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QoS-based MAC protocol for cognitive radio networks

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Abstract: In order to improve the throughput performance of the secondary users (SUs) in the cognitive radio (CR) environment, a quality of service (QoS) based media access control (MAC) protocol is proposed. In this protocol, the CR node maps the channel state as a vector, and the transmitter and the receiver obtain the final channel map through an AND operation to prepare for an optional channel set. Data from the upper application layer are classified into two priority levels according to the QoS requirement. The data of each level relate to different contention windows so that the priority of real time data can be guaranteed. A two-dimensional discrete-time Markov chain is utilized to evaluate the system performance, and mathematical expressions of the system throughput are derived. Simulation results show that compared with the IEEE 802.11 distributed coordination function (DCF), the proposed MAC protocol can achieve higher throughput.

Key words: quality of service (QoS); cognitive radio; media access control (MAC); channel map; Markov chain

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The rapid growth in wireless communications has resulted in an excessive scarcity of spectrum. In recent years, industrial scientific and medical (ISM) unlicensed bands have stimulated the development of technologies such as WiFi, Bluetooth, cordless phones, etc. The great success of this band has given rise to the problem of the coexistence of heterogeneous systems that might interfere with each other. Nevertheless, the research studied by the FCC show that most allocated spectra experience inefficient utilization[1]. Cognitive radio (CR) emerges as a way to improve the overall spectrum usage by exploiting spectrum opportunities in both the licensed and the unlicensed bands. And cognitive radio networks (CRNs) have been receiving more and more research attention from industry and academia since it is a promising technique to improve the utilization of the existing radio spectra. In the cognitive radio networks, the unlicensed users or secondary users (SUs) can dynamically utilize the licensed radio spectra to communicate without causing any interference to the licensed users or primary users (PUs).

Designing an efficient MAC protocol is one of the most challenging issues in CRNs. A thorough description of MAC protocols for both CR infrastructure-based and ad hoc networks is provided in Ref. [2]. In addition, the number of radio transceivers also decides the performance of the MAC protocol. A typical random access protocol based on the CSMA is proposed in Ref. [3], which uses a single transceiver and in-band signaling. This protocol ensures the coexistence among the CR users and the PUs by adapting the transmission power and rate of the CR network. IEEE 802.22[4] is a centralized standard that uses base stations for spectrum access and sharing. The base station manages its own cell and all the associated consumer premise equipments (CPE) or CR users in this case. The dynamic channel assignment (DCA)-based MAC protocol[5] employs a default control channel while other channels can be used for data transmission. It assumes that each cognitive radio is equipped with two transceivers in which one constantly monitors the common channel, allowing it to avoid the multichannel hidden terminal problem. SYN-MAC[6] is a non-dedicated common control channel (CCC) based MAC protocol. In this protocol, time is divided into slots and each slot is dedicated to one channel for control message exchange. All the SUs in a network are synchronized and switch to the channel in predefined time slots.

Although a number of MAC protocols for CRNs exist in the literature, there are many areas where improvements are desirable and possible. As an extended research of Ref. [7], this paper selects random access CSMA/CA for the media access control protocol with combining the characteristics of the distributed cognitive radio network and the IEEE 802.11 family of standards[8]. Moreover, considering the QoS support, we study the system performance in the cognitive environment.

1 Proposed Protocol

As one of the random access algorithms, the proposed MAC protocol employs the successive frame exchange sequences (FES) RTS-CTS-DATA-ACK as in IEEE 802.11 DCF. Before transmitting, each transmitter must find the carrier to be idle for a time period of the distributed coordination function inter-frame space (DIFS). After

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deferring for the DIFS period, the station selects a backoff value for an additional deferral time before transmitting. This backoff period corresponds to an integer number of time slots, and is selected according to some algorithms. The proposed protocol is based on IEEE 802.11 DCF and combined with the characteristics of cognitive radio networks to make it suitable for the cognitive environment.

1.1 Channel model

We employ the same channel model as described in Ref. [8]. As the SUs are under the influence of the PUs, their spectra are time-varying. The available channels may be different at the transmitter and receiver sides. So before the data transmission, they must determine the available channels in both sides with control channel (CC). The footprints of the channel mapping process are shown in Fig. 1. Suppose that the transmitter has determined whether the channel within the sharing spectrum is available through the corresponding physical layer technology or not, and has mapped the channel state as a vector (channel mapping vector). In the vector, element "1" indicates that a channel is available, otherwise, "0" means unavailable. The transmitter vector shows the channel mapping vector at the transmitter in Fig. 1, and the vector is transmitted to the receiver through CC. At the same time, the receiver establishes its own channel mapping vector and obtains a final vector through an AND operation of the first two vectors by phase. Element "1" in the final vector indicates that the channel is available on both the transmitter and receiver sides. Finally, the receiver sends the final vector back to the transmitter with CC.

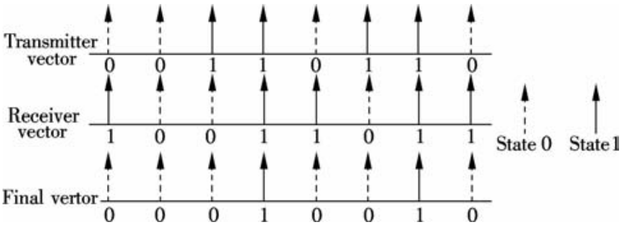

Fig. 1 Channel map

1.2 Backoff mechanism

Considering different QoS requirements, we classify the data into two types: realtime and non-realtime. Each data type relates to a different contention window range $[W_{\min,i}, W_{\max,i}]$, $i=1, 2$. The contention window with a smaller size means a lower transmit delay or a higher transmit rate. The MAC layer acquires the QoS parameters from the upper application layer and perceives ACK and the frame error rate (FER) from the PHY layer.

When a node has packets to send, it listens to the medium. If the channel is sensed idle for more than a predefined period, it may select a backoff interval (BI), and then transits into a backoff state. After the backoff counter decreases to zero, it transmits the first packet in the waiting queue. The BI is uniformly chosen in the range of $[0, W-1]$, where W is an integer between the minimum contention window $W_{\min}$ and the maximum contention window $W_{\max}$. There are different $W_{\min}$ and $W_{\max}$ according to different QoS. W is initiated to $W_{\min,i}$. After each unsuccessful transmission, W is doubled up to $W_{\max,i}$. Fig. 2 describes the flowchart of the backoff mechanism.

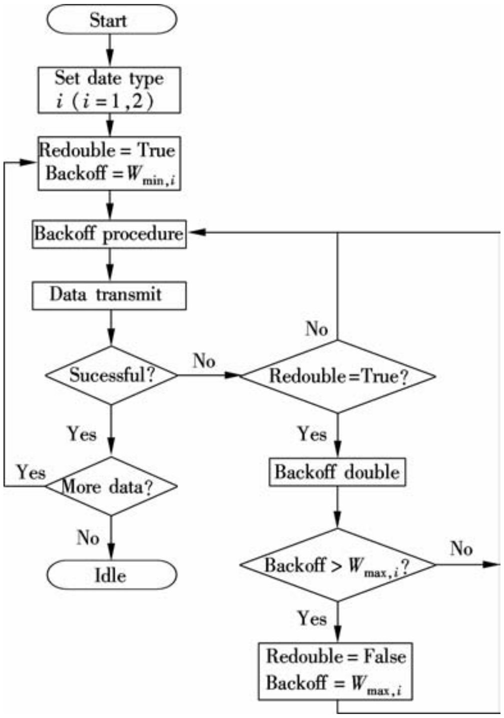

Fig. 2 Flowchart of the backoff mechanism

1.3 RTS/CTS frame format

As shown in Fig. 3, the RTS-CTS frame appends a field called "channel map" to identify channel mapping vectors. According to the received RTS frame, the receiver feedbacks the CTS message to the transmitter. The channel map in the RTS frame is extracted by the receiver and do the AND calculation with the local vector, thus, obtaining the final vector for the channel map field of the CTS frame, as shown in Fig. 1. Similarly, the CTS control frame has also been revised, and the channel map word is appended to identify the ultimate channel mapping vector that both the sending and receiving nodes are recognized. If the transmitter cannot receive ACK after the maximum retry times, the channel may be unavailable at that time. Before the next spectrum sensing period comes, the nodes pair can switch to the backup channel of the channel map, and thus decrease the outage probability and increase the spectrum utilization ratio.

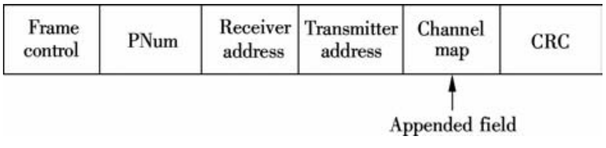

Fig. 3 RTS-CTS frame format

2 Performance Analysis

Ref. [9] proposed the analytical evaluation of the saturation throughput of IEEE 802.11 DCF based on the assumption of ideal channel conditions, i. e., no hidden terminals and capture. Similarly, in the following analysis, we assume a fixed number of stations, each of which always has a packet available for transmission. In other words, we operate in saturation conditions; i. e., the transmission queue of each station is assumed to be always nonempty.

We use a two-dimensional discrete-time Markov chain to evaluate the throughput. Consider a fixed number of N contending nodes, and no hidden terminals exist. A smaller priority value corresponds to a higher priority level. We denote n_i, $i=1,2$ as the number of nodes with data of a priority level i to transmit (in other words, the node of priority level i). Obviously, $N=n_1+n_2$.

For a node of priority level i, let $s(i,t)$ be the backoff stage at time t, where $s(i,t)$ is chosen from the range of $[0, L]$, and L denotes the maximum retransmission times. We also denote $b(i,t)$ as the value of the backoff time counter. When $s(i,t)=m$, $0 \leqslant m \leqslant L$, the corresponding $b(i,t)$ is chosen from the range of $[0, W_{i,m}]$, where $W_{i,m}$ denotes the content window size of the m-th backoff stage. Thus, $\{s(i,t), b(i,t)\}$ can represent the backoff state of the node with priority level i at time t. The Markov Chain model for the backoff process is depicted in Fig. 4.

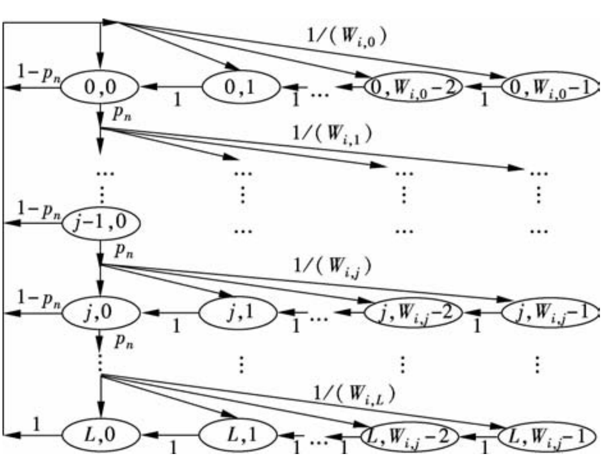

Fig. 4 The Markov chain model for the backoff process

In Fig. 4, state $(j, 0)$ refers the end of the backoff stage, and afterwards the node will begin to transmit data. If collision occurs, the contention window size will be resumed and the next backoff stage begins. p_n is the conditional collision probability, meaning that this is the probability of a collision seen by a packet being transmitted on the channel. If the transmission fails after the L-th attempt, a spectrum switch process will start according to the channel map in the RTS/CTS frame.

The stationary distribution of node n with priority level i can be written as follows:

$$b_{n,m,k} = \lim_{t\to\infty} P\{s(i,t)=m, b(i,t)=k\}$$
$$0<m<L;\ 0<k<W_{i,m}-1;\ 1 \leqslant n \leqslant N \quad (1)$$

where L denotes the maximum retransmission times and $W_{i,m}$ satisfies

$$W_{i,m} = \begin{cases} 2^m W_{\min,i} & 0 \leqslant m < M_i \\ W_{\max,i} & M_i \leqslant m \leqslant L \end{cases} \quad (2)$$

where M_i is the maximum backoff stage. Usually, $M_1 = M_2 = M$.

Note that

$$b_{n,m,0} = p_n^m\, b_{n,0,0} \quad (3)$$

$$b_{n,m,k} = \frac{W_{i,m}-k}{W_{i,m}} p_n b_{n,m-1,0} = \frac{W_{i,m}-k}{W_{i,m}} b_{n,m,0} \quad (4)$$

$$1 = \sum_{m=0}^{L}\sum_{k=0}^{W_{i,m}} b_{n,m,k} = \sum_{m=0}^{L} b_{n,m,0} \sum_{k=0}^{W_{i,m}-1} \frac{W_{i,m}-k}{W_{i,m}} = \sum_{m=0}^{L} b_{n,m,0} \frac{W_{i,m}+1}{2} \quad (5)$$

where $0<m<L$, $0<k<W_{i,m}-1$, $1 \leqslant n \leqslant N$. Thus, we can deduce that

$$b_{n,0,0} = \frac{1}{\sum_{m=0}^{L}\left[1+\frac{1}{1-p_n}\sum_{k=0}^{W_{i,m}-1}\frac{W_{i,m}-k}{W_{i,m}}\right]p_n^m} \qquad 1 \leqslant n \leqslant N \quad (6)$$

The access probability of the n-th node τ_n can be expressed as

$$\tau_n = \sum_{m=0}^{L} b_{n,m,o} = b_{n,0,0}\frac{1-p_n^{L+1}}{1-p_n} \qquad 1 \leqslant n \leqslant N \quad (7)$$

If node n transmits data with the access probability τ_n in any time slot, the collision probability p_n can be written as

$$p_n = 1 - \prod_{j=1, j\neq n}^{N}(1-\tau_j) \qquad 1 \leqslant n \leqslant N \quad (8)$$

The success probability for the n-th node $p_{n,\mathrm{s}}$ equals the probability that other $N-1$ nodes do not transmit. Thus, we obtain

$$p_{n,\mathrm{s}} = \tau_n \prod_{j=1, j\neq n}^{N}(1-\tau_j) \qquad 1 \leqslant n \leqslant N \quad (9)$$

Therefore, the total success probability of any time slots p_s is

$$p_\mathrm{s} = \sum_{n=1}^{N} p_{n,\mathrm{s}} \quad (10)$$

The channel busy probability p_b can be defined as the probability that N cognitive nodes transmit data, and it can be denoted as

$$p_\mathrm{b} = 1 - \prod_{j=1}^{N}(1-\tau_j) \quad (11)$$

The throughput of the n-th node S_n can be defined as the ratio of success transmission time duration T_{trans} vs. the total time in one time slot T_{total}. ε is the time interval, and T_{data} is the time for data transmission. T_{su} is the average time that the channel is sensed busy (i. e., the slot time lasts) because of a successful transmission, and T_{co} is the average time that the channel is sensed busy by each station during a collision. Thus, we obtain

$$S_n = \mu p_{\mathrm{c}} \frac{E[T_{\mathrm{trans}}]}{E[T_{\mathrm{total}}]} = \mu p_{\mathrm{c}} \frac{p_{n,\mathrm{s}} T_{\mathrm{data}}}{(1-p_{\mathrm{b}})\varepsilon + p_{\mathrm{s}} T_{\mathrm{su}} + (p_{\mathrm{s}} - p_{\mathrm{b}}) T_{\mathrm{co}}} \tag{12}$$

where μ is the ratio of effective transmission time, and it can be defined as

$$\mu = \frac{T - t_{\mathrm{scan}}}{T} \tag{13}$$

p_{c} is the probability of the spectrum sensing successfully, and it can be written as

$$p_{\mathrm{c}} = \exp\left(-\frac{\mathrm{a}}{t_{\mathrm{scan}}}\right) \tag{14}$$

where $\alpha = 5 \times 10^{-4}$ according to IEEE 802.22[4]. δ is the maximum delay. By the RTS/CTS model, T_{su} and T_{co} can be defined as[9]

$$\left.\begin{aligned} T_{\mathrm{su}} &= T_{\mathrm{DIFS}} + T_{\mathrm{RTS}} + T_{\mathrm{CTS}} + T_{\mathrm{DATA}} + T_{\mathrm{ACK}} + T_{\mathrm{SIFS}} + 3\delta \\ T_{\mathrm{co}} &= T_{\mathrm{DIFS}} + T_{\mathrm{RTS}} + \delta \end{aligned}\right\} \tag{15}$$

where T_{DIFS}, T_{RTS}, T_{CTS}, T_{DATA}, T_{ACK} and T_{SIFS} refer to the time duration of the DIFS, the request-to-send (RTS) frame, the clear-to-send (CTS) frame, the data frame, the acknowledgement (ACK) frame, and the short inter frame space (SIFS), respectively, as specified by the IEEE 802.11 standard.

Finally, we obtain the throughput S of a single unoccupied channel as follows:

$$S = \sum_{n=1}^{N} S_n = \mu p_{\mathrm{c}} \frac{p_{\mathrm{s}} T_{\mathrm{data}}}{(1-p_{\mathrm{b}})\varepsilon + p_{\mathrm{s}} T_{\mathrm{su}} + (p_{\mathrm{s}} - p_{\mathrm{b}}) T_{\mathrm{co}}} \tag{16}$$

3 Simulation and Evaluation

The parameters used to evaluate our proposed cognitive MAC protocol are summarized in Tab. 1.

Tab. 1 Parameters for proposed MAC protocol

Parameter	Value	Parameter	Value
$T_{\mathrm{SIFS}}/\mu\mathrm{s}$	15	L	5
$T_{\mathrm{DIFS}}/\mu\mathrm{s}$	34	$W_{\mathrm{min},1}$	8
L_{RTS}/Byte	44	$W_{\mathrm{max},1}$	64
L_{CTS}/Byte	38	$W_{\mathrm{min},2}$	64
L_{DATA}/Byte	1024	$W_{\mathrm{max},2}$	512
$T_{\mathrm{simulation}}$/s	2	$T_{\mathrm{SlotTime}}/\mu\mathrm{s}$	20
$R_{\mathrm{Transmission\ rate}}/(\mathrm{Mbit \cdot s^{-1}})$	1	T_{scan}/ms	20

In the evaluation of the MAC protocol throughput, we assume that each node has one priority level data to transmit. The probability of realtime data (level 1) is p_1, and the probability of non-realtime data (level 2) is p_2. Obviously, $p_1 + p_2 = 1$.

Fig. 5 shows the impact of the maximum transmission delay δ on throughput S when $p_1 = p_2 = 0.5$. As δ increases, the system throughput decreases. While given a fixed δ, the system throughput keeps approximately stable as the number of nodes increases. The system throughput is normalized with respect to the channel rate.

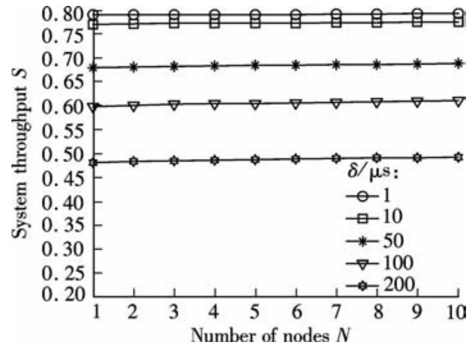

Fig. 5 Impact of maximum transmission delay δ on throughput S

Fig. 6 describes the impact of the number of nodes on the throughput with different priority levels when $\delta = 10$ μs. It shows that nodes with a higher priority level can occupy relatively much more bandwidth resource. But with the increase in the number of nodes with the lower priority

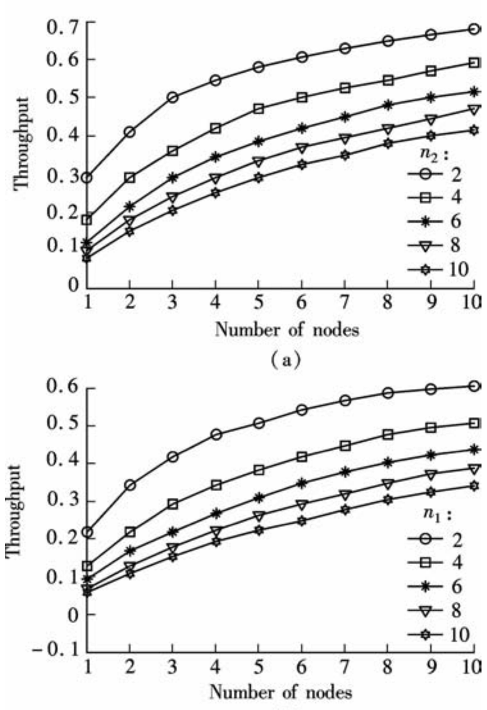

Fig. 6 Impacts of the number of nodes on throughput with different priority levels. (a) The number of nodes with priority level 2 on throughput of nodes with priority level 1; (b) The number of nodes with priority level 1 on throughput of nodes with priority level 2

level, the throughput of nodes with the higher priority level decreases.

Fig. 7 illustrates the impact of different p_1 and p_2 on the system throughput, and is compared with the result in the DCF model. We find that the proposed QoS-based MAC protocol achieves a higher system throughput than the DCF model. And when p_1 is bigger than p_2, we can expect a higher throughput, because with the increase in p_1, the average contention window will decrease, thus improving the system throughput.

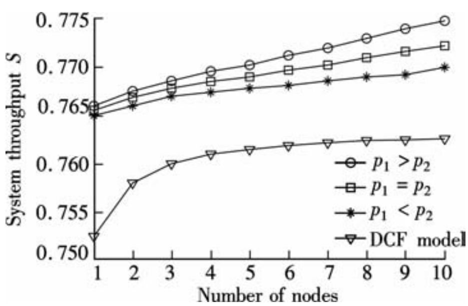

Fig. 7 Impact of different p_1 and p_2 on the system throughput and DCF model

From Figs. 5, 6 and 7, we can conclude that, with the increase in the number of nodes, the proposed QoS-based MAC protocol can guarantee the stable throughput of each priority level group and the total system, thus improving the network performance compared with DCF.

4 Conclusion

In this paper, we propose a QoS-based MAC protocol, which is revised from IEEE 802. 11 DCF to adapt to the cognitive radio environment. And we utilize a two-dimensional discrete-time Markov chain to evaluate the system performance. Simulation results verify the improvement of throughput with the proposed protocol. More researches on the joint optimization of MAC and routing protocol are needed to be done in the future.

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基于 QoS 的认知无线电网络 MAC 协议

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摘要:为提高认知环境中次用户的吞吐量性能,提出了一种基于 QoS 的 MAC 协议. 认知节点将信道状态映射为向量,收端与发端通过“与”操作得到最终的信道映射,并获得备选信道集合. 上层应用程序传来的数据根据 QoS 要求被划分为 2 个优先级,每种级别的数据对应不同的竞争窗口,从而保证了实时数据具有较高的优先级. 使用二维离散时间马尔科夫链分析了系统的性能并推导出系统吞吐量的数学表达式. 仿真结果证实,与 IEEE 802. 11 DCF 相比,所提协议有助于提高系统吞吐量.

关键词:服务质量;认知无线电;媒体接入控制;信道映射;马尔科夫链

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