proceedings of IEEE International Conference on Communications*, New York USA, 2005; 3401–3406.
9. So J, Vaidya NH. Multichannel MAC for ad hoc networks: Handling multichannel hidden terminals using a single transceiver. *Proceedings of ACM MOBIHOC*, Tokyo, Japan, 2004; 222–233.
10. Kyasanur P, Vaidya NH. Routing and link-layer protocols for multichannel multi-interface ad hoc wireless networks. *ACM SIGMOBILE Mobile Computing and Communications Review* 2006; **10**(1):1559–1662.
11. So J, Vaidya NH. A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver. *UIUC Technical Report*, October 2004.
12. Raniwala A, Chiueh T. Architecture and algorithms for an IEEE 802.11-based multichannel wireless mesh network. *Proceedings of IEEE INFOCOM*, Miami, USA, March 2005; 2223–2234.
13. Ramachandran KN, Belding EM, Almeroth KC, Buddhikot MM. Interference aware channel assignment in multi-radio wireless mesh networks. *Proceedings of IEEE INFOCOM*, Barcelona, Catalunya, Spain, 2006; 1–12.
14. Skalli H, Ghosh S, Lenzini L, Conti M. Channel assignment strategies for multiradio wireless mesh networks: issues and solutions. *IEEE Communications Magazine* 2007; **45**(11):86–95.
15. Mishra A, Shrivastava V, Banerjee S, Arbaugh W. Partially overlapped channels not considered harmful. *Proceedings of ACM SIGMetrics/Performance*, Saint Malo, France, 2006; 63–74.
16. Yang L, Zhao BY, Zheng HT. The spaces between us: setting and maintaining boundaries in wireless spectrum access. *Proceedings of ACM MobiCom*, Chicago, Illinois, USA, 2010; 37–48.
17. Wang JT. Joint rate regulation and power control for cochannel interference limited wireless networks. *International Journal of Communication Systems* 2011; **24**(8):967–977.
18. Cho HN, Lee JW, Lee YH. Cooperative power allocation with partial channel information in multi-cell multi-user dual-hop MIMO relay systems. *International Journal of Communication Systems* 2011; **24**(5):586–606.
19. Kao HH, Wu PJ, Lee CN. Analysis and enhancement of multi-channel MAC protocol for ad hoc networks. *International Journal of Communication Systems* 2011; **24**(3):310–324.
20. Feng ZH, Yang YL. How much improvement can we get from partially overlapped channels. *Proceedings of WCNC*, Las Vegas, NV USA, 2008; 2957–2962.
21. Bononi L, Felice MD, Molinaro A, Pizzi S. A cross-layer architecture for effective channel assignment with load-balancing in multi-radio multi-path wireless mesh networks. *International Journal of Communication Systems* 2009; **22**(10):1267–129.
22. Bononi L, Felice MD, Molinari A, Pizzi S. Enhancing multi-hop communication over multi-radio multi-channel wireless mesh networks: A cross-layer approach. *Computer Communications* 2011; **34**(13):1559–1569.
23. Sun WF, Cong R, Xia F, Chen X, Qin ZQ. R-CA: A routing-based dynamic channel assignment algorithm in wireless mesh networks. *Proceedings of Workshop on Mobile Cyber-Physical Systems (MobiCPS),* in conjunction with *UIC*, Xi'an, China, 2010; 228–232.
24. Tan K, Liu H, Zhang JS, Zhang YG, Fang J. High performance software radio using general purpose multi-core processors. *Proceedings of the 6th USENIX Symposium on Networked System Design and Implementation*, Boston, Massachusetts, 2009; 75–90.

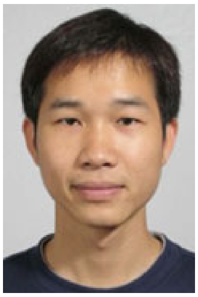
DOI: 10.1002/dac

AUTHORS' BIOGRAPHIES

Weifeng Sun is an Assistant Professor in Software School at Dalian University of Technology (DUT), China. He received his PhD and Bachelor degrees from the University of Science and Technology of China (USTC). His research focuses on high quality communications over wireless networks (such as wireless mesh networks, wireless sensor networks, MIPv6, and so on), scheduling and applications over distributed networks (including grid computing and cloud computing).

Tong Fu was born in Liaoning Province, China, in 1987. He received his Bachelor degree from Dalian University of Technology (DUT), China, in 2010. He is currently pursuing the MS degree in the School of Software, Dalian University of Technology. His research interests include wireless mesh networks and vehicle networks.

Feng Xia is an Associate Professor and PhD Supervisor in School of Software, Dalian University of Technology, China. He is the (Guest) Editor of several international journals. He serves as General Chair, PC Chair, Workshop Chair, Publicity Chair, or PC Member of a number of conferences. Dr Xia has authored/co-authored one book and over 110 scientific papers in international journals and conferences. His research interests include mobile and social computing, intelligent systems, and cyber-physical systems. He is a member of IEEE, IEEE Computer Society, IEEE SMC Society, ACM, and ACM SIGMobile.



Zhenquan Qin received both his Bachelor degree in Security Engineering and his PhD in Communication and Information Systems from the University of Science and Technology of China, in 2002 and 2007, respectively. He is currently an Assistant Professor in the School of Software of Dalian University of Technology, China. His research interests include network analysis and network security.

Rong Cong was born in Inner Mongolia, China, in 1982. He received his Bachelor degree from the North University of China in 2004 and his MS degree from the Dalian University of Technology, China in 2010. His research interests include routing and MAC in wireless mesh networks.

DOI: 10.1002/dac