Modified 802.11-Based Opportunistic Spectrum Access in Cognitive Radio Networks

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In this letter, a modified 802.11-based opportunistic spectrum access is proposed for single-channel cognitive radio networks where primary users operate on a slot-by-slot basis. In our opportunistic spectrum access, control frames are used to reduce the slot-boundary impact and achieve channel reservation to improve throughput of secondary users. An absorbing Markov chain model is used to analyze the throughput of secondary users. Simulation results show that the analysis accurately predicts the saturation throughput.

Keywords: Cognitive radio networks, 802.11, opportunistic spectrum access, control frames, slot-by-slot, throughput.

I. Introduction

Cognitive radio [1] has recently emerged to improve the current spectrum usage. In cognitive radio networks, the primary users (PUs) do not always utilize their spectrum. Therefore, the secondary users (SUs) can temporally occupy the unused spectrum. Some works were proposed for opportunistic spectrum access in cognitive radio networks [2]-[4]. Chong and others [2] proposed a slot-based MAC protocol for multichannel cognitive radio networks. Hoang and others [3] presented a slot-based opportunistic spectrum access for single-channel networks. For slot-based spectrum access schemes, when the remaining time of a slot is not enough for a data packet transmission, SUs cannot transmit data packets to avoid extending the slot boundary. Thus, the remaining time is wasted, which is called slot-boundary impact. To reduce the slot-boundary impact, Bae and others [4] proposed a scheme in which SUs transmit variable length packets depending on the remaining time of a slot. However, the operation details of packet fragmentation and aggregation were not mentioned.

To amend the slot-boundary problem, this letter presents a modified 802.11-based opportunistic spectrum access. In an available slot unused by PUs, control frames are used to reserve the channel when the remaining time is not enough for SUs to finish a data packet transmission. If a channel reservation succeeds, the SU that has reserved the channel transmits a data packet at the beginning of the next available slot: this transmission occurs before that of other SUs. As a result, this data transmission will succeed without collision, and the throughput of SUs is improved. Accounting for control frames, the throughput of our opportunistic spectrum access is estimated with an absorbing Markov chain model.

II. 802.11-Based Opportunistic Spectrum Access

In our system, whenever a PU has an opportunity to transmit, it utilizes the channel during a whole slot. At the beginning of each slot, each SU performs spectrum sensing to find out whether the channel is used by PUs or not. We assume that the spectrum sensing is perfect and sensing period is negligible. If the channel is sensed idle at the beginning of the slot, each SU attempts to access the channel according to our opportunistic spectrum access. Each slot has fixed slot length T_f and all SUs transmit fixed size data packets. We divide a slot into M equal mini-slots and use a mini-slot as a backoff slot unit.

In an available slot unoccupied by PUs, each SU decreases its backoff counter following 802.11 DCF [5]. When the remaining time of an available slot is enough to finish a data packet transmission, each SU will transmit a data packet after its backoff counter reaches zero. After each successful or

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collision transmission, the operational principle of SUs is the same as for 802.11 DCF. When the remaining time of an available slot is not enough to finish a data packet transmission, control frames including request-to-send (RTS) and clear-to-send (CTS), which are shorter than data packets, are introduced to reduce the slot-boundary impact and reserve the channel. Then, we focus on the exchange process of control frames.

When the remaining time of an available slot is not enough to finish a data packet transmission, each SU still decreases its backoff counter while the channel is idle. This is different from the scheme in [3], where all SUs freeze their backoff counters even if the channel is idle. Once an SU's backoff counter reaches zero, the SU transmits an RTS frame to its destination. If the RTS is transmitted successfully, a CTS frame will be answered. When the SU sending the RTS frame receives the CTS frame successfully, the exchange of control frames succeeds. Then, the SU reserves the channel successfully and waits for the beginning of the next available slot unoccupied by PUs to transmit a data packet. All other SUs, overhearing the exchange of control frames, freeze their backoff counters until the SU that has reserved the channel finishes a data transmission at the next available slot. If the exchange of control frames fails, the SU proceeds to retransmit the RTS until one exchange of control frames succeeds or the remaining time to the end of the current slot is not enough to finish an exchange of control frames.

While no exchange of control frames succeeds and the remaining time of the slot is not enough to finish an exchange of control frames, the backoff counters of all SUs are frozen from that point until the end of the slot. In the next available slot, the backoff process of each SU is resumed with the backoff counter frozen in the previous slot.

Let T_p be the time to transmit the packet payload, T_s be the duration of a successful data transmission, T_c be the duration of a data collision, T_{cs} be the duration of a successful transmission for control frames, and T_{cc} be the duration of a collision for control frames. According to IEEE 802.11 DCF, T_s= PHY header + MAC header + T_p+ SIFS + ACK + DIFS, T_c=PHY header + MAC header + T_p + EIFS, T_{cs}=RTS + SIFS + CTS + DIFS, and T_{cc}=RTS + EIFS. T_p, T_s, T_c, T_{cs}, and T_{cc} are all in the unit of mini-slot. As shown in Fig. 1, in an available slot (slot i), if the backoff counter of an SU named A reaches zero first, it transmits a data packet. Then, A chooses a new backoff counter for the next data transmission. We assume the new backoff counter of A equals 6, and meanwhile, the backoff counter of another SU named B equals 4. After 4 mini-slots become empty, B's backoff counter reaches zero. At that point, the remaining time is not enough to finish a data packet transmission. Thus, B exchanges control frames with its destination. After the successful exchange of control frames, all SUs freeze their backoff counters. At the beginning of the next available slot (slot i+1), B transmits a data packet. After the data transmission of B is finished, all SUs resume their backoff counters frozen in slot i. After 2 mini-slots become empty, A's backoff counter reaches zero. At that point, the remaining time is enough to finish a data packet transmission, so A transmits a data packet. After this transmission, the remaining time is not enough to finish an exchange of control frame. Therefore, all SUs freeze their backoff counters until the next available slot.

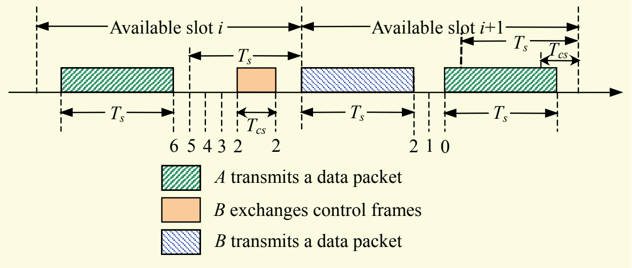

Fig. 1. 802.11-based opportunistic spectrum access.

III. Saturation Throughput Analysis

We assume there are N SUs in cognitive radio networks. Let W be the minimum backoff window, m be the maximum backoff stage, τ be the probability that an SU transmits in a mini-slot, and p be the collision probability for each transmission. Using the same method as in [6], we express τ and p as

$$\begin{cases} \tau = \dfrac{2(1-2p)(1-p)}{(1-2p)(W+1)+pW(1-(2p)^m)}, \\ p = 1-(1-\tau)^{N-1}, \end{cases} \qquad (1)$$

where τ and p are uniquely determined by equation (1). Then, $P_1=(1-\tau)^N$ denotes the probability that there is no transmission, $P_2=N\tau\,(1-\tau)^{N-1}$ denotes the probability that there is a successful transmission, and $P_3=1-P_1-P_2$ denotes the probability that there is a collision in a random mini-slot.

The saturation throughput of SUs is defined as the proportion of time used for successful data transmissions in an available slot. To evaluate the throughput, we use an absorbing Markov chain to describe mini-slot transitions in the system-level within an available slot. Because of control frames introduced, each mini-slot no longer corresponds to only one state. In some cases, one mini-slot corresponds to two states.

In our model, an available slot is divided into M mini-slots numbered from 1 to M. When the system is in mini-slot j ($1\le j\le M-T_s$), all SUs attempt to transmit data packets. When the system is in mini-slot j ($M-T_s<j\le M-T_s+T_{cs}$), all SUs attempt to transmit control frames. Therefore, a mini-slot numbered in the range $[1, M-T_s+T_{cs}]$ corresponds to one state which is denoted by the same number as the mini-slot, namely, mini-slot j

corresponds to state j. When the system is in mini-slot j ($M-T_s+T_{cs}<j\le M-T_{cs}$), one mini-slot no longer corresponds to only one state. If an exchange of control frames has succeeded, all SUs freeze their backoff counters until the end of this available slot. Otherwise, all SUs continue to attempt to transmit control frames. Therefore, to make all transitions in the state space have Markovian property, a mini-slot numbered in the range ($M-T_s+T_{cs}$, $M-T_{cs}$) corresponds to two mutually exclusive states. We use state j and j' to denote the corresponding state for mini-slot j, where state j indicates that a control frame exchange has not been finished when the system reaches mini-slot j, and state j' indicates that a control frame exchange has been finished successfully before the system reaches mini-slot j. When the system is in mini-slot j ($M-T_{cs}<j\le M$), the remaining time is not enough to finish an exchange of control frames. No matter whether an exchange of control frames succeeds or not, all SUs freeze their backoff counters. Therefore, one mini-slot corresponds to one state, namely, mini-slot j corresponds to state j. According to the description above, the state space of the corresponding Markov chain has $M+T_s-2T_{cs}$ states.

Then, we use $\mathbf{Q}=\begin{bmatrix}\mathbf{R} & \mathbf{R_0}\\ \mathbf{0} & 1\end{bmatrix}$ to denote one-step transition probability matrix, where $\mathbf{R}$ is a square matrix of order $M+T_s-2T_{cs}-1$ and $\mathbf{R_0}=\mathbf{1}-\mathbf{R}$ is a column vector of order $M+T_s-2T_{cs}-1$. According to the definition of the state space, the elements of matrix $\mathbf{Q}$ are obtained as follows:

i) When the system is currently in the mini-slot j ($1\le j\le M-T_s$), after one-step transition, the system will reach state $j+1$ with the probability P_1, or state $j+T_s$ with the probability P_2, or state $j+T_c$ with the probability P_3. Thus, for $1\le j\le M-T_s$, $\mathbf{Q}_{j,j+1}=P_1$, $\mathbf{Q}_{j,j+Ts}=P_2$, and $\mathbf{Q}_{j,j+Tc}=P_3$.

ii) When the system is currently in the mini-slot j ($M-T_s<j\le M-T_s+T_{cs}$), the system will reach state $j+1$ with the probability P_1, or state $(j+T_{cs})'$ with the probability P_2, or state $j+T_{cc}$ with the probability P_3. Therefore, for $M-T_s<j\le M-T_s+T_{cs}$, $\mathbf{Q}_{j,j+1}=P_1$, $\mathbf{Q}_{j,(j+Tcs)'}=P_2$, and $\mathbf{Q}_{j,j+Tcc}=P_3$.

iii) When the system is currently in the mini-slot j ($M-T_s+T_{cs}<j\le M-T_{cs}$), one mini-slot corresponds to two states. While the current state is j, if $j+T_{cs}\le M-T_{cs}$, the system will move to state $j+1$ with the probability P_1, or state $(j+T_{cs})'$ with the probability P_2, or state $j+T_{cc}$ with the probability P_3; if $j+T_{cs}>M-T_{cs}$, the system will move to state $j+1$ with the probability P_1, or state $j+T_{cs}$ with the probability P_2, or state $j+T_{cc}$ with the probability P_3. While the current state is j', if $j<M-T_{cs}$, the system will move to state $(j+1)'$ with the probability 1; if $j=M-T_{cs}$, the system will move to state $j+1$with the probability 1. Thus, for $M-T_s+T_{cs}<j\le M-T_{cs}$, $\mathbf{Q}_{j,j+1}=P_1$, $\mathbf{Q}_{j,(j+Tcs)'}=P_2$ ($j+T_{cs}\le M-T_{cs}$), $\mathbf{Q}_{j,j+Tcs}=P_2$ ($j+T_{cs}>M-T_{cs}$), $\mathbf{Q}_{j,j+Tcc}=P_3$, $\mathbf{Q}_{j',(j+1)'}=1$ ($j<M-T_{cs}$), and $\mathbf{Q}_{j',j+1}=1$ ($j=M-T_{cs}$).

iv) When the system is currently in the mini-slot j ($M-T_{cs}<j\le M$), the system will reach state $j+1$ with the probability 1. Consequently, for $M-T_{cs}<j\le M$, $\mathbf{Q}_{j,j+1}=1$.

For a random slot, if there is a successful transmission of control frames in the previous slot, the slot starts at mini-slot $1+T_s$ because of channel reservation, with initial distribution $\eta_1=[\underbrace{0,\cdots,0}_{T_s},1,0,\cdots,0]$. Otherwise, the slot starts at mini-slot 1, with initial distribution $\eta_2=[1,0,\cdots,0]$. Let K_1 and K_2 denote the number of steps required until the system reaches the absorbing state M starting from mini-slot $1+T_s$ and mini-slot 1, respectively. We can derive

$$\begin{cases}P(K_1=n)=\eta_1\mathbf{R}^{n-1}\mathbf{R_0},\ 1\le n\le M-T_s-1,\\ P(K_2=n)=\eta_2\mathbf{R}^{n-1}\mathbf{R_0},\ 1\le n\le M-1.\end{cases}\tag{2}$$

Then, we introduce the matrix $\mathbf{Q}(x,y)$ associated to matrix $\mathbf{Q}$ with dummy variables x and y. The $\mathbf{Q}(x, y)$ is defined as follows:

For $1\le j\le M-T_s$, $\mathbf{Q}(x, y)_{j,j+1}=P_1$, $\mathbf{Q}(x, y)_{j,j+Ts}=xP_2$, and $\mathbf{Q}(x, y)_{j,j+Tc}=P_3$.

For $M-T_s<j\le M-T_s+T_{cs}$, $\mathbf{Q}_{j,j+1}=P_1$, $\mathbf{Q}_{j,(j+Tcs)'}=yP_2$, and $\mathbf{Q}_{j,j+Tcc}=P_3$.

For $M-T_s+T_{cs}<j\le M-T_{cs}$, $\mathbf{Q}_{j,j+1}=P_1$, $\mathbf{Q}_{j,(j+Tcs)'}=yP_2$ ($j+T_{cs}\le M-T_{cs}$), $\mathbf{Q}_{j,j+Tcs}=yP_2$ ($j+T_{cs}>M-T_{cs}$), $\mathbf{Q}_{j,j+Tcc}=P_3$, $\mathbf{Q}_{j',(j+1)'}=1$ ($j<M-T_{cs}$), and $\mathbf{Q}_{j',j+1}=1$ ($j=M-T_{cs}$).

For $M-T_{cs}<j\le M$, $\mathbf{Q}(x, y)_{j,j+1}=1$.

Let $\mathbf{R}(x, y)$ and $\mathbf{R_0}(x, y)$ denote the matrices associated to matrices $\mathbf{R}$ and $\mathbf{R_0}$, respectively. Then, we define

$$\begin{cases}r_n(x,y)=\eta_1(\mathbf{R}(x,y))^{n-1}\mathbf{R_0}(x,y),\ 1\le n\le M-T_s-1,\\ v_n(x,y)=\eta_2(\mathbf{R}(x,y))^{n-1}\mathbf{R_0}(x,y),\ 1\le n\le M-1,\end{cases}\tag{3}$$

$r_n(x,y)$ and $v_n(x,y)$ can be expressed by

$$\begin{cases}r_n(x,y)=\sum\limits_{n_1+n_2\le n} f(n_1,n_2)x^{n_1}y^{n_2},\ 1\le n\le M-T_s-1,\\ v_n(x,y)=\sum\limits_{n_1+n_2\le n} g(n_1,n_2)x^{n_1}y^{n_2},\ 1\le n\le M-1,\end{cases}\tag{4}$$

where the coefficient $f(n_1, n_2)$ and $g(n_1, n_2)$ indicate the probability that the system reaches state M with n_1 successful data transmissions and n_2 successful control frame transmissions after n-step transitions from mini-slot $1+T_s$ and mini-slot 1, respectively. Therefore, $\sum_{n=1}^{M-T_s-1} r_n(x,1)$ and $\sum_{n=1}^{M-T_s-1} r_n(1,y)$ are the probability generating functions for the number of successful data transmissions and successful control frame transmissions, respectively, for a slot which starts at mini-slot $1+T_s$. $\sum_{n=1}^{M-1} v_n(x,1)$ and $\sum_{n=1}^{M-1} v_n(1,y)$ are the probability generating functions for the number of successful data transmissions and successful control frame transmissions for a slot which starts at mini-slot 1, respectively.

When a slot starts at mini-slot $1+T_s$, let U_1 be the number of successful data transmissions and U_2 be the number of successful control frame transmissions in the whole slot. Because of channel reservation, U_1 contains an additional successful data transmission at the beginning of the slot. Then,

$$\begin{cases} U_1 = 1+\dfrac{\partial}{\partial x}\displaystyle\sum_{1\le n\le M-T_s-1} r_n(x,1)\,|_{x=1}, \\ U_2 = \dfrac{\partial}{\partial y}\displaystyle\sum_{1\le n\le M-T_s-1} r_n(1,y)\,|_{y=1}. \end{cases} \tag{5}$$

Let U_3 be the number of successful data transmissions and U_4 be the number of successful control frame transmissions in a slot that starts at mini-slot 1. Then,

$$\begin{cases} U_3 = \dfrac{\partial}{\partial x}\displaystyle\sum_{1\le n\le M-1} v_n(x,1)\,|_{x=1}, \\ U_4 = \dfrac{\partial}{\partial y}\displaystyle\sum_{1\le n\le M-1} v_n(1,y)\,|_{y=1}. \end{cases} \tag{6}$$

Let q denote the probability that a slot starts at mini-slot $1+T_s$. Then, the probability that the slot starts at mini-slot 1 is $1-q$. According to our scheme, the number of successful control frame transmissions is not more than 1. So, the probability q that a slot starts at mini-slot $1+T_s$ equals the number of successful control frame transmissions in the previous slot:

$$q = qU_2 + (1-q)U_4. \tag{7}$$

Then, U_1, U_2, U_3, U_4, and q can be calculated. The saturation throughput for SUs can be obtained by the proportion of time used for successful data transmissions in an available slot unused by PUs. Thus, the saturation throughput S is derived as

$$S = \frac{[qU_1 + (1-q)U_3]T_p}{T_f}. \tag{8}$$

IV. Experiment Results

The system parameters are set as follows: channel bit rate=2 Mbps, slot size T_f=5 ms, M=100, basic mini-slot=50 µs, DIFS=50 µs, PHY header=128 bits, MAC header=272 bits, packet payload=2,000 bits, ACK=112 bits+PHY header, RTS=160 bits+PHY header, and CTS=112 bits+PHY header. The maximum backoff stage is set to 5.

Figure 2 shows the throughput of our scheme and the basic scheme in [3]. We do simulations based on two conditions in an available slot, ideal and practical. Under the ideal condition, all SUs sense the channel perfectly and try to access the idle channel by contention. Under the practical condition, 90% of SUs that sense the channel perfectly can access the channel by contention, and the other 10% of SUs that mistake the idle channel as active cannot access the channel. The analytical results of our scheme are very close to those obtained from simulations under two conditions. Also, our scheme achieves higher throughput than the basic scheme because control fames are introduced to reduce slot-boundary impact and achieve channel reservation, which leads to successful transmission.

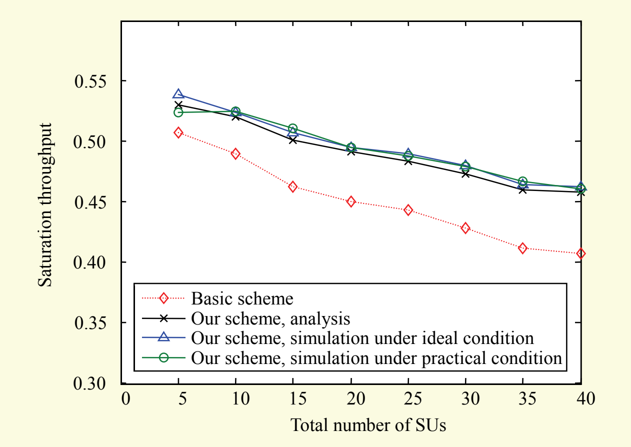

Fig. 2. Saturation throughput versus total number of SUs.

V. Conclusion

In this letter, control frames were introduced for SUs to reduce the slot-boundary impact and achieve channel reservation. Therefore, the throughput of SUs is improved. An analytical model is used to evaluate the throughput of SUs. Experiment results show that our scheme achieves better throughput than the existing one.

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