Spectrum-aware QoS MAC for Multimedia Services in Cognitive Radio Networks

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1. Introduction

Cognitive radio (CR) has been emerging as a promising solution for addressing the spectrum scarcity problem by allowing unlicensed secondary users (SUs) to explore the spectrum access opportunities for data transmissions when licensed primary users (PUs) are vacant from the medium. As the PUs access the reserved spectrum bands from time to time, the spectrum opportunities available for SUs are highly dynamic. In addition, SUs may carry multiple types of traffic which have different quality of service (QoS) requirements. Therefore, it is crucial to design an efficient spectrum-aware medium access control (MAC) protocol with QoS provisioning to allow SUs to effectively probe the available spectrum bands and share them with other SUs.

2. Distributed QoS-aware Cognitive (QC) MAC

The design of spectrum-aware CR MAC differs from that of the classic MAC protocols in the close coupling with the physical layer and the cognitive hardware support [1], e.g., spectrum access opportunity is detected by physical layer radio frequency (RF) unit and MAC layer spectrum sensing and spectrum access. As spectrum sensing is crucial in CR MAC, most of the previous works mainly focus on the design of spectrum sensing policies with/without cooperation among multiple SUs to improve the sensing accuracy while maintaining a low level coordination overhead[2][3][4].

Some recent works study QoS provisioning in CR networks in support of real time multimedia applications. Wang *et a*l. [5] analyze the capacity of a voice only CR network in terms of the maximum number of voice connections that can be supported with QoS guarantee, and Feng *et al.* [6] study studies the performance of telemedicine service with real time constant bit rate traffic pattern mixed with urgent messages in an infrastructure-based CR network. In a CR network, the traffic patterns in different spectrum bands may vary depending on the activities of PUs. For example, the OFF periods in TV bands are relatively long when programs terminate, while they could be very short in cellular bands where a large number of cellular customers carry voice traffic with a very low rate. Moreover, different SUs may have various applications with different traffic characteristics and QoS demands. To efficiently probe the spectrum access opportunity for QoS provision of SUs, it is essential to consider the characteristics of both the traffic and the channel usage pattern in the MAC design.

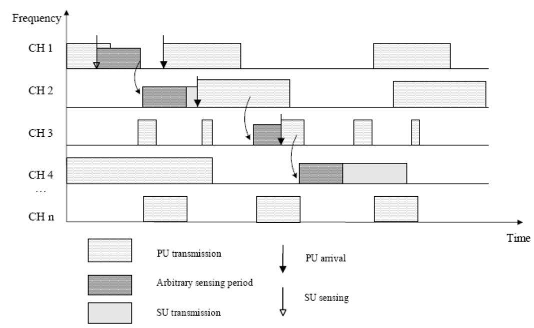

Fig. 1 Multi-channel Transmissions

We propose a distributed cognitive MAC protocol for multimedia services over CR networks. By exploiting diverse channel usage patterns, SUs select appropriate channels that satisfy their QoS requirements for channel sensing and data transmissions. The transmission procedure of an SU is shown in Fig. 1. Without loss of generality, an SU senses the first channel and starts data transmission if the channel is sensed idle for a sensing interval. To reduce possible collisions among SUs, each SU will sense the channel for an arbitrary sensing period (ASP), which consists of the basic sensing period that assures satisfactory sensing accuracy plus some random slots selected from a sensing window [0, SW_i]. If the channel is sensed busy, the SU switches to the second channel. At the beginning of the channel sensing period, the sender will initiate a handshake with its receiver over the control channel for transceiver synchronization. It is also possible that a PU may appear during SU's data transmission, in which case the transmission fails and the SU will switch to the next channel to retransmit the data. The procedure repeats until the SU exploit the spectrum access opportunity and successfully transmit the data. The key research issue in the CR MAC design is how to effectively probe the spectrum opportunities and select an appropriate set of channels to assure the QoS satisfactory of SUs, without causing undue interference to PUs.

Channel Sensing: To fully utilize the spectrum opportunity, SUs calculate the probability that the current frame can be successfully transmitted over a channel. Based on the calculated successful transmission probability in each channel, SUs can determine the channel sensing sequence with two different policies: greedy and ascending. For the greedy policy, SUs simply sort channels in a descending order and always use channels with the highest success probability for achieving a low delay and high throughput. However, the channel with less PUs' activity is more likely to be selected by SUs, which causes high contention level among SUs sharing the same radio resources and degrades the performance accordingly. Therefore, we propose the second sensing policy that allows different SUs to select various channels based on the QoS requirements of their applications. Specifically, each real-time frame is associated with the maximum tolerable one hop delay t_i. To satisfy the delay requirement, an SU should select a set of channels such that the expected transmission time over the channel is smaller than t_i. Notice that although SU can estimate the channel usage pattern by PUs, it is difficult, if not impossible, for an SU to accurately estimate the number of SUs currently sharing the spectrum bands. For a simple yet robust MAC design, an SU should set a stringent delay bound and select a channel set with more opportunities to absorb the impacts of other SUs.

Table I Sensing Window Design for Multimedia Services

	Strict Priority	Statistical Priority	No Priority
Voice	[0,31]	[0,31]	[0,31]
Video	[32,63]	[0,63]	[0,31]
Data	[64,127]	[0,127]	[0,31]

Service Differentiation: We further enhance the QoS provisioning of the proposed cognitive MAC by introducing service differentiation in the arbitrary sensing periods of different traffic flows. Basically, a smaller sensing window is applied for a higher priority real time applications so that they have a higher chance to access data channels when opportunity appears, i.e., $SW_{voice} < SW_{video} < SW_{data}$. In addition, by carefully determining the sensing windows for different types of traffic, multiple levels of QoS provisioning can be achieved for multimedia applications in CR networks. As shown in Table I, a statistical priority is provided by simply doubling the sensing windows for various types of traffic, while a strict priority can be achieved when non-overlapped sensing windows are used.

The performance of the service differentiation scheme is shown in Fig. 2. There are 10 voice (iLBC codec [7]) and 10 video (Star Trek – First Contact" trace [8]) flows in the network, and one saturated background data flow in each channel. The delay of voice traffic does not change much with the traffic loads in the network; the delay of video traffic slightly increases; while the data throughput decreases when more video SUs join in the network. By applying different sensing windows for voice, video, and data, multimedia traffic have a higher priority to be transmitted when opportunity appears. When a strict priority setting is applied, data packets have a lower probability to access the channel, and thus multimedia applications achieve a better delay at the cost of a lower throughput for data flows.

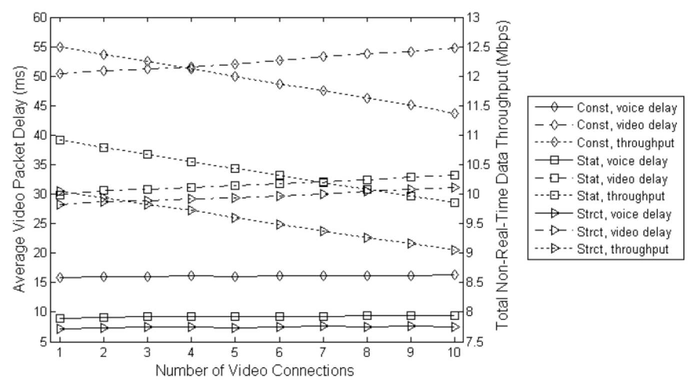

Fig. 2 Performance Comparison with Different Sensing Windows

3. Performance Analysis

We develop an analytical model to study the delay performance of the proposed CR MAC for multimedia services. An SU senses a channel and attempts to transmit if the channel is sensed idle for an ASP. During the channel sensing, an SU may fail if 1) the channel is occupied by a PU at the beginning of sensing, or 2) a PU turns on in an idle channel during the ASP, or 3) the tagged SU loses the contention due to other SUs' transmissions in channel access. SU transmits data when its sensing succeeds, or it switches to the next channel when the sensing fails. Without loss of generality, an SU checks the set of selected channels in a sequence, {CH_1, CH_2,..., CH_N, CH_1, ... }, until the packet is successfully transmitted. In [9], we have established the probability that an SU transmission succeeds in the selected channel at the r-th attempts as

$$Ps(r) = P_{TS}^{r} \prod_{j=1}^{r-1} (1 - P_{TS}^{j}) \quad (1)$$

where P_{TS}^{r} corresponds to the probability of a successful transmission over the channel in the r-th attempt. Thus, given the average time an SU uses for one transmission attempt $E[T^r]$, we can obtain the average transmission delay of an SU as

$$E[T] = \sum_{r=1}^{\infty} E[T^r] P_{TS}^{r} \prod_{j=1}^{r-1} (1 - P_{TS}^{j}) \quad (2)$$

The delay performance of the proposed cognitive MAC is shown in Fig. 3. All SUs use the same sensing window [0, 31] without service differentiation. As it is very complicated to track the number of SUs in each data channel due to highly dynamic spectrum access in CR networks, we use the average number of SUs to estimate the contention level in each channel. It can be seen that the analytical results approximate the simulation ones well. It can be seen that the average delay of voice/video traffic increases with the number of SUs. The delay of voice packets are low because small voice packets are more likely to be transmitted opportunistically when PUs are inactive. For video traffic with much larger payloads, the probability of transmission failure becomes high as a PU is more likely to turn on and interfere with the SU during a longer transmission time of a video packet. When a transmission fails, an SU will switch to the next channel for sensing and retransmission, which results in a longer delay. It is also shown that in comparison with fractional (FRC) scheme which senses the channel in the descending order of the average channel available time, the proposed QC MAC achieves much lower delay because SUs always select a proper set of channels that assure high probability of successful frame transmissions, while only the average channel utilization is considered in FRC.

4. Conclusions

In this paper, we have proposed a distributed QoS-aware MAC with service differentiation for cognitive radio networks in support of heterogeneous multimedia applications. We have demonstrated that the proposed MAC provides satisfactory QoS support for multimedia services.

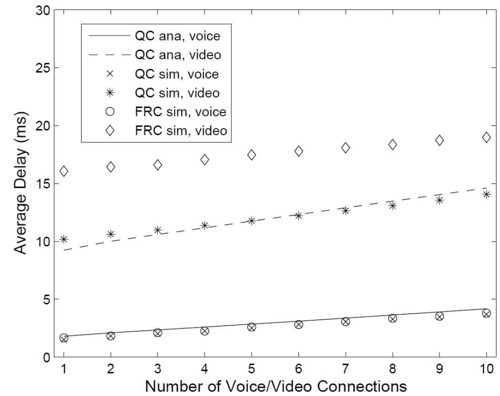

Fig. 3 Average Delay of Voice/Video Flows

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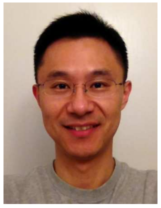

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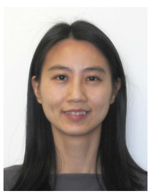

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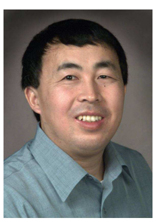

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