

# Self-adaptive Multi-channel MAC for Wireless Mesh Networks

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## 1. Introduction

In order to enhance the transmission rate, multiple channels and multiple transceivers are employed in wireless mesh networks (WMNs). However, the bandwidth utilization rate is still low, and it is hard to design efficiency MAC. There are mainly three reasons. The first reason is that there are different kinds of nodes in WMN: some nodes are single transceiver and some nodes are multiple transceivers or multiple radios (Ian & Wang, 2005). The MAC needs to be suitable for single transceiver nodes and multiple transceiver nodes at the same time. The second reason is that the MAC not only needs to control multiple nodes but also multiple transceiver or multiple radios to access multiple channels. How to coordinate all the nodes and the transceivers, radios of each node to access the channels and enhance the bandwidth utilization rate is a multi-parameter optimization problem. The third reason is that the traffic load on each link is varying. The channel allocation scheme need be adaptive to the load of links.

Common control channel (CCC) based multi-channel MAC is a representative proposal (Benveniste & Tao, 2006) for WMN. All the MAC control signals are exchanged on a common control channel, and the data are sent on data channel. This MAC scheme is very flexible to combine with existing channel allocation schemes. However, the handshaking is made on the control channel, which can't avoid the interference of the non CCC based MAC on data channel. The second problem is that the switching time on the data channel is longer than the transmission time of sending a data packet, which will reduce the efficiency of CCC. Moreover, when there is only one radio, CCC will have the hidden terminal problem (N. Choi, et al. 2003).

Based on CCC, a self-adaptive multi-channel MAC is proposed in this chapter. To keep the flexibility of CCC, common control channel still remains in our scheme. To reduce the channel switching delay and avoid interference from non-CCC based MAC, spreading code based channel division scheme is employed on the data channel. Our scheme can inherit the merits of CCC and remove its faults. Moreover, based on the common control channel framework, we proposed a self-adaptive channel allocation scheme which can adjust the medium access process according to the number of idle channels, and the load of the links on a node to maximize the bandwidth utilization rate of the WMN system.

The rest of this chapter is organized as follows: section 2 makes a survey of the existing multi-channel medium access schemes, section 3 proposes our scheme and makes theory analysis and simulation, and conclusion is drawn in the last section.

## 2. Related work

To enhance the transmission rate, multi-channels are introduced into WMN. To present our scheme, we need to introduce the related multi-channel MAC first.

### 2.1 Random medium access schemes

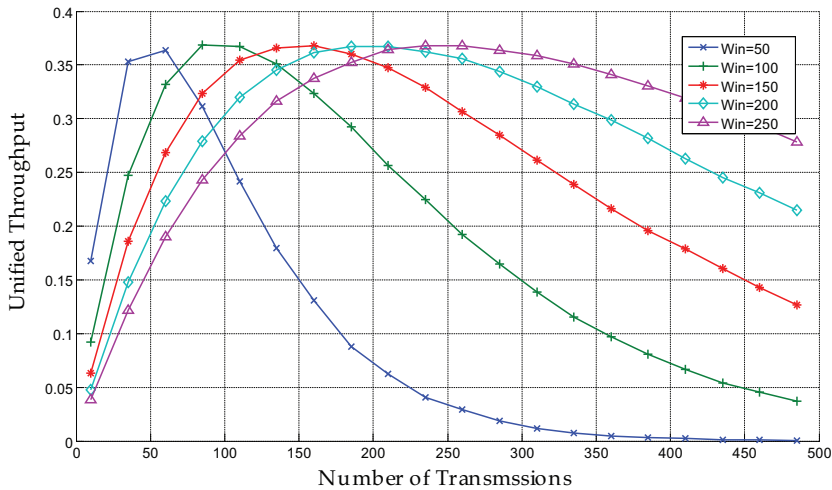


Fig. 1. The throughput vs. the number of transmissions of ALOHA based MAC

MAC controlling signals need be exchanged among the nodes within the communication range. Since no fixed channel is allocated to each node, the MAC controlling signals are sent following random medium access scheme which are mainly Carrier Sensing Multiple Access/Collision Avoidance (CSMA/CA) scheme. CSMA/CA is gotten from ALOHA based scheme. Fig.1 shows that the throughput of ALHOA varies with the number of transmissions. The system throughput can be maximized if the number of transmissions is properly set, which is the original idea of CSMA/CA. CSMA/CA can maximize the system throughput by controlling the number if transmissions in the contention window. CSMA/CA employs carrier sensing, and random back-off schemes to access the channels. There are many kinds of CSMA/CA schemes, and the one used in WLAN is the most common one. The CSMA/CA adopted by IEEE 802.11 works as follows. Before accessing the channel, a node needs to generate a random time which is uniformly distributed within contention window and sense the carrier to get the channel conditions: idle or busy. If the channel is idle, the node will do back-off with a back-off timer. If the channel is busy, the node will turn off the timer until the channel is idle again, and if the channel become idle, the node will turn on the timer after a distributed inter-frame space (DIFS) (IEEE 802.11-1999 (R2003), 2003). If the timer expires, the node can access the channel immediately. Fig.2 shows the CSMA/CA based medium access process of 4 nodes in IEEE 802.11. Node 2, 3, 4 are ready to send frame during node 1 sending frame. Then, node 2, 3, 4 generate back-off times respectively which are 5, 21, 12 seconds, and then begin deferring. After node 1 finish sending the frame, the three nodes start their back-off clocks after a short time DIFS and

then begin back-off. This process is done in the contention window during which the three nodes compete for the channel. Since node 2's back-off time is the smallest one, this node's timer timeout first and sends its frame immediately. Node 3, 4's left back-off time are 16s and 7s respectively and this two nodes stop the back-off timers and then go to defer. After node 2 finish sending the frame, node 3, 4 follow the similar process like node 2.

**2.2 Channel division scheme**

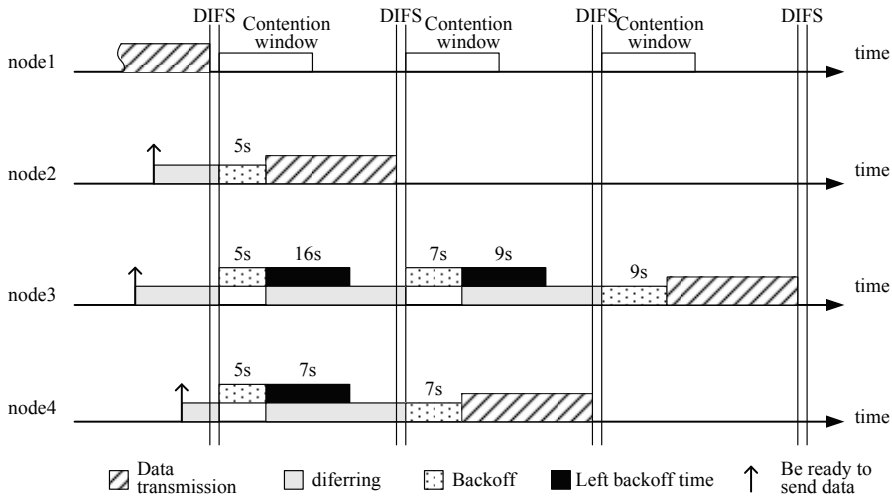


Fig. 2. The CSMA/CA based medium access process in IEEE 802.11

The wireless resource needs be divided into multiple channels, and the resource division scheme is very important. The wireless resource can be divided with frequency, time, space, and spreading code. These schemes have different features and can be used in corresponding conditions. Properly selecting the resource division schemes can enhance the system's performance, otherwise, the performance might be declined. Frequency based channel division scheme can effectively remove inter-channel interference through properly set the band of each channel, and the transmission on each channel can be done simultaneously. Once the band of each channel is set, the capacity of each channel will be constant, and can't be adjusted according to requirements. Time based channel division scheme divides a period of time into many time slots, and allocates each channel with several time slots. The capacity of each channel is based on the number of time slots, and can be arbitrarily changed through setting the number of time slots. To realize time based channel division scheme, synchronization among the nodes in a communication area must be needed, which could consume much wireless resource. Space based channel division scheme divides channels through setting the covering area of each antenna. By properly designing the antenna's covering area, frequency reuse rate can be increased, but space based channel division scheme can't realize full duplex transmission. Spreading code based channel division scheme divides channels through setting spreading code for each channel. The spreading codes have low cross correlation and high autocorrelation, which is employed to divide wireless resource. This scheme can arbitrarily adjust the transmission

rate according to the interference and data transmission requirements of services. Moreover, this scheme can weaken the interference from the same channel. However, this scheme is a interference constrained system, and too many channels can increase the interference and reduce the transmission rate.

The proposed scheme in this chapter employs frequency, and spreading code based channel division scheme which is shown in Fig. 3. To avoid interference from data channel and realize simultaneous transmission on these channels, control channel and data channel are divided with frequency. The data channel is divided into several sub-channels with spreading codes. Employing the spreading code channel division scheme can weaken the hidden terminal interference and make the transmission on sub-channel be adjustable according to the interference and the service requirements.

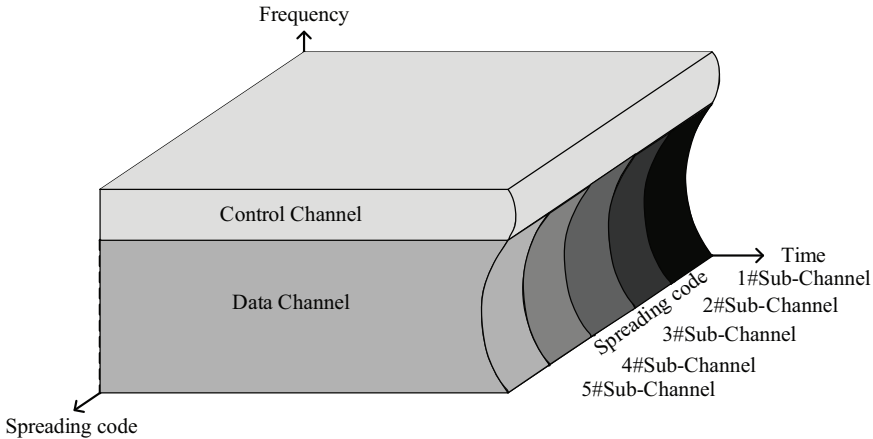


Fig. 3. Channel division scheme of the proposed scheme

**2.3 Related medium access control schemes**

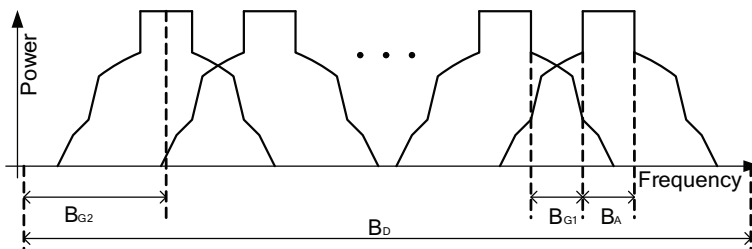


Fig. 4. Sub-band allocation of CCC's data channels

Since mesh has been employed in Wireless Personal Area Networks (WPAN), Wireless Local Area Networks (WLAN), Wireless Metropolitan Area Networks (WMAN), corresponding Medium Access Control (MAC) schemes have to be proposed to enhance the network performance. IEEE has set up IEEE 802.11s working group for the mesh networks in WLAN networks. The draft of IEEE 802.11s has been proposed in 2006 (802.11s Working Group, 2006), but there are still many issues demanding solutions (Wang & Lim, 2008).

During the drafting process, common control channel (CCC), a common control channel based MAC for multi-channel WMN, is a representative proposal (Benveniste and Tao, 2006). CCC divides the wireless resource with frequency which is shown in fig.4, and there are one control channel and several data channel. Control channel is used for the transmission of request-to-send (RTS) and clear-to-send (CTS) which are distributed coordinating signals. After the handshaking on control channel, the nodes can access the requested channel for data transmission. This scheme has two problems.

1. The first problem is that when all the data channels are occupied, the control channel will be idle, and this is a waste of wireless resource. Fig. 5 shows one control channel and two data channels of a CCC system, and node B accesses channel 1 and node C accesses channel 2 after handshaking on control channel with RTS and CTS respectively. When node B and node C occupy the two data channel, the control channel become idle until one of the data channel become idle again, and then node A can send handshaking signals on the control channel to make channel request. The idle time of the control channel is a waste of wireless resource.
2. The second problem is the hidden terminal interference. RTS and CTS handshaking process can constrain the hidden terminal interference, but the interference radius is larger than the communication radius, so the hidden terminal interference can't be entirely removed.

Moreover, CCC didn't proposed channel allocation scheme to enhance the bandwidth utilization rate.

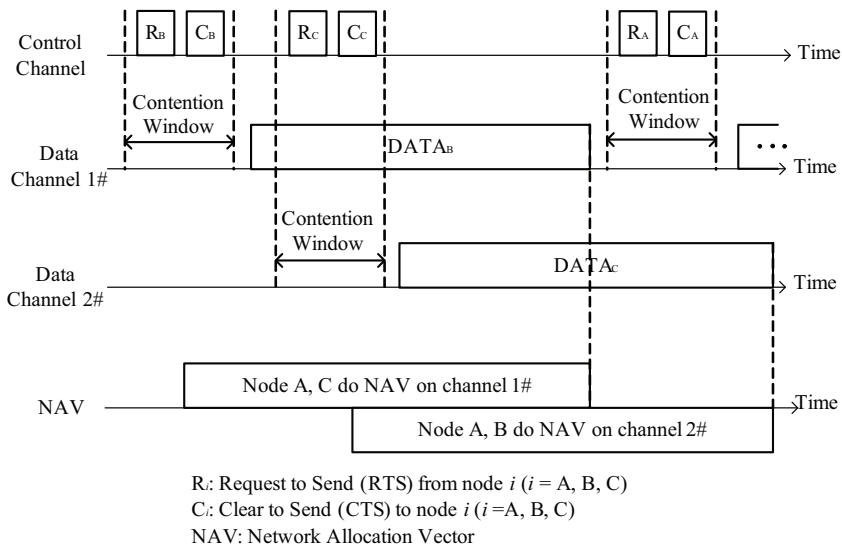


Fig. 5. DCF of CCC.

### 3. Self-adaptive multi-channel MAC for wireless mesh networks

This scheme employs the channel division scheme shown in fig. 3, does channel request with RTS-CTS handshaking scheme on the control channel, and sends data on the data sub-

channels. The channel allocation process can adapt to the traffic load on each link to reduce congestions and maximize the bandwidth utilization rate.

### 3.1 Medium access control scheme

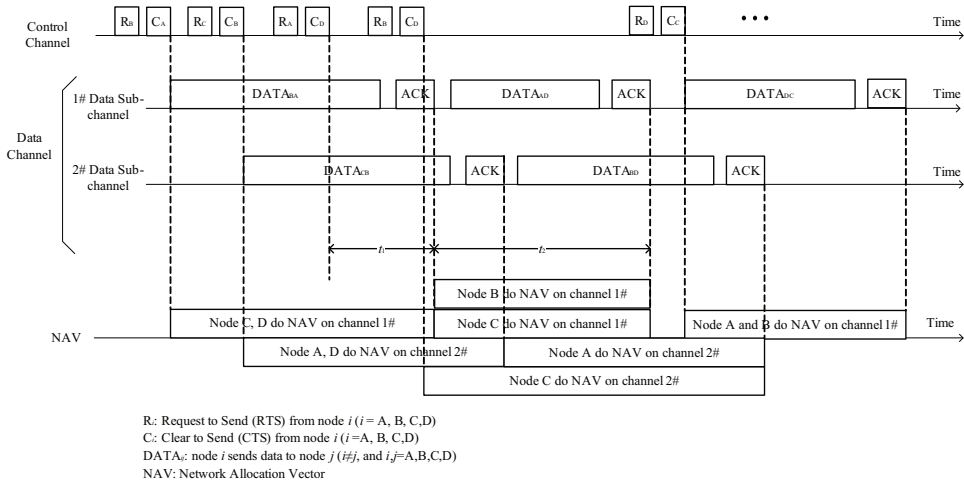


Fig. 6. DCF of the proposed scheme

The main goal of our scheme is to reduce the channel access delay and increase the system's throughput. Our scheme has a control channel and a data channel which are divided by frequency. The data channel is divided into data sub-channels with spreading codes. One spreading code corresponds to one data sub-channel. We use the sub-channel for short instead of data sub-channel in the following. RTS-CTS handshake is used on the control channel. The process of RTS-CTS handshake is designed as follows:

- a. Node A sends RTS to node B for data transmission on a sub-channel. CSMA/CA is used as the medium access control scheme.
- b. When node B receives RTS from node A, it sends CTS to node A after a short time interval, named short-inter-frame-space (SIFS).
- c. If the sub-channel in Step 1 isn't occupied, node A will send data to node B immediately on the sub-channel. Otherwise, the data will be arranged for transmission on the sub-channel.

In our scheme, both RTS and CTS messages are of the same form which is composed of source ID, destination ID, spreading code ID, and duration. Source ID is the ID of the node which sends the message; destination ID is the ID of the node which receives the message; and spreading code ID is the ID of the selected spreading code for transmission. Duration is the length of time will be spent for the data transmission and is estimated according to the amount of data, the length of the spreading code, and the data rate of the system. In the data channel, data packet and ACK are transmitted.

Data channel reservation is proposed in our scheme. In IEEE 802.11 MAC, DCF was proposed for single channel system. Data, ACK, RTS and CTS are sent on the same channel. Data is transmitted immediately after a successful RTS-CTS handshake. In our scheme, RTS and CTS are transmitted in control channel; data and ACK are transmitted in data channel.

Data shall not be transmitted immediately after a successful RTS-CTS handshake as in Step 3. When there is no idle sub-channel, RTS-CTS handshake can still be done on control channel. After a successful RTS-CTS handshake, data is arranged for transmission on a sub-channel. When the time for transmission comes, the data will be transmitted immediately. In this process, data channel reservation is needed for the arrangement. It is realized with virtual carrier sensing, which was proposed in IEEE 802.11 MAC, and is realized with networks allocation vector (NAV). In our scheme, NAV records the start time and the duration of an arranged traffic on the sub-channel based on duration information in RTS/CTS message. When a node receives RTS/CTS with destination ID which is different from its own ID, it need conduct virtual carrier sensing. The virtual carrier sensing acts differently in the following three conditions:

- A node receives RTS/CTS when it is idle. The start time of NAV is the current time. Duration of NAV is that in RTS/CTS. The node does NAV immediately.
- A node receives RTS/CTS when it is doing NAV and the remaining duration is  $t_n$ . The node needs to substitute the  $t_n$  with the duration in RTS/CTS. The start time of NAV is the current time.
- A node receives RTS/CTS when it is sending data, and the remaining transmission time is  $t_d$ . The start time of NAV is the sum of current time and  $t_d$ . Let  $t$  be the duration in RTS/CTS. The duration of NAV is  $t$  minus  $t_d$ . When this node finishes the transmission, it starts doing NAV.

For example, there are four nodes A, B, C and D within the radio coverage of each other, and there are two sub-channels and a control channel. The communication process is shown in fig. 6. At first, node B sends data to node A on sub-channel #1 (sub-channel #1 is simply named #c1 below). After a while, node C sends data to node B on sub-channel #2 (sub-channel #2 is simply named #c2 below). Since the two channels are all idle, these two transmissions start immediately after the CTS on #c1 and #c2. Nodes C and D do NAV on #c1, and nodes A and D do NAV on #c2. After a while, node A has data to send to D when the two sub-channels are all busy. Node A finds that the transmission on #c1 will finish soon, so node A makes a reservation for #c1. Node A sends RTS to node D. In RTS, the spreading code ID is that of #c1, and the duration  $D_{AD1}$  is  $t_1+t_2$ .  $t_1$  is the remaining occupying time on #c1, and  $t_2$  is the estimated data transmission length of time from nodes A to D. Then, nodes B and C should start doing NAV. Node C is in the state of NAV now. The remaining NAV time of node C on #c1 is  $t_1$ . Then, this node extends the NAV time by  $t_2 = D_{AD1} - t_1$ . Node B is transmitting data to node A on #c1 now, and the remaining time of the transmission is  $t_1$ . In this case, node A arranges the NAV from the end of its transmission on #c1, and the NAV duration is  $t_2 = D_{AD1} - t_1$ . After some time, node B has data to be sent to node D. At this time, the two data channels are all busy. Fig. 6 shows that #c1 has been reserved, and #c2 will be the first one to finish transmission. Therefore, node B makes reservation on #c2. Some time later, node D needs to send data to node C when #c1 is idle. In this case, node D needn't do channel reservation and requests for the idle channel as usual.

To enhance the throughput of the system, traffic flow adaptive channel allocation scheme is proposed. This scheme adaptively allocates the channels to the node according to the node's load level. The node with heavy load accesses the channel with high priority, and the node with light load accesses the channel with low priority. This scheme can help the node with heavy load occupy more channel than the node with light load. In this way, the node with heavy load can borrows idle channels from the node with low load, and the system's

channel utilization rate and throughput is enhanced. The traffic load can be estimated through the self-similarity of the traffic (Crovella & Bestavros, 1997) (Leland, et. al., 1994). Then, each node's busy level is defined as follows:

Let  $\psi(i)$  be the expected load of node  $i$ , and let  $h$  be the number of data channels. Suppose the capacity of each data channel is constant and it is denoted with  $C$ . Then, the capacity within node  $i$ 's coverage is:

$$\Phi(i) = C * h \tag{1}$$

Let  $\rho(i)$  be the ratio of ratio of the expected load and the channel capacity within node  $i$ 's coverage.

$$\rho(i) = \psi(i) / \Phi(i) \tag{2}$$

$\rho(i)$  is employed to denote the busyness degree of node  $i$ . Based on  $\rho(i)$ , the busyness level can be gotten with the following formula :

$$B(i) = \begin{cases} 1 & \rho(i) > (1 - a) \\ k + 1 & (1 - a * k) \geq \rho(i) > (1 - a - a * k) \\ h & \dots \quad (1 + a - a * h) \geq \rho(i) \end{cases} \tag{3}$$

In (3),  $k=1,2,\dots,(h-2)$ , and  $a$  is the stem-length of business level and  $a * h < 1$ .  $B(i)=1$  is the highest busyness level and  $B(i)=h$  is the lowest busyness level. In this algorithm, all the data channels are being numbered first, and channels are allocated according to the numbered channel and busyness level of each node. The channel allocation process is as follows:

- a. let  $\Theta(k, m)$  ( $k=1,2,\dots, h$ ;  $m=1,2,\dots, h$ ) be the traffic load of the node with busyness level  $m$  on channel  $k$ . Firstly, node  $i$  needs to decide whether channel  $k$  satisfy following condition which is named condition 1:

$$\psi(i) < C - \sum_{m=1}^h \Theta(k, m) \tag{4}$$

(4) means that node  $i$ 's expected load is smaller than channel  $k$ 's available bandwidth. If only one channel satisfy condition 1, this channel will be selected by node  $i$ . If there is more than one channel satisfy condition 1, minimum interference hybrid channel allocation algorithm (Jeng & Jan 2006) shall be employed to select a channel from them.

- b. If no channel satisfies condition 1, node  $i$  will search for channels satisfy condition 2:

$$\psi(i) < \left[ C - \sum_{m=1}^h \Theta(k, m) \right] + \left[ \sum_{m > B(i)} \Theta(k, m) \right] \tag{5}$$

In the right side of (5), the former part is the available bandwidth on channel  $k$ , and the latter part is the bandwidth occupied by the node with busyness level lower than  $B(i)$ . If there is one channel satisfies condition 2, this channel will be selected. If there are more than one channel satisfy condition 2, minimum interference hybrid channel allocation algorithm shall be employed to select a channel from them.

- c. each node periodically estimate their traffic load, and search the channel with the step a and step b.



### 3.2 Performance analysis models

#### A. Throughput with hidden terminals

a. *Throughput of our scheme without hidden terminals*

Let  $N$  be the number of channels. Each channel  $i$ ,  $1 \leq i \leq N$ , is assigned an  $n$  bit pseudo-random noise (PN) sequence. From (Hui, 1984), we can get the sum capacity of the CDMA channels in binary input Gaussian condition is:

$$C_{b/c} = \frac{N}{n} \left( \log_2 2\pi e - \int_{-\infty}^{\infty} P(y) \log_2 P(y) dy \right) \quad (6)$$

in which

$$P(y) = (P_1(y) + P_{-1}(y)) / 2$$

and

$$P_m(y) = \exp \left[ -(y - m\sqrt{n/N})^2 / 2 \right] / \sqrt{2\pi}$$

This capacity is denoted with bits/chip. Let  $r_d$  be the chip rate of the data channel. Then we can get the capacity  $C_d$  denoted with bit/s.

$$\begin{aligned} C_d &= C_{b/s} \cdot r_d \\ &= \frac{Nr_d}{n} \left( \log_2 2\pi e - \int_{-\infty}^{\infty} P(y) \log_2 P(y) dy \right) \end{aligned} \quad (7)$$

Let  $B$  be the bandwidth of the WMN. In our scheme,  $B$  is composed of two parts: control channel and data channel. The bandwidth of the control channel is  $B_C$ . Then the bandwidth of the data channel is  $B_D = B - B_C$ . According to Shannon formula, the capacity of WMN is:

$$C = B \log_2 \left( 1 + \frac{E}{n_0 B} \right) \quad (8)$$

in which  $E$  is the signal power. Let  $E(P)$  be the average length of the data packet. Since packet rate equals bit rate dividing by average packet length, the capacity of WMN denoted with packet rate is:

$$P_{WMN} = \frac{\text{bits} \cdot \text{per} \cdot \text{second}}{\text{packet} \cdot \text{length}} = \frac{C}{E(P)} \quad (9)$$

According to Shannon formula, the capacity of data channel  $r_{DHMA}$  of our scheme is:

$$r_{DHMA} = B_D \log_2 \left( 1 + \frac{E}{n_0 B_D} \right) \quad (10)$$

in which  $E$ ,  $n_0$  and  $B_D$  have been defined in the upper parts.

Replacing  $r_d$  in (7) with  $r_{DHMA}$  in (10), we can get the sum capacity of the sub-channels:

$$C_{DHMA} = \frac{Nr_{DHMA}}{n} \left( \log_2 2\pi e - \int_{-\infty}^{\infty} P(y) \log_2 P(y) dy \right) \quad (11)$$

in which  $N$  is the number of sub-channels and  $n$  is the length of the spreading code. Sum capacity of the sub-channels is the capacity of the data channel with CDMA access scheme, and the sum capacity of the sub-channels is named achievable data rate of the data channel. The achievable packet rate of the data channel is the ratio of the achievable data rate of the data channel  $C_{DHMA}$  to the average data packet length  $E[P]$ . Then the achievable packet rate of the data channel is:

$$P_{DHMA} = \frac{C_{DHMA}}{E(P)} \quad (12)$$

According to Shannon formula, the capacity of control channel  $r_{CC}$  in our scheme is:

$$r_{CC} = B_C \log_2 \left( 1 + \frac{E}{n_0 B_C} \right) \quad (13)$$

in which  $E$ ,  $n_0$  and  $B_C$  have been defined in the upper parts.

Let  $E(RTSCSTS)$  be the average cycle of a success RTS-CTS two-way handshake. From (Liu, 2004), we can get  $E(RTSCSTS)$  as follows:

$$E(RTSCSTS) = T_{RTS} + SIFS + \delta + T_{CTS} + DIFS + \delta \quad (14)$$

in which  $T_{RTS}$  and  $T_{CTS}$  are the transmission time of RTS and CTS, and they are equal to  $T_{RTS} = RTS/r_{CC}$ ,  $T_{CTS} = CTS/r_{CC}$ .  $RTS$  and  $CTS$  are the frame length of the RTS and CTS.  $SIFS$  is short inter-frame space, and  $DIFS$  is DCF inter-frame space.  $\delta$  is propagation delay.

Then, the capacity of the control channel denoted with packet rate is the inverse of average cycle of a success RTS-CTS handshake, that is:

$$P_{CC}^{DHMA} = \frac{1}{E(RTSCSTS)} \quad (15)$$

From (Kleinrock & Tobagi, 1975), we can get the throughput of CSMA/CA on control channel under the offered load  $G$ :

$$S_{DHMA} = \frac{Ge^{-aG}}{G(1-2a) + Ge^{-aG}} \quad (16)$$

in which  $a$  is normalized propagation delay of the radio.

Since throughput can be denoted with the ratio of achievable packet rate to channel capacity (Liu, 2004), achievable packet rate can be denoted with the product of throughput and channel capacity. From (15) and (16), we can get the achievable packet rate of control channel under the offered load  $G$ :

$$R_{CC}^{DHMA} = P_{CC}^{DHMA} S_{DHMA} \quad (17)$$

Let  $L_{DHMA}$  be the achievable packet rate on data channel of DHMA under offered load  $G$ . In our system, every transmission of a data packet on data channel needs a success of RTS-CTS handshake on control channel. Therefore,  $L_{DHMA}$  is equal to the achievable packet rate on control channel when the achievable packet rate on control channel is smaller than the

achievable packet rate on data channel. When the achievable packet rate on control channel is higher than the achievable packet rate on the data channels, the data channels are full loaded, and  $L_{DHMA}$  is equal to the achievable packet rate on data channel. Then,  $L_{DHMA}$  is as follows:

$$L_{DHMA} = \begin{cases} R_{CC}^{DHMA} & R_{CC}^{DHMA} \leq P_{DHMA} \\ P_{DHMA} & R_{CC}^{DHMA} > P_{DHMA} \end{cases} \quad (18)$$

The throughput of our scheme under offered load  $G$  is the ratio of  $L_{DHMA}$  to the capacity of the WMN  $P_{WMN}$ . From (9) and (18), we can get the throughput of our scheme under the offered load  $G$ :

$$T_{DHMA} = \frac{L_{DHMA}}{P_{WMN}} \quad (19)$$

b. *Throughput of CCC without hidden terminals*

CCC is a multi-channel MAC proposed for IEEE 802.11 mesh networks. In order to make a comparison of CCC and our scheme, we analyze the throughput of CCC. In CCC, there is control channel and data channels. The bandwidths of them are denoted with  $B_C$  and  $B_D$ . The data channels are divided by frequency. The bandwidth allocation of the data channels is shown in Fig. 5. In this figure,  $B_A$  is the allocated bandwidth for a data channel,  $B_{G1}$  is the guard band between data channels, and  $B_{G2}$  is the guard band at the edge of data channels. Supposing there are  $N$  data channels, we can get  $B_A$  by the following equation:

$$B_A = \frac{1}{N} [B_D - 2B_{G2} - (N-1)B_{G1}] \quad (20)$$

From Shannon formula, we can get the capacity on each data channel:

$$r_A = B_A \log_2 \left( 1 + \frac{E}{n_0 B_A} \right) \quad (21)$$

in which  $E$  and  $n_0$  have been defined in the upper parts.

The bandwidth of the control channels in CCC and DHMA are equal. From (13), we can get the capacity on control channel in CCC. The access process of CCC in Fig.6 shows that the contention window is between two data packets. Then, the average cycle of a success RTS-CTS handshake  $E'(RTSCTS)$  is the sum of the average cycle of a success RTS-CTS handshake in DHMA and the average data transmission interval. Let  $E(P)$  be the average data packet length, and  $N$  be the number of data channels. Then the average data transmission interval is  $E(P)/r_A/N$ . From (15), we can get  $E'(RTSCTS)$  as follows:

$$E'(RTSCTS) = E(RTSCTS) + E(P)/r_A/N \quad (22)$$

The capacity of control channel denoted with packet rate is the reverse of average cycle of a success RTS-CTS handshake  $E'(RTSCTS)$ :

$$P_{CC}^{CCC} = \frac{1}{E'(RTSCTS)} \quad (23)$$

Suppose the offered load of the system is  $G$ . Since contention window is embedded between two data packets in CCC, contention window can not be arranged at any place on the control channel. Therefore, the offered load  $G$  is converged in short intervals on the control channel. Then, the load in the contention window is:

$$G' = (E'(RTSCTS) * G) / E(RTSCTS) \tag{24}$$

From (Kleinrock & Tobagi, 1975), we can get the throughput of CSMA/CA of control channel in CCC under the offered load  $G$ :

$$S_{CCC} = \frac{G' e^{-aG'}}{G'(1-2a) + e^{-aG'}} \tag{25}$$

Similar to (17), we can get the achievable packet rate on control channel in CCC from (23) and (25):

$$R_{CC}^{CCC} = P_{CC}^{CCC} S_{CCC} \tag{26}$$

Let  $L_{CCC}$  be the achievable packet rate on data channel of CCC under offered load  $G$ . Because each success of RTS-CTS handshake is followed by a data packet on the data channels immediately,  $L_{CCC}$  is equal to the achievable packet rate on control channel:

$$L_{CCC} = R_{CC}^{CCC} \tag{27}$$

Similar to (19), we can get the throughput of CCC under the offered load  $G$ :

$$T_{CCC} = \frac{L_{CCC}}{P_{WMN}} \tag{28}$$

c. *Throughput of the two system with hidden terminals*

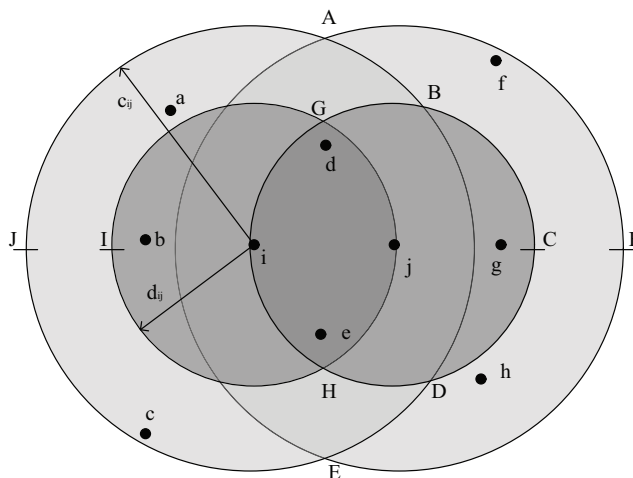


Fig. 7. The coverage areas and capture areas of node i and j.

When there are hidden terminals in the system as shown in Fig. 7, we estimated the throughput of our system and CCC.

In Fig. 7, capture area of node  $i$  is circle AJE, and is denoted with  $I_i$ .  $c_{ij}$  is the capture distance of node  $i$ , and is the radius of the capture areas of node  $i$  in Fig. 7.  $c_{ij}$  can be denoted with  $c_{ij}=ad_{ij}$ .  $a$  is the capture factor and  $1 \leq a$ .  $d_{ij}$  is the distance from node  $i$  to node  $j$ . Coverage area of node  $i$  is circle GIH which is maximum communication area of node  $i$ , and is denoted with  $C_i$ .  $d_{ij}$  is the radius of node  $i$ 's coverage area.

Let  $H_i$  be the aggregate of node  $i$ 's hidden terminals. Let  $C(i,j)$  be the aggregate of the communication pair  $(m,n)$ , and  $m \in C_i \cup C_j - H_i$ ,  $n \in C_i \cup C_j - H_j$ . Suppose the data transmitted from node  $i$  to node  $j$  follow Poisson distribution. Then, the length of the data's inter-arrival time follows exponential distribution, and the average of the inter-arrival time is denoted with  $G(i,j)$ . Let  $O_i$  be the aggregate of hidden terminals during the transmission from node  $i$  to node  $j$  with RTS-CTS handshake scheme.  $O_i$  is as follows:

$$O_i = I_i \cup I_j - I_i \cup C_j \tag{29}$$

In Fig. 7, the coverage of  $O_i$  equals to the area ABCDEF. Let  $\beta$  be the propagation delay from node  $i$  to node  $j$ , and  $T_{RTS}$  be the transmission time of RTS.

From (Liu, 2004), we can get the success probability of a transmission from node  $i$  to node  $j$  in hidden terminal condition as follows:

$$P_S(i,j) = \exp \left\{ -\beta \sum_{(m,n) \in C(i,j)} G(m,n) - T_{RTS} \sum_{m \in O_i, n \in C(m,n)} G(m,n) \right\} \tag{30}$$

In our scheme, suppose the spreading code is m-sequence. Then, we can get the autocorrelation  $\rho(\tau)$  of the spreading code from (Goldsmith, 2005).

$$\rho(\tau) = \begin{cases} 1 - \frac{|\tau|(1+1/N)}{T_C} & |\tau| \leq T_C \\ 1/N & |\tau| > T_C \end{cases} \tag{31}$$

in which  $\tau$  is the delay offset of spreading code,  $T_C$  is the chip duration of the spreading code, and  $n$  is the length of the spreading code. Since the medium accesses of two nodes are independent, the delay offset  $\tau$  is uniformly distributed on  $[0, nT_C]$ . The expectation of  $\rho(\tau)$  is  $E(\rho(\tau))=3(n-1)/(2n^2)$ . Suppose the radio signal is transmitted in free space. From (Goldsmith, 2005), we can get the path loss:

$$P_L = \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2} \tag{32}$$

in which  $G_t$  and  $G_r$  are the antenna gain of transmitter and receiver respectively.  $\lambda$  is the wave length of the radio, and  $d$  is the distance from transmitter to receiver. In CSMA/CA, there is a power sensing threshold of the capture area. Nodes with sensed power lower than the power sensing threshold take the channel as busy; otherwise take the channel as idle. From (32), we can denote the power sensing threshold  $P_0^{CCC}$  of CCC as follows:

$$P_0^{CCC} = \frac{G_t G_r \lambda^2}{(4\pi)^2 (c_{ij}^{CCC})^2} P \tag{33}$$

in which  $c_{ij}^{CCC}$  is the capture distance of CCC, and  $P$  is the transmission power. Since spreading code is used in our scheme, the power sensing threshold  $P_0^{DHMA}$  of DHMA is the product of sensed power and the average autocorrelation of the spreading code. So,  $P_0^{DHMA}$  is as follows:

$$P_0^{DHMA} = \left( \frac{G_t G_r \lambda^2}{(4\pi)^2 (c_{ij}^{DHMA})^2} P \right) E(\rho(\tau))$$

$$= \frac{G_t G_r \lambda^2}{(4\pi)^2 (c_{ij}^{DHMA})^2} \frac{3(n-1)}{2n^2} P \tag{34}$$

in which  $c_{ij}^{DHMA}$  is the capture distance of DHMA, and  $P$  is the transmission power. Supposing the power sensing threshold of CCC and DHMA is equal, from (33) and (34), we can get the ratio  $\eta_C$  of capture distances of CCC and our scheme.

$$\eta_C = \frac{c_{ij}^{CCC}}{c_{ij}^{DHMA}} = \frac{n}{\sqrt{3(n-1)/2}} \tag{35}$$

From (35), it can be seen that  $\eta_C > 1$ , which indicates that the capture distance of CCC is longer than that of our scheme. Fig.7 shows that the longer of capture distance, the heavier of hidden terminal interference. Moreover,  $\eta_C$  is in direct ratio with  $n$ . When the length of spreading code is increased,  $\eta_C$  is increased. Supposing the capture distance of CCC is constant, we can see that the capture distance of our scheme is decreased when the length of spreading code is increased. So, the hidden terminal interference in CCC is heavier than that in our scheme, and the hidden terminal interference in our scheme can be removed when the spreading code is long enough.

Suppose node  $i$ 's coverage areas in our scheme and CCC are equal, and they are denoted with  $C_i$ . In Fig.7,  $C(i,j)$  is the aggregate of the communication pair  $(m,n)$  and  $m \in C_i \cup C_j - H_i$ ,  $n \in C_i \cup C_j - H_j$ . Therefore,  $C(i,j)$  in our scheme and CCC are same. Suppose the transmission power of every node in our scheme and CCC is equal. From (35), it can be seen that node  $i$ 's capture areas in our scheme and CCC are different, and they are denoted with  $I_i^{DHMA}$  and  $I_i^{CCC}$  respectively. From (29), we can get  $O_i$  of our scheme and CCC:

$$O_i^{DHMA} = I_i^{DHMA} \cup I_j^{DHMA} - I_i^{DHMA} \cup C_j \tag{36}$$

$$O_i^{CCC} = I_i^{CCC} \cup I_j^{CCC} - I_i^{CCC} \cup C_j \tag{37}$$

$O_i^{DHMA}$  and  $O_i^{CCC}$  are corresponding to the area ABCDEF in Fig. 7. Suppose the nodes are uniformly distributed in the WMN with density  $\zeta$ . From Fig. 7, we can get  $O_i^{DHMA}$  and  $O_i^{CCC}$  as follows:

$$O_i^{DHMA} = \zeta \left( \pi - 2 \arccos \frac{d_{ij}}{2c_{ij}^{DHMA}} \right) \left( c_{ij}^{DHMA} \right)^2 + \zeta d_{ij} c_{ij}^{DHMA} - \zeta \left( 4d_{ij} - 2 \left( c_{ij}^{DHMA} \right)^2 \right) \arccos \frac{c_{ij}^{DHMA}}{2d_{ij}} - \zeta c_{ij}^{DHMA} \sqrt{d_{ij}^2 - \left( c_{ij}^{DHMA} / 2 \right)^2} \tag{38}$$

$$O_i^{CCC} = \zeta \left( \pi - 2 \arccos \frac{d_{ij}}{2c_{ij}^{CCC}} \right) \left( c_{ij}^{CCC} \right)^2 + \zeta d_{ij} c_{ij}^{CCC} - \zeta \left( 4d_{ij} - 2 \left( c_{ij}^{CCC} \right)^2 \right) \arccos \frac{c_{ij}^{CCC}}{2d_{ij}} - \zeta c_{ij}^{CCC} \sqrt{d_{ij}^2 - \left( c_{ij}^{CCC} / 2 \right)^2} \tag{39}$$

Let  $P_S^{DHMA}(i, j)$  and  $P_S^{CCC}(i, j)$  be the success transmission probability of our scheme and CCC respectively. From (29), we can get  $P_S^{DHMA}(i, j)$  and  $P_S^{CCC}(i, j)$  :

$$P_S^{DHMA}(i, j) = \exp \left\{ -\beta \sum_{(m,n) \in C(i,j)} G(m,n) - T_{RTS} \sum_{m \in O_i^{DHMA}, n \in C(m,n)} G(m,n) \right\} \tag{40}$$

$$P_S^{CCC}(i, j) = \exp \left\{ -\beta \sum_{(m,n) \in C(i,j)} G(m,n) - T_{RTS} \sum_{m \in O_i^{CCC}, n \in C(m,n)} G(m,n) \right\} \tag{41}$$

in which  $T_{RTS}$  and  $T_{CTS}$  are the same with that in (14).

The throughputs of our scheme and CCC with hidden terminals are the product of throughput without hidden terminals and the transmission success probability with hidden terminals, and they are as follows:

$$T_H^{DHMA} = T_{DHMA} P_S^{DHMA}(i, j) \tag{42}$$

$$T_H^{CCC} = T_{CCC} P_S^{CCC}(i, j) \tag{43}$$

$n$	$N$	$e$	$B$	$B_D$
100	10	2.718	100MHz	99MHz
$B_C$	$B_{G1}$	$B_{G2}$	$\beta$	$n_0$
1MHz	2MHz	4.9MHz	0.005	70dBm
$RTS$	$CTS$	$E(P)$	$a$	$SIFS$
20Byte	14Byte	3000Byte	0.1	0.03
$DIFS$	$E$	$G_t$	$G_r$	
0.14	90dBm	1	1	

Table 1. The evaluation parameter

## B. Access delay

Access delay is the length of time from a node sending RTS to this node starting to send data. Access delay  $D_A$  is the sum of contention access delay  $D_{CA}$  and data channel waiting delay  $D_W$ , that is,

$$D_A = D_{CA} + D_W \quad (44)$$

Contention access delay is the length of time from a node sending RTS to this node receiving CTS. Data channel waiting delay is the length of time from a node receiving the CTS to this node starting to send data.

### a. Access delay of our scheme

In our scheme, RTS-CTS handshake is used on the control channel, so the collision happens only at RTS period. Since CSMA/CA is used during RTS, according to (Kleinrock & Tobagi, 1975), we can get the average contention access delay on control channel:

$$D_{CA}^{DHMA} = (G / S_{DHMA} - 1)(1 + 2a + \alpha + \delta) + 1 + a \quad (45)$$

in which  $G$  is the offered load for the WMN,  $S_{DHMA}$  is the throughput of the control channel defined in (16),  $a$  is the propagation delay normalized by the transmission time of RTS  $T_{RTS}$ ,  $\alpha$  is the ratio of frame length of CTS to that of RTS, and  $\delta$  is ratio of the average length of backoff time  $E[B]$  to the transmission time of RTS. From (Cali, et. al., 1998), we can get the average length of backoff time  $E[B] = (E[CW] - a^* T_{RTS}) / 2$ . Here,  $a^* T_{RTS}$  is the propagation delay. Then,  $\delta = E[B] / T_{RTS}$ .

When the RTS-CTS handshake is succeeded, transmission of a data packet will be arranged on the data channels. This process can be modeled as an M/M/1 queuing process. The average packet arriving rate of the queue is  $R_{CC}^{DHMA}$  defined in (17), and the average packet serving rate is the product of the throughput of DHMA and the capacity of WMN system, that is,  $P_H^{DHMA} = T_H^{DHMA} P_{WMN}$ . Then, the average waiting delay  $D_W$  is the average waiting delay in the queue. According to Little formula, we can get the average waiting time:

$$D_W^{DHMA} = \frac{R_{CC}^{DHMA}}{P_H^{DHMA} (P_H^{DHMA} - R_{CC}^{DHMA})} \quad (46)$$

Replacing  $D_{CA}$  and  $D_W$  in (44) with  $D_{CA}^{DHMA}$  and  $D_W^{DHMA}$ , we can get the access delay of our scheme:

$$D_A^{DHMA} = D_{CA}^{DHMA} + D_W^{DHMA} \quad (47)$$

### b. Access delay of CCC

Suppose  $G$  is the offered load of the WMN. From (24), we can get the offered load  $G'$  in the contention window of CCC. According to (Kleinrock & Tobagi, 1975), the contention access delay is:

$$D_{CA}^{CCC} = (G' / S_{CCC} - 1)(1 + 2a + \alpha + \delta) + 1 + a \quad (48)$$

$G'$  and  $S_{CCC}$  are defined in (24) and (25). All the other parameters are the same with that of (45). In Fig.6, data packet is transmitted on data channel immediately after the success of RTS-CTS handshake on control channel. Then, the data channel waiting delay is equal to



zero in CCC. From (44), we can get that the access delay in CCC is equal to the contention access delay on control channel, that is:

$$D_A^{CCC} = D_{CA}^{CCC} \tag{49}$$

### 3.3 System evaluation and comparisons

Table 1 offers the required parameters of our system and CCC during the evaluation. Suppose the nodes are uniformly distributed as shown in Fig. 7.  $C(i,j)$  is  $\{(b,i), (d,i), (d,j), (e,i), (e,j), (j,g)\}$ . From (35), it can be seen that the capture distance of our scheme is smaller than that of CCC. When  $n=100$ , the ratio of the two capture distances  $\eta_C$  is 8.2. Therefore,  $c_{ij}^{CCC}$  is much larger than  $c_{ij}^{DHMA}$ . Since  $c_{ij}^{CCC}$  and  $c_{ij}^{DHMA}$  are the radiuses of  $I_i^{CCC}$  and  $I_i^{DHMA}$ ,  $I_i^{CCC}$  is larger than  $I_i^{DHMA}$ . From (36) and (37), we can see that  $O_i^{CCC}$  is larger than  $O_i^{DHMA}$ . In Fig. 7, suppose  $O_i^{CCC} = \{h, f\}$ , and  $O_i^{DHMA} = \{h\}$ .

Firstly, the throughput of DHMA is estimated. From (19), we can get the throughput of DHMA without hidden terminals. The estimation results are shown in Fig.8. When the offered load is increased, the throughput of DHMA is increased at first and decreased when the control channel is overloaded. The estimation curve for CCC without hidden terminals is similar to that of our scheme. However, because the contentions on control channel of CCC are more serious than that of ours, the throughput of CCC is lower when the offered load is over 23. When there are hidden terminals, the throughputs of our scheme and CCC are decreased. Because of the hidden terminal immune property which is analyzed in (35), our scheme has smaller throughput reduction than CCC does.

Then, the access delay of DHMA is estimated. The access delay of our scheme can be estimated with (47). Fig.9 shows the estimation results which imply: when the offered load is bellow 20, the access delay increases slowly; when the offered load is over 60, the access delay increase quickly. Comparing with CCC, the access delay of our scheme is shorter. When the offered load is increased, the access delay of our scheme increases slower than

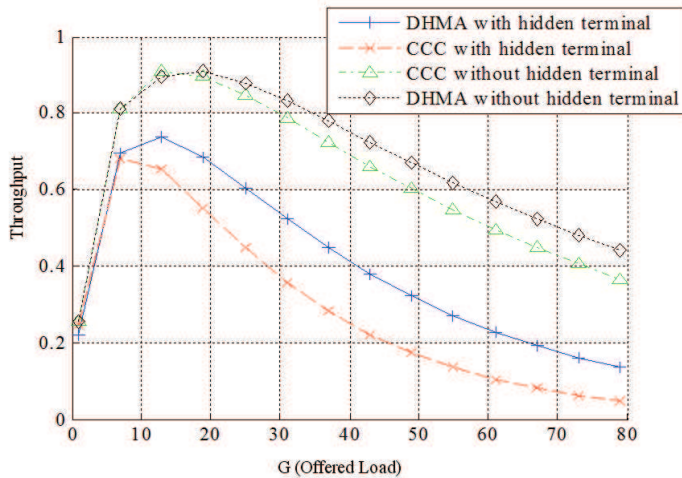


Fig. 8. Throughput vs. offered load of DHMA and CCC.

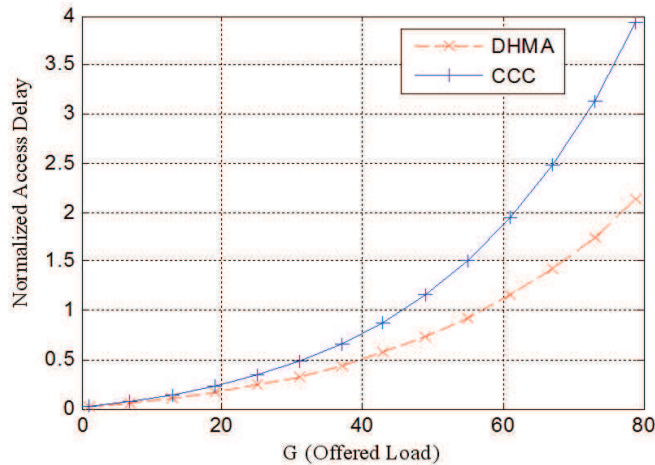


Fig. 9. Throughput vs. offered load of DHMA and CCC.

that of CCC. The reason is that the contention window of our scheme can be arranged at any place on the control channel while that of CCC must be arranged between the two data transmissions. So, when the offered loads in DHMA and CCC are equal, there are fewer RTSs within each contention window in our scheme than those in CCC.

#### 4. Conclusions and future works

This chapter proposes a medium access scheme for multi-channel WMN. Our scheme is designed to reduce the channel access delay and increase the system's throughput. Since CDMA is used to divide sub-channels on data channel, data-rate on each sub-channel can be adjusted by changing the length of spreading code. Because the transmissions between different communication pairs aren't synchronized, hidden terminal interference can be reduced. From the theory analyses and performance evaluations, we can see that our scheme has high throughput and short access delay and outperforms CCC.

However, there are still problems needed to be solved. This scheme can be employed for the nodes with multiple transceivers. For the system with single transceiver, the node needs to switch transceiver from control channel and data channel frequently. When the node switches to the data channel, the handshaking information on the control channel might be missed, and cause system malfunction. Therefore, transceiver adaptive MAC need be further studied. Cognitive radio has been introduced into WMNs (Chen et al., 2008), which can relax the conflict between wireless resource supply and demand. But cognitive radio makes the medium access control more difficult. In cognitive radio based WMNs, wireless resources are unlicensed and licensed users' actions will cause mesh node's frequent channel switching, which makes the MAC of WMNs more complicated. QoS guarantee of MAC in WMN need be studied. Channel allocation and channel switching processes might cause delay for transmission which will reduce the QoS of real-time services, especially the real-time multimedia services. Because of frequent channel switching, QoS guarantee in cognitive radio based WMN is much more difficult. If the QoS problem isn't solved, WMN won't be widely accepted by the consumer.

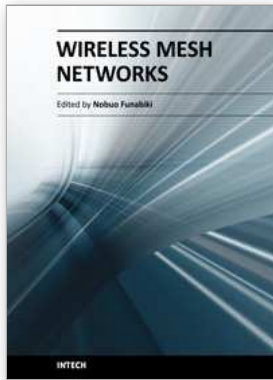
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## **Wireless Mesh Networks**

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The rapid advancements of low-cost small-size devices for wireless communications with their international standards and broadband backbone networks using optical fibers accelerate the deployment of wireless networks around the world. The wireless mesh network has emerged as the generalization of the conventional wireless network. However, wireless mesh network has several problems to be solved before being deployed as the fundamental network infrastructure for daily use. The book is edited to specify some problems that come from the disadvantages in wireless mesh network and give their solutions with challenges. The contents of this book consist of two parts: Part I covers the fundamental technical issues in wireless mesh network, and Part II the administrative technical issues in wireless mesh network. This book can be useful as a reference for researchers, engineers, students and educators who have some backgrounds in computer networks, and who have interest in wireless mesh network. It is a collective work of excellent contributions by experts in wireless mesh network.

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