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An Improved Multi-Channel MAC Protocol for Wireless Mesh Networks*

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关于无线 Mesh 网络多通道 MAC 协议的改进 *

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摘　要: 针对 IEEE 802.11 协议中的单访问点环境,研究了多访问点和移动终端的无线 Mesh 网络存在的问题,提出了基于修改 IEEE 802.11 协议的单信道自组网络解决方案。方案存在的主要问题是单信道结构的性能低,就此提出改进的多信道 Mesh 结构。该结构针对互连的多访问点,基于分布式协调功能技术来实现。在 OPNET 8.1 上进行了仿真实验,结果表明信息通过量和信道利用率均获得了好的性能。

关键词: 无线 Mesh 网络;隐藏终端;多信道媒体访问控制
文献标识码: A　　**中图分类号:** TP393

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Abstract: The current IEEE 802.11 protocol is aimed at single Access Point (AP) environments and many problems related to the wireless meshed interconnection of APs and Mobile Terminals (MTs) remain to be solved. Some proposed solutions to build such mesh architectures are based on single-channel ad-hoc oriented schemes in which IEEE 802.11 protocol has been modified. The main problem with this type of schemes, however, lies in the very low performance of the single-channel architecture itself. An improved multi-channel mesh architecture is presented which works using a Distributed Coordination Function (DCF)-based technique

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for interconnecting APs. The simulations results obtained in OPNET 8.1 show a good performance of our proposed scheme in terms of throughput and channel utility.

Key words: Wireless Mesh Networks; Hidden Terminal Problem (HTP); multi-channel Medium Access Control (MAC)

1 Introduction

Recently Wireless Mesh Networks have been attracting a great attention from both academia and commercial world. The low price and wide use of IEEE 802.11 Network Interface Cards (NICs) make the mesh architecture based on this technology a very attractive and cost-effective alternative to realize the service area extension of WLAN hot zones in both outdoor and indoor environments. However, the IEEE 802.11 infrastructure networks are aimed at supporting services for a number of stations connected to a single AP but neither at supporting terminal mobility nor at providing wireless interconnections among a group of APs and their respective Mobile Terminals (MTs). Based on methods applied on ad-hoc environments, most of the solutions found in the literature to create a mesh architecture for IEEE 802.11 infrastructure networks use a single channel and work over a modified MAC protocol of IEEE 802.11 that generally add newly defined packets to the standard. However, the main problem with single channel solutions lies on the scarce network capacity of the single channel architecture itself.

The IEEE 802.11 WLAN allows a number of non-overlapping frequency channels to be used simultaneously increasing the aggregate bandwidth available to end-users. However, bandwidth aggregation is rarely used in the context of multi-hop networks based on IEEE 802.11. The idea of using multiple channels is particularly appealing in the context of mesh networks due to the great amount of backhaul traffic forwarded by APs located in the central area of the network.

In this paper, we propose an improved communication scheme which allows adjacent APs in a Wireless Mesh Network to exchange data packets by simply using the Distributed Coordination Function (DCF) procedure of IEEE 802.11. In the proposed system every AP has only 1 NIC and uses a number of channels provided for IEEE 802.11a/g. From the implementation viewpoint, a great advantage of the proposed system is that, putting routing issues aside, it does not introduce any change into the MAC protocol of IEEE 802.11 and its AP to AP transmission mechanism is also able to work on a single-channel network, that is, it has a very strong compatible trait.

2 Related Works

2.1 Review IEEE 802.11 MAC Protocol

IEEE 802.11 is an international WLAN standard which covers the specification for the Medium Access Control (MAC) sub layer and the Physical (PHY) layer. One commonly used function to coordinate channel access for wireless STAtions (STAs) in the IEEE 802.11 MAC protocol is called Distributed Coordination Function (DCF). Firstly, we briefly review the IEEE 802.11 Distributed Coordinated Function (DCF)[1]. As described in [1], transmitting mobile station must first sense an idle channel for a time period corresponding to the Distributed Inter Frame Spacing (DIFS), after which it generates a random back off timer chosen uniformly from the range [0,w−1], where w is referred to as the contention window. At the first transmission attempt, w is set to the minimum contention window CW_{min}. After the back off timer reaches 0, the mobile station transmits a short Request-To-Send (RTS) message. If successfully received, the receiving mobile station responds with a short Clear-To-Send (CTS) message. Any other mobile stations which hear either the RTS or CTS message uses the duration field of this control message to update their Network Allocation Vector (NAV) containing information about the time period during which the channel will remain busy. Thus, all mobile stations, including hidden nodes, can defer transmission so as to avoid collisions. Finally, a binary exponential back off scheme is used such that the value of w is $2^{n+5}-1$ (retry counter n=0,…,5), beginning with an initial value of 31, up to a maximum value 1 023. Fig.1 presents the sequence of packets transmitted with DCF in IEEE 802.11 ad hoc mode.

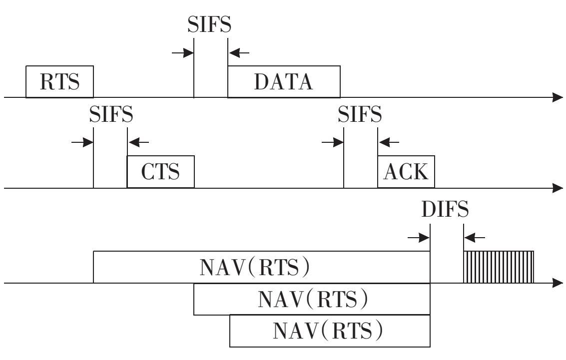

Fig.1 Transmitted with DCF in IEEE 802.11 ad hoc mode

图 1 在 IEEE 802.11 自组网络模式中具有分布式协调功能的传输

2.2 Problem Definition

If all transmissions among STAs are taken place on a single channel, signal interference will limit network throughput and we should face lots of other problems, such as Erroneous Reservation Problem (ERP).

From Fig.2 (a), STA C cannot start communication with STA D, if STA A and STA B are already establish a communication link between them. Let's take another situation into account, it's assume that STA B is a sender and STA A is a receiver, as we clearly see that STA C's sending message cannot influence reception of STA A. Unfortunately, continuously data transmission between STA A and STA B breaks handshake of STA C and STA D, so we conclude, in single channel, STA C and D cannot start communication if STA A and B are currently communicating with each other. Fig.2(b) shows us something worse when STA A and B establish a communication session through double handshakes (RTS/CTS), STA A sends a RTS packet to notify STA B, STA B replies CTS packet to STA A, because of some serious noise existing or some other reasons, CTS control packet transmitting through link B to A missed, so the session establishment fails. But STA C is in the transmission range of STA B, so it also can sensor CTS packet sending by B, when it captures CTS, it will reserve the bandwidth for STA B and renew its Network Allocation Vector (NAV).

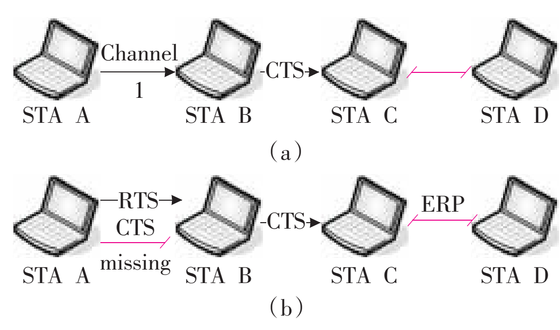

Fig.2 Single channel problem

图 2 单通道问题

2.3 Previous Solutions

Because of the disadvantages of single channel protocol, multi-channel proposal has been deduced. There are two general approaches: dedicated control channel and common control period. Fig.3 shows. In the first approach, one or more control channels are dedicated to exchange control packets for negotiations. The remaining available channels are called data channels. Any transmission pair can do negotiations anytime on the dedicated control channel and then switch to the commonly selected data channel for data exchanges. Examples of this category include AMNP[2], DCA[3], DPC[4], RBCS[5], MCDA[6] and MCMAC[7]. In the second approach, there is no dedicated control channel but one data channel (called common channel) will temporarily act as a control channel. All STAs will synchronously alternate between control and data periods. During a control period, all STAs have to switch to the common channel and do negotiations with the destined STAs of pending data packets. A transmission pair after successful negotiations has to wait for the ending of the current control period and then will switch to the commonly selected data channel for data exchanges. Note that the common channel can be selected as a data channel for data exchanges. Examples of this category include MMAC[8] and MAP[9].

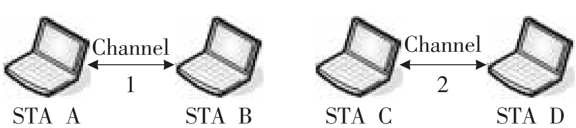

Fig.3 Multi-channel

图 3 多通道

The advantages and disadvantages of these two approaches are summarized below.

(1)Dedicated control channel

Advantages: The dedicated channel can serve as a broadcast channel. Channel negotiations can be done anytime.

Disadvantages: The dedicated channel on which only control packets are transmitted may have low channel utilization. The data capacity is dependent on the bandwidth of the dedicated channel, which can not be dynamically adjusted.

(2)Common control period

Advantages: The common channel can be used to transfer data packets during data periods, which increases channel utilization. The hardware cost is low because only one transceiver is needed. The data capacity is dependent on the length of a control period, which can be dynamically adjusted.

Disadvantages: Time synchronizations among STAs are needed. It takes high cost to transmit any broadcast message during a data period. Channel negotiations can not be done anytime, and hence this may cause a long delay on the delivery of any pending data packet.

Furthermore, multi-channel MAC protocols suffer from some problems such as multi-channel hidden terminal, deafness and broadcast problems. The key is that when the STAs are located on different channels and are unaware of the channel activities of their neighbors. A STA is called multi-channel hidden terminal if it causes interference on one of its neighbors by attempting transmission after switching to the same channel, this neighbor is currently used. We can see this problem clearly from Fig.4. A deafness problem occurs when a STA continuously attempts to contact with another STA which is located on a different channel. The sending of broadcast messages to the STAs which are located on different channels becomes costly, since multiple unicast messages should be sent instead.

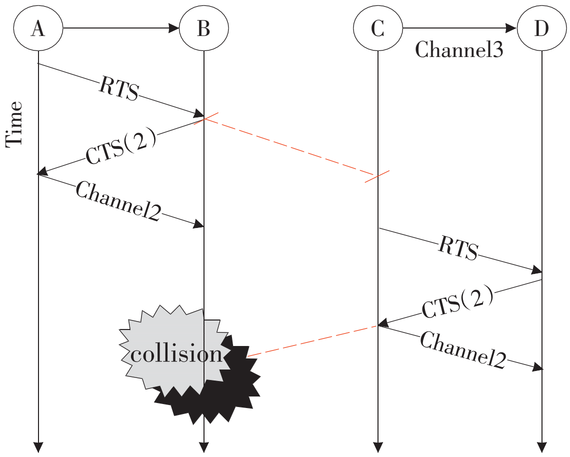

Fig.4 Multi-channel hidden terminal

图 4 多通道隐藏终端

3 Multi-Channel MAC Protocol

3.1 Basic Idea

Because of hardness of times synchronization among the STAs, many previously proposed multi-channel MAC protocols are based on the idea of dividing the radio channel into two or more sub-channels with one sub-channel working as the control channel, others working as the data channel(s). In the IEEE 802.11b and the IEEE 802.11a systems, there are totally three and twelve non-overlapping channels available, respectively. Among the channels that are able to be used simultaneously, one channel is reserved for control messages, and the remaining channels are available for data transfer. By monitoring the control channel, a node can obtain the global status of data channels. Control messages are sent through the control channel and real data is sent through the data channel negotiated during RTS-CTS exchange. In addition to RTS, CTS and ACK messages, a new control message, CONFIRM[10], is introduced for channel negotiation. CONFIRM message confirms which channel number is used for the following data communication. Each node maintains a channel table that stores channel-related information for all of data channels. The control channel is channel 0.

When a node has data to send, it first sends RTS control packet (Fig.5) to notify the destination node its intention of communication. The Dst retrieves the list of available channels from its channel table. Then it sends the list to the sender inside the CTS message (Fig.6). The sender selects one channel (which is idle at both nodes) and informs the selected channel number inside the CONFIRM (Fig.7).

2	2	6	6	4
Ctrl	Duration Time	Dst	Src	FCS

Fig.5 RTS control frame

图 5 RTS 控制帧

2	2	6	6	16	4
Ctrl	Duration Time	Dst	Src	Idle Channel table	FCS

Fig.6 CTS control frame

图 6 CTS 控制帧

2	2	6	6	2	4
Ctrl	Duration Time	Dst	Src	Select Channel	FCS

Fig.7 CONFIRM control frame

图 7 CONFIRM 控制帧

Now the two nodes can start data transfer through the selected channel (Fig.8). At each data transfer, an ACK is transmitted over the common control channel. But how we resolve the HTP (Hidden Terminal Problem)? As described in [10], the MTT (Maximum Transmission Time) is defined for each data channel. The MTT is the maximum time allowed for a packet to be transmitted over the associated channel. If a mobile station wants to communicate with some other station, it waits for a length of time equal to the MTT (Fig.9(a)), before declaring the data channel to be available. This is

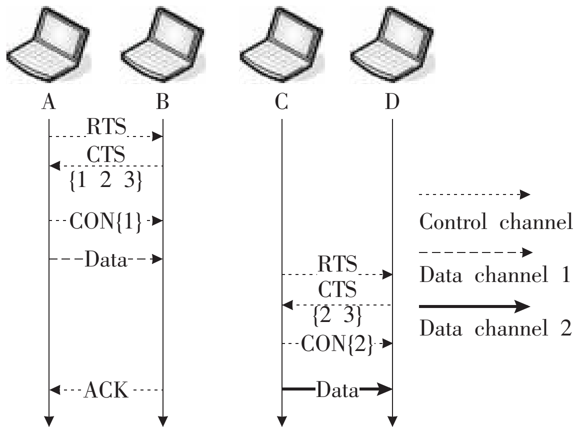

Fig.8 Timeline of multi-channel protocol

图 8 多通道协议时序

because if the data channel were in the busy state, it would receive an ACK through the control channel in its MTT. That is, a mobile station can know the associated channel utilization status in at least each MTT, if the station in a state of waiting MTT has already retrieves ACK, then it reduces the back off timer and prepares to send message. Fig.9(b) clearly shows us the timeline of multi-channel MAC protocol using MTT.

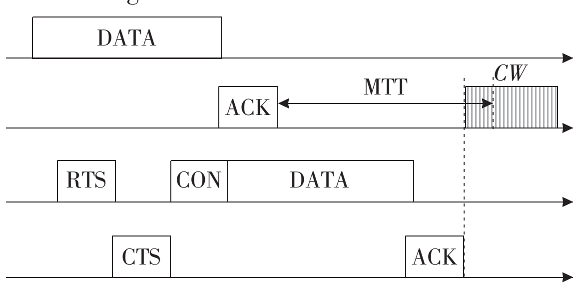

Fig.9(a) Multi-channel protocol using MTT to resolve HTP

图 9(a) 用 MTT 解决 HTP 的多通道协议

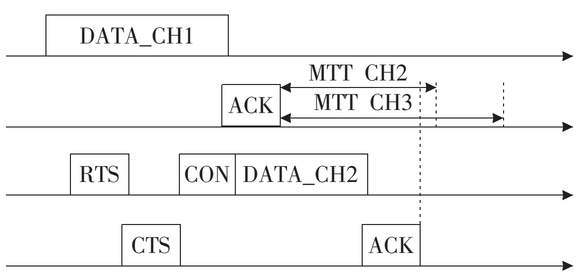

Fig.9(b) Different MTT means transmitted priority

图 9(b) 不同的 MTT 意味着被传输的优先级

Different MTT is used for providing different level services. A channel with a shorter MTT is used for higher priority traffic. The short and delay-sensitive packets are transmitted through a high priority data channel, in order to minimize the duration of the transfer, while large packets are transmitted through a low priority data channel, for which the MTT is sufficient to allow the transfer to be completed.

3.2 Make the Solution Robust

Multi-channel media access control protocol perfectly resolves the multi-channel HTP and enhances the throughput of networks. Unfortunately, the dedicated channel on which only control packets are transmitted may have low channel utilization. Even worse, if data transmission duration time or MTT value is set a small value, some data channels may be wasted. That is, during data transmission time, it is unable to set up enough negotiations to make a full use of data channels.

Let T_n and T_d respectively denote the average time to complete negotiations and the average time to complete data exchanges for a transmission pair. M denotes total number of channels. Suppose that $T_n<T_d$, there are at most min $(T_d/T_n, M-1)$ transmission pairs that can finish negotiations on the control channel during one T_d on the data channel.

Hence the data capacity is min $(T_d/T_n, M-1)$. If $T_d/T_n<M-1$, means that several data channels may not be used, as we see clearly from Fig.12, the transmission data length sets too small, there is not enough time to make any more handshakes, so STA C and D cannot communicate concurrently when STA A, B, C, D are communicating, data channel 3 is wasted (Fig.10(b)). If $T_d/T_n>M-1$, means that the dedicated control channel is not make a full usage, as Fig.11 shows us. Clearly to see, the best case is that $T_d/T_n=M-1$.

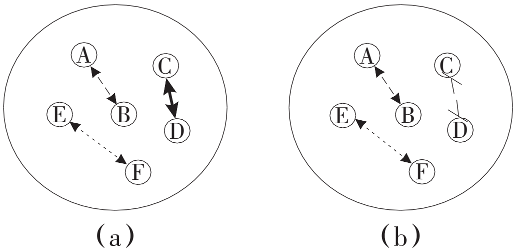

Fig.10 Communication using multi-channel protocol

图 10 使用多通道协议通信

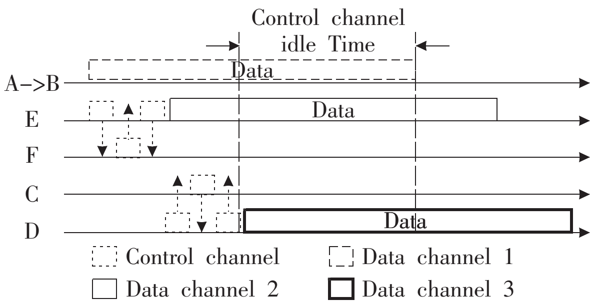

Fig.11 Long data transmission length's impact on control channel

图 11 长数据传输在控制通道上长的影响

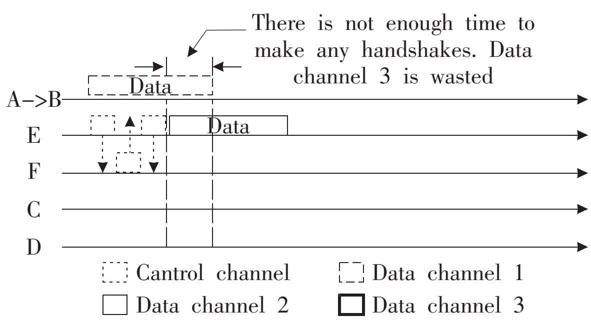

Fig.12 Short data transmission length's impact on data channel

图 12 短数据传输在控制通道上长的影响

Should we make $T_d/T_n=M-1$? Obviously not, because the equation is correct only when the negotiation packets come in order. Frame collision should be taken into account.

We assume that there are N stations in the network, each station wants to send a message base on a probability $P(0<p<1)$.

$$P=C_N^1\rho(1-\rho)^{N-1} \tag{1}$$

$$Q=(1-p)^j p \tag{2}$$

P and Q respectively denote the probability of successfully sending a packet and fails j times but next time succeeds to transmit. So we can deduce $AFCC$ (Average Frame Collision Counts):

$$AFCC=\sum_{j=1}^{\infty} j(1-p)^j p=\frac{1-p}{p} \tag{3}$$

From formula (1), we can get the max value $P_{\max}=[1-1/N]^{1/N}\approx 0.368$ when $p=1/N$. So $AFCC_{\min}\approx 3$. Let's L_d and L_n respectively denote the data transmission length and negotiation frame length ($L_n=RTS+CTS+CON$). We also equally divide channel into m sub-channels, so each one has the same data transmission rate.

$$\frac{T_d}{T_n}=\frac{L_d}{L_n}=(m-1)+\frac{AFCC}{2}\times(m-1)=\frac{5}{2}(m-1) \tag{4}$$

$$\Rightarrow \min L_d=\frac{5}{2}m-1L_c \tag{5}$$

Another problem is that different MTT settings for different priority services, as describe in [10], A channel with a shorter MTT is used for higher priority traffic. The short and delay-sensitive packets are transmitted through a high priority data channel, in order to minimize the duration of the transfer, while large packets are transmitted through a low priority data channel, for which the MTT is sufficient to allow the transfer to be completed. For example, suppose that the MTT of channel 1 (highest priority) is 2 units, while that of channel 2 is 5 units and that of channel 3 is 8 units. If a node has a 4-unit long packet to send, data channel 2 or 3 can be used. In order to increase the channel utilization, packets are sometimes assigned to higher priority channels. For example, when channel 1 is continuously idle, while channel 2 and 3 are both overloaded,packets for channel 2 are fragmented and sent over channel 1. Such channel migration is activated in two different situations; Firstly when the waiting time for the current channel exceeds the predefined channel access threshold timer, and secondly when the utilization of the high priority channel is below the utilization threshold. Fragmented packets are transferred in a row. For each fragment, an ACK is returned through the control channel. This may cause unfairness for end-users who require the same highest priority service. For example, there are 3 users in the BSS, they want the same kind service,such as video service, packets transmitting over 3 differ streams content the same sub channel (data channel 1) which is the highest priority sub channel. Because of this, data sub channel 2 and 3 keep idle all the time. The reason leading this problem is channel priority pre-allocation.

It can be seen from the basic DCF mechanism in section 2, that at least two parameters can be used to provide channel access differentiation: The defer time *DIFS* and *CW*,based on which the random back off timer is generated. Lower *DIFS* and *CW* values give higher priority for channel access. This is essentially how EDCF is developed[11]. Instead of treating all traffic with a single *DIFS* value and a single (CW_{min},CW_{max}) set, *EDCF* defines that the channel access has up to four Access Categories (*AC*),each with its own defer time called Arbitrary Distributed Inter Frame Space (*AIFS*) and CW_{min}/CW_{max} values.

According to the draft, one or more user priorities can be assigned to one AC and normally packets belonging to the same priority share one buffering queue. Multiple instance of these enhanced variant of DCF shall be running simultaneously in each STA as shown in Fig.13.

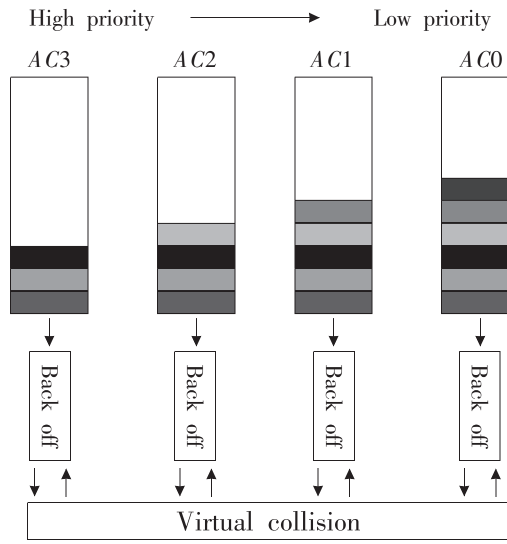

Fig.13 Internal contention of different Access Categories

图 13 不同访问类内部竞争

Therefore,there exist two levels of channel access contention: internal contention among traffic of different priorities internal contention among traffic of different priorities inside the same STA and external contention among traffic from different STAs.

Collisions may happen at both levels and are resolved similarly such that higher priority traffic will most probably obtain the channel first and lower priority traffic will have to back off. In short, different values of defer timer and back off timer are used to enable prioritized channel access for different traffic. Specifically,the draft provides default QoS parameter set for the four ACs as shown in Table 1.

Table 1 Recommended values of *AIFS* and *CW*

表 1 建议 *AIFS* 和 *CW* 的值

AC	*AIFS*	CW_{min}	CW_{max}
0(Best Effort)	2	31	1 023
1(Video Probe)	1	31	1 023
2(Video)	1	31	63
3(Voice)	1	7	15

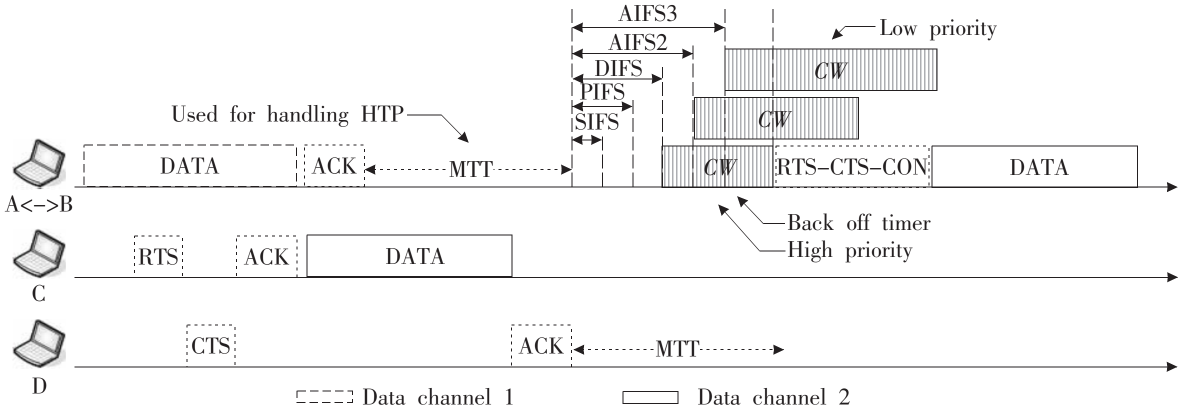

Fig.14 Timeline of this multi-channel MAC protocol based on QoS

图 14 基于 QoS 的多通道 MAC 协议的时序

We can use this mechanism to set up a new multi-channel MAC protocol based on QoS. Fig.14 shows us the timeline of this multi-channel MAC protocol based on QoS.

4 Simulation

We simulated DSR extended with 802.11DCF, multi-channel MAC protocol and improved multi-channel MAC based on MTT and QoS using the OPNET 8.1 simulator. Our simulation included 6 flows in a random topology consisting of 16 nodes. Each of 6 flows belonged to one of 3 possible service classes: Class A for premium service (Exponential on/off distribution), class B for assured service (Pareto distribution) and class C for best-effort service (CBR). We measured the throughput and channel utility for each service class in a multi-channel network for 600 s. The multi-channel network was composed of 5 channels and RTS CTS and CONFIRM control frame is set as we see in Fig.15~17, the other network parameters were the same as those defined in IEEE802.11b. We can calculate the best data packet length from formula (5). Fig.15 shows the total throughput for three MAC protocol. Better throughput was obtained by improved multi-channel MAC protocol based on both QoS and MTT, and high utility of both data channels and control channel can also be obtained.

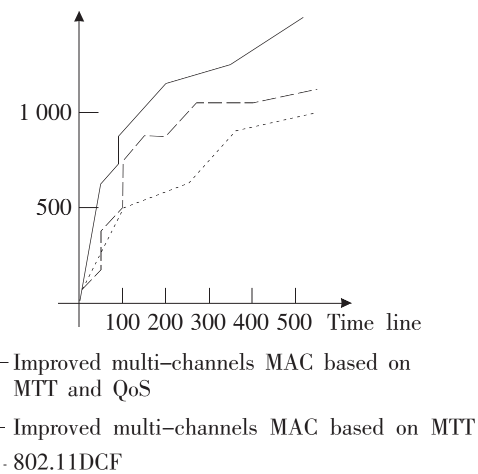

Fig.15 The throughput for different data transmission length

图 15 不同数据传输长度的通过量

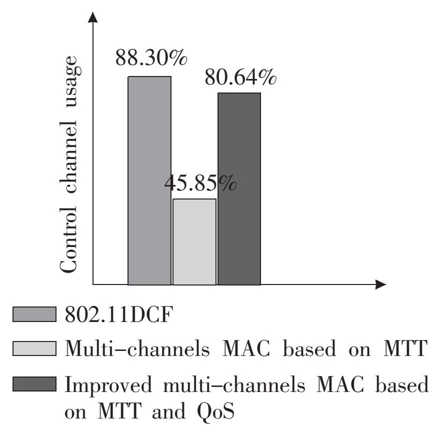

Fig.16 The control channels usage for different data transmission length

图 16 不同数据传输长度的控制通道运用

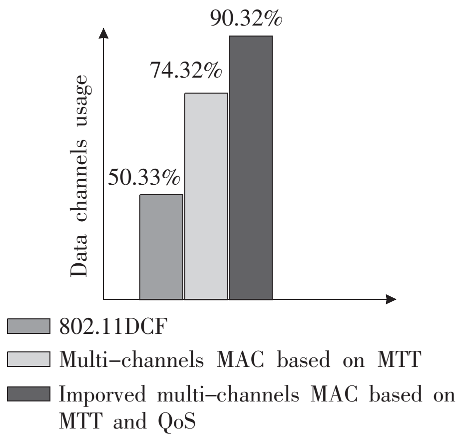

Fig.17 The data channels usage for different data transmission length

图 17 不同数据传输长度的数据通道运用

5 Conclusion

In this paper, we present the multi-channel MAC protocol and its use in mobile ad hoc networks to improve network performance. The advantages of this protocol are that several communications can occur concurrently using multiple channels without any interference and fully usage of every sub-channel. Furthermore, the proposed protocol solves the hidden multi-channel problem that can occur in a network environment involving the use of multiple channels. We evaluated the use of the improved multi-channel MAC protocol in mobile ad hoc networks using the OPNET simulator. The evaluation results show that better network throughput can be obtained and that fully utility of each sub-channel (Fig.16 and Fig.17).

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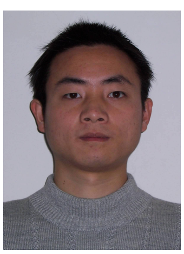

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