Multi-channel Opportunistic Spectrum Access with Channel Switching Cost Awareness

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Abstract

Opportunistic spectrum access is an efficient solution to improve spectrum efficiency. In multi-channel opportunistic spectrum access, secondary users switch channels to escape from primary user occupied channels. This channel switching cost is significant. It depends on difference between current channel and the target switching channel. We build a model to reflect this switching cost based upon the existing protocols. We design a protocol and perform simulations to evaluate our proposal.

1. Introduction

Opportunistic Spectrum Access (OSA) is a viable solution for overcrowded (e.g. ISM band) and underused (e.g. TV White Space) radio channels [1][2]. In OSA, there are two user tiers, primary users (PUs) and secondary users (SUs) [3]. PUs have exclusive rights to their assigned channels and can transmit at any time [3]. On the other hand, SUs are opportunistic users who can access the unused portion of the channel temporally and/or spatially.

2. Modeling the Primary User Activity

We assumed that there is a control channel (c_0) which is not interfered by any PU, i.e. we reserved a channel solely for control message exchanges by SUs for our protocol. Furthermore, we assumed that there are M data channels, $\mathbf{C} = \{c_1, c_2, \dots, c_M\}$ which can be accessed opportunistically by the set of SUs, $\mathbf{U} = \{u_1, u_2, \dots, u_N\}$. We can model the PU activity on each of these channel as an alternating renewal process. Let $\mathbf{B} = \{\beta_1, \beta_2, \dots, \beta_M\}$ be the occupancy (busy probability) profile of each channel by PUs, where

$$\beta_m = \frac{\mathrm{E}[T_X]}{\mathrm{E}[T_Y]} = \frac{\int_0^\infty t.f_X(t)\,dt}{\int_0^\infty t.f_Y(t)\,dt}, \quad \beta_m \in [0,1] \tag{1}$$

Assuming that the time intervals are independent and identically distributed (i.i.d.), $f_X(t)$ and $f_Y(t)$ are p.d.f's of time intervals for data transmission and inter-arrival of data packets as depicted in Fig.(1).

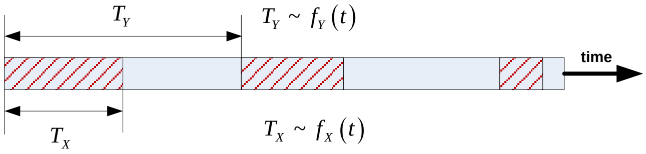

Fig.(1) ON-OFF channel model for each data channel.

Let N_c be the number of IDLE data channels. From the channel occupancy profile, we can calculate the probability that at least one channel is free as follows:

$$P_F = \Pr[N_C > 0] = 1 - \prod_{m=1}^{M} \beta_m, \quad \beta_m \in [0,1]. \tag{2}$$

3. Frame Structures

We will now design the frame structures for our proposal, based on the existing CSMA/CA protocol. In order to operate in the multi-channel OSA environment, we modify the some of the control messages and defined a new message, Confirmed-to-Transmit (CTT), as shown in Fig.(2). Since there are multiple data channels, several concurrent SU transmissions are possible. However, the concurrent transmissions must not interfere with each other, i.e. only one SU pair must be on an available data channel as depicted in Fig.(3). A single pair of secondary sender and receiver must be able to choose and agree on a specific data channel for their communication. This can be achieved by 3-way handshaking (RTS-CTS-CTT) on the control channel. The handshaking procedure is as follows:

As depicted in Fig.(3), firstly, u_1 sends RTS to u_2, which includes the list of available channels for u_1. If u_2 is idle when it receives RTS, it will choose one available channel, c_1 in this case, and reply with CTS. This CTS will set NAVs for neighboring SUs of u_2 on channel, c_1. Similarly, when receiving the CTS, u_1 will reply with CTT to set NAVs for its neighboring SUs on channel c_1. If this 3-way handshaking is successful, both u_1 and u_2 will move to c_1 to transmit DATA and ACK. In this way, it is ensured that no other SU pairs are on channel c_1. As can be observed from Fig.(3), neighboring SUs can transmits simultaneously on other available channels which is not used by any PU.

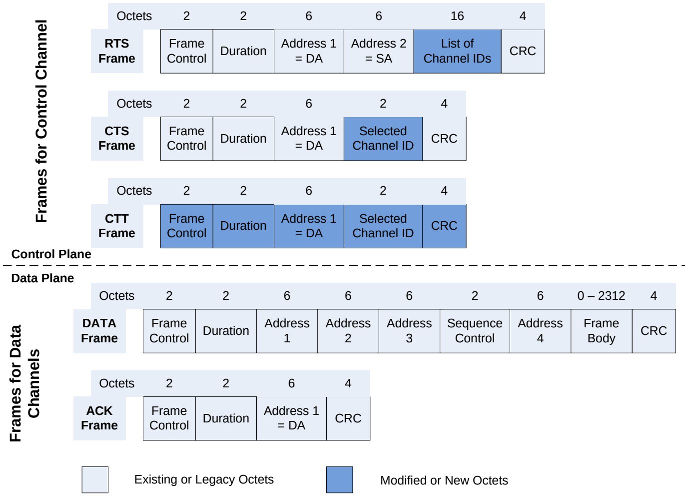

Fig.(2) Control and data frame structures for proposed protocol.

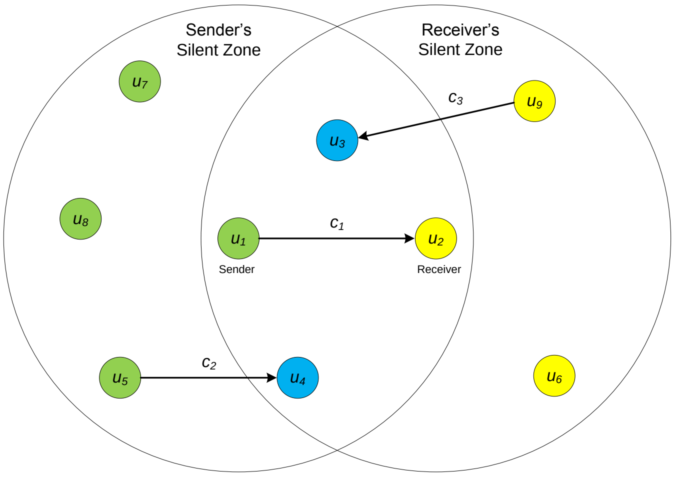

Fig.(3) While u_1 is transmitting to u_2 on channel c_1, all neighboring SUs in the silent zones cannot transmit on c_1.

4. Analysis

The number of concurrent SU transmissions that can be achieve depends on the number of available data channels and the number of successful handshakes on the control channel during a DATA frame transmission. Following CSMA/CA analysis in [4], we obtain the time intervals for a handshake success and a handshake collision;

$$\begin{aligned} T_S^0 &= DIFS + RTS + \delta + SIFS + CTS + \delta + SIFS + CTT + \delta, \\ T_C^0 &= DIFS + RTS + \delta. \end{aligned} \tag{3}$$

Using the Markov chain model given in [4] for the control channel, we have the probability τ that a SU transmits RTS frame randomly on the control channel at a chosen slot time as:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)}, \tag{4}$$

and the probability p that transmitted RTS frame encounters a collision is given by:

$$p = 1-(1-\tau)^{N-1} \tag{5}$$

The probabilities P_{Tx}^0 and P_S^0 refer to the transmit probability of a SU and success probability of a SU handshake and are given as:

$$P_{Tx}^0 = 1-\left(1-\tau\right)^N, \quad P_S^0 = \frac{N\tau\left(1-\tau\right)^{N-1}}{1-\left(1-\tau\right)^N}. \tag{6}$$

The average time interval that a SU needs to complete a successful handshake on the control channel is given [4] as:

$$T_{Avg}^0 = T_S^0 + \sigma\left(\frac{1-P_{Tx}^0}{P_{Tx}^0 P_S^0}\right) + T_C^0\left(\frac{1}{P_S^0}-1\right), \tag{7}$$

Let T_{CS} be time necessary for transmitting and receiving SU pair to switch to the selected channel m. Then, the transmission time for a DATA frame on any data channel can be given as:

$$T_{Data}^m = T_{CS}^m + H + E[Pkt] + \delta + SIFS + ACK + \delta, \tag{8}$$

The maximum number of possible concurrent transmissions is given as:

$$N_{Tx} = \left\lfloor T_{Data}^m / T_{Avg}^0 \right\rfloor \tag{9}$$

where $\lfloor\cdot\rfloor$ is the floor operator. Moreover, assuming there is no PU activity on the data channels, we have the probability that a free data channel is available at the time of handshaking as:

$$\begin{cases} P_A = 1, & N_{Tx} \le M, \\ P_A < 1, & N_{Tx} > M, \end{cases} \tag{10}$$

For a successful secondary packet transmission, the following conditions must be satisfied at the time of the contention process:

1) At least one of the data channels must be free of

PU activity corresponding to P_F.

2) The control channel must be free of another SU contention corresponding to P_S^0.
3) No other SU must be present on at least one of the free data channels corresponding to P_A.

Therefore, the effective probability of a successful SU transmission can be obtained as:

$$\eta = P_F \cdot P_S^0 \cdot P_A. \qquad (11)$$

The system throughput of the proposed protocol can be calculated as:

$$S = \frac{\eta \cdot E[Pkt]}{T_{Avg}^0 + T_{Data}^m}. \qquad (12)$$

We will now discuss the effects of channel switching cost on the performance. From (7), (8) and (9), we can see that the number of concurrent transmissions depends on the time intervals. The channel switching cost increases linearly with respect to the difference between current frequency (channel) and the target switching frequency increasing the time interval for data transmission on the data channel. This in turn increases number of concurrent transmission, N_{Tx}. As discussed in (10), if $N_{Tx} > M$, there will be no available data channel for SU transmission and have a data channel bottleneck. On the other hand, if $N_{Tx} < M$, there are available data channels but SUs are congested on the control channel causing a control channel bottleneck.

5. Numerical Results

We perform numerical analysis to confirm our proposal. Fig.(4) depicts aggregate throughput versus number of SUs. The solid lines displays aggregate throughput and the dotted line displays achievable number of concurrent transmissions. As the number of SUs increases, the average time for handshaking increases and therefore the achievable number of concurrent transmission decreases. Fig (5) displays the aggregate throughput versus average packet payload. As the packet payload increases, the data transmission time increases and additional handshakes can be made during this time increment.

6. Conclusions

We propose a multi-channel MAC protocol for OSA with channel switching cost awareness. We derived a closed-form expression for the aggregate throughput. We discover that our protocol exists either in control channel bottleneck and data channel bottleneck. We simulate our proposal and presented our results.

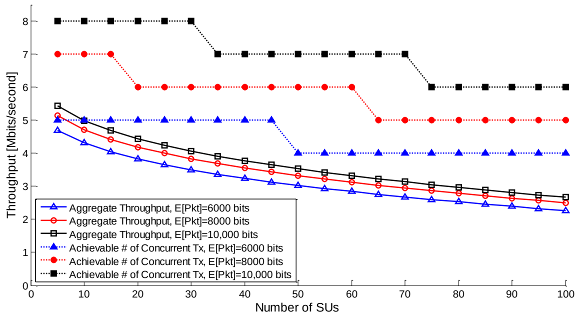

Fig.(4) Aggregate throughput versus number of SUs.

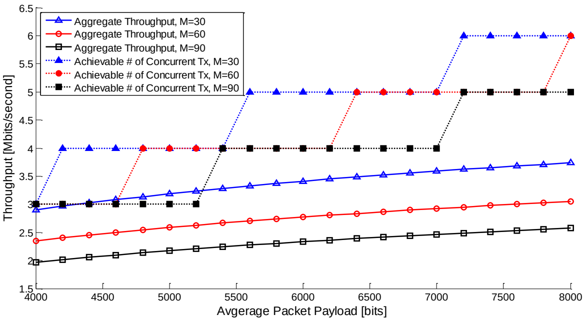

Fig.(5) Aggregate throughput versus average packet payload.

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