Analysis of Medium Access Protocols with Channel Bonding for Cognitive Radio on TV bands

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Abstract - *Underutilized television (TV) channels, while potentially being fragmented, still offer a significant amount of idle bandwidth and great communication areas. Using cognitive radio (CR) technology with orthogonal frequency division multiplexing (OFDM) would enable multiple contiguous or non-contiguous TV channels to be bonded to offer a scalable channel bandwidth. In this paper, the performance of a Cognitive Radio Network operating in TV bands using the slotted ALOHA and the non-persistent CSMA protocol is studied for the fixed-carrier -number (FCN) and fixed-carrier-spacing (FCS) OFDM schemes. An analytical model is also presented for throughput estimation. Our results show that np-CSMA achieves superior than the slotted Aloha protocol with channel bonding on TV bands and that the capture effect is very effective.*

Key Words: **access protocols, cognitive radio, OFDM, TV bands, wireless networks.**

1. INTRODUCTION

TV spectrum has the potential to provide much-needed bandwidth over long transmission ranges. Sharing of underutilized parts of the TV spectrum with network services would provide an opportunity for more effective use of the spectrum [1]. The devices that would be permitted to operate in the idle parts of the TV spectrum would use cognitive radio (CR) technology. The fragmented nature of available bandwidth also necessitates use of channel bonding on TV bands that are not necessarily contiguous to increase the channel width. Also, a new trend in wireless technology is exploration of the use of scalable channel widths. The 2007 version of the IEEE 802.11 wireless standard specifies 5, 10 and 20 MHz channel widths for use in the 4.9 GHz band [2]. Recent research revealed that aggregating contiguous and noncontiguous channels may result in improved throughput [3-4]. On the other hand, OFDM techniques can be exploited to assist both the physical (PHY)-layer and Multiple Access Control (MAC)-layer mitigation.

In most existing wireless technologies utilizing OFDM physical layer, the sub carrier bandwidth is kept constant by fixing subcarrier (FCS) for various channel widths. In this approach the number of subcarriers is allowed to change with channel width while the subcarrier width is fixed.

A second approach that can be often used in OFDM based networks is Fixed Subcarrier Number (FCN) where the subcarrier spacing is allowed to change while number of subcarriers is fixed. When subcarrier spacing is fixed, changes in bandwidth will not require a new design for PHY and MAC layer but preamble and pilot subcarrier allocation may need to be reconfigured.

It is important to investigate and understand these two OFDM paradigms for at least two reasons. First, these studies enhance our fundamental understanding of spectrum agile systems. Second, the proposed schemes may be important for home networking applications, where multiple wireless networks often coexist.

In this paper, the performance of a Cognitive Radio Network operating in TV bands using the slotted ALOHA and the non-persistent CSMA protocol [5] is studied. Slotted Aloha and CSMA are simple, mature, well-known and effective random access protocols. They have been suggested for use in CR networks and TV white spaces in several recent studies [6-8]. The main contribution of this paper is to adapt OFDM physical layer with multiple channel widths to specify the basis for operation of cognitive radio in the contiguous and noncontiguous TV bands. Also, the paper aims to investigate the performance of FCN and FCS type OFDM on scalable channel width in TV bands with different MAC protocols.

The paper is organized as follows: In section II, the signal analysis of the MAC layers is introduced. Section III presents the system model development and simulation details. Finally, in section IV, our conclusions are given.

2. SIGNAL ANALYSIS

To use the TV spectrum for efficient Wi-Fi networking, multiple contiguous and non-contiguous available channels on the TV spectrum can be bonded to have higher data rates while avoiding having occupied channels spread among the TV channels. More than two contiguous TV channels may join together to get a wider one by using bonding approaches. Note that at 6 MHz, TV channels are narrower than Wi-Fi channels.

Non-contiguous TV channels can be merged using the non-contiguous OFDM (NC-OFDM) technique, which can deactivate subcarriers across its transmission bandwidth.

These deactivated subcarriers allow us to avoid potential interference with transmissions by other users and nulls. Sensing measurements determine the parts of the spectrum occupied by the TV broadcasters. OFDM subcarriers corresponding to the occupied spectrum are then deactivated [9]. Each 6 MHz TV channel provides a 5 MHz bandwidth with a centre frequency of a corresponding TV channel. The channel bonding process proposes to use Wi-Fi hardware with an 802.11 physical layer. When compatibility is not an issue, the bonded channel can be used in a highly efficient manner.

IEEE 802.11a is an OFDM system and is defined as a PHY layer that divides a signal across 52 different subcarriers to support transmission of data rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. Four of the 52 subcarriers are used as pilot subcarriers for reference to track phase shifts during transmission. The subcarriers are placed 312.5 kHz apart. Each symbol is extended with an 800 ns guard time. The total symbol duration is thus 4.0 µs [2]. The 52 subcarriers are modulated using binary or quadrature phase shift keying (BPSK/QPSK), or 16 or 64 quadrature amplitude modulation (QAM). Convolution coding is also used with coding rates of 1/2, 2/3, or 3/4. In this paper, an IEEE 802.11 PHY layer frame structure was used. Fig. 1 shows the frame structure of 802.11a OFDM [2].

In our analysis, to adapt a cognitive network approach, the number of subcarriers was kept constant, whereas the subcarrier spacing and the symbol time were chosen to be variable when the FCN approach is used. To comply with the IEEE 802.11 standard, the sub-channel spacing was 78.13 kHz, 156.25 kHz and 312.5 kHz for operation over the 5 MHz, 10 MHz and 20 MHz channels in the TV spectrum, respectively. This led to changes in symbol duration, as 12 µs, 6.4 µs and 3.2 µs, respectively. Similar to 802.11a, 48 of the 64 subcarriers were assumed as data subcarriers, 4 subcarriers were as pilots and 12 subcarriers were not used. The other PHY and MAC layer parameters that were affected by the bandwidth changes are given in Table 1.

In the FCS-based approach, and without being dependent on the bandwidth, the subcarrier spacing was fixed. This sets the symbol time to be constant, whereas the number of subcarriers was allowed to change. In the FCS case, symbol duration of 16 µs with a guard interval of 3.2 µs was chosen using 78.13 kHz constant subcarrier spacing.

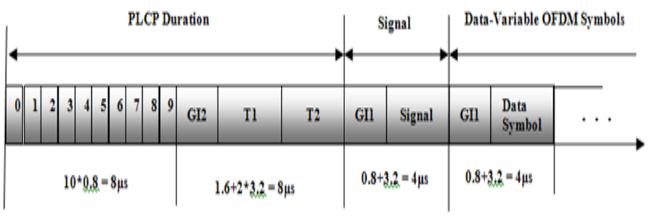

Fig -1: IEEE 802.11a OFDM frame structure

Table -1. Parameters used for FCN and FCS models

PARAMETERS	FCS			FCN		
Bandwidth - B (MHz)	5	10	20	5	10	20
FFT Size - N_{FFT}	64	128	256	64	64	64
No. of Data Subcarrier - N_{SD}	48	110	232	48	48	48
No. of Pilot Subcarrier - N_{SP}	4	6	10	4	4	4
Total No. of Subcarrier - $N_{ST} = N_{SD} + N_{SP}$	52	116	242	52	52	52
Subcarrier Spacing (KHz) - $\Delta F = B / N_{FFT}$	78.13	78.13	78.13	78.13	156.25	312.5
FFT Duration (µs) - $T_{FFT} = 1/\Delta F$	12.8	12.8	12.8	12.8	6.4	3.2
PLCP Duration(µs) - $T_{preamble}$	64	64	64	64	32	16
Symbol Duration (µs) - $T_{Signal} = T_{FFT} + T_{GI}$	16	16	16	16	8	4
Guard Interval(µs) - $T_{GI} = T_{FFT}/4$	3.2	3.2	3.2	3.2	1.6	0.8
Training Symbol GI - T_{GI2}	6.4	6.4	6.4	1.6	3.2	6.4

The number of subcarriers was specified as 64, 128 and 256 points respectively. Besides, altering data subcarriers (N_{SD}) number would change the value of the modulation-dependent parameter such as N_{CBPS}.

The single packet transmission time will be affected when the channel width is varied. The single packet transmission (T_{packet}) time must be predictable. The total transaction time contains the T_{BO} (backoff time), and the distributed interframe space (DIFS), short interframe space (SIFS), data and acknowledgement durations, as given below:

$$T_{packet} = T_{BO} + T_{DIFS} + T_{DATA} + T_{SIFS} + T_{ACK}$$

If the maximum packet transmission delay (propagation delay constant) due to protocol overheads is denoted by "α", then α can be found by dividing the single packet transmission time by packet transmission time T_{DATA}:

$$\frac{T_{packet}}{T_{DATA}} = 1 + \alpha$$

In our work, α is assumed to be a constant and very small when compared to the packet transmission time. The transmission time of an L-bytes-long data packet T_{DATA} can be expressed as in [2]:

$$T_{DATA} = T_{preamble} + T_{signal} + T_{symbol} * \left\lceil \left(\frac{16+8+L+6}{R * N_{CBPS}} \right) \right\rceil$$

In FCN case, total transmission time can be expressed as:

$$T_{DATA/FCN} = 20 + 4 * \left\lceil \left(\frac{16+8+L+6}{R * N_{CBPS}} \right) \right\rceil$$

In the FCS case, the total transmission time can be expressed as:

$$T_{DATA/FCS} = 20 + 80 + 16 * \left\lceil \left(\frac{16+8+L+6}{R * N_{CBPS}} \right) \right\rceil$$

here L is chosen as 1460 bytes for the data packets, and the MAC header is specified as 34 bytes. The function ceiling ⌈·⌉ is a function that returns the smallest integer value greater than or equal to its argument value. The parameters T_{signal}, T_{symbol}, and T_{preamble}, are the signal field, symbol and preamble duration required for receiver synchronization. Equations show how FCS differs from FCN in this study. T_{symbol} is 16.0 µs long in FCS. Also, a 20 µs signal field on $T_{\text{DATA/FCS}}$ is added to guarantee backward compatibility with $T_{\text{DATA/FCN}}$ [10].

The throughput for the slotted Aloha protocol is given in [11] as:

$$S = Ge^{-\alpha}$$

The throughput S for the np-CSMA protocol can be written as:

$$S = \frac{Ge^{-\alpha G}}{\left(G*(1+\alpha)+e^{-\alpha G}\right)}$$

where G is the total traffic which include generated and retransmitted packets and α is the normalized transmission delay.

3. SYSTEM MODEL AND PERFORMANCE ANALYSIS

In the system model, two multiple access networks are considered to be allocating a cell coverage area, as shown in Fig. 2. The first is a secondary network that accesses TV channels opportunistically using the np-CSMA or slotted Aloha protocols. This secondary network is also able to sense idle TV channels. The second network is a contention-free broadcast network based on TDMA. Each network has a number of terminals. These terminals receive transmitted signals via a TV tower or a base station (BS). All terminals are located far away from BS or tower. In that hybrid structure, all nodes in the secondary system have also geo-location capability combined with a database system to reach an idle TV channel list or receive a control signal (beacon) or sense the channel, not only via np-CSMA or Aloha transmissions but also via TDMA transmissions. In contrast, the TDMA circuit has already reserved channels for TV broadcast services.

To simulate the FCN/FCS OFDM throughput, an event-based MATLAB simulator [11] was used to validate our analytical model. The throughput performances for both cases were taken as references and the IEEE 802.11 Distributed Coordination Function (DCF) was selected for channel management. Shadowing and propagation losses are taken as constant. The Poisson distribution was accepted at the receiver and enough number of packets was produced randomly. The capture effect occurs if a sent packet sometimes survives. The capture effect strongly affects the secondary system throughput. In our study, the capture effect is also accounted.

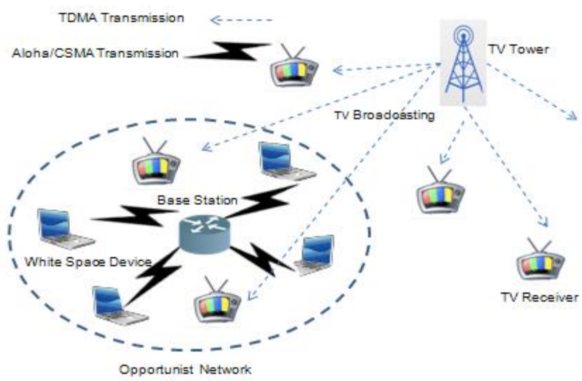

Fig -2: Network structure for simulation of TV bands

When the channel is sensed as being busy, the node schedules the packet transmission behind a backoff time, which is accepted as the random arrival time. Retransmission and arrival times are assumed to be independent of each other and are exponentially distributed.

In our network structure for simulation, The service area in meters, Position of nodes (x,y,z) in meters and The capture ration in dB are taken as 100, 0,05 and 10 respectively. Also, for the channel related parameters, Normalized propagation delay, fixed number of loss and standard deviation of shadowing in dB are chosen as 0,01 ,3 and 6 respectively. Finally, the number of nodes in the network is 100 and carrier to noise ratio is accepted as 30 dB. In our simulations, a 16 QAM modulation scheme with a 1/2 code rate and a payload length of 1460 is assumed.

3.1 Throughput Analysis of Slotted Aloha

In the following discussion, we consider the effects of the FCN and FCS schemes on slotted Aloha and np-CSMA throughput for the various channel widths. The traffic value is the result of prosperous trials to catch the BS. The traffic is given by the ratio of total packet transmission duration to total simulation time and is plotted on a linear scale. The throughput performance values on the vertical axis are determined as the ratio of the total packet duration where packets are successfully received by a receiver to the total simulation time.

Figs. 3, 4 and 5 depict throughput variation as a function of the traffic for the FCN and FCS OFDM schemes for both simulated and analytical results for slotted Aloha with various channel widths. The slotted Aloha peak throughput is computed analytically as 0.36 when G=1. The simulation results under ideal channel conditions agree with the analytical computations, as shown in Figs. 3–5. Fig. 3 shows that the throughput increases with the traffic at the beginning of the simulation in both cases, and the peak throughput is achieved when the traffic is nearly 1. The traffic value denotes the successful attempts to seize the BS. For the 5 MHz channel, FCN and FCS carry out in the same way because their PHY layer parameters are same. Peak throughput values for slotted Aloha for channels affected by shadowing and capture effects are given in Table 2.

Table -2: Peak throughput for slotted ALOHA

OFDM Scheme	Bandwidth	Peak Throughput
FCN	5 MHz	0,5067
	10 MHz	0,4898
	20 MHz	0,4603
FCS	5 MHz	0,4734
	10 MHz	0,5057
	20 MHz	0,4845

A reverse relationship was observed between the fluctuations in the MAC throughput and the frame duration in Figs. 3 through 5 as the frame duration decreased. Higher fluctuations were observed in the MAC throughput. For the 10 MHz channel width in Fig. 5, the FCS throughput is slightly higher than the FCS case because the fragmentation of packet is not accepted in this study. The possibility that a long packet is not able to send is more likely to occur if the frame duration is not long that makes greater the resulting throughput [10]. However, in the 20 MHz channel, FCS slightly outperforms FCN, as shown in Fig. 5.

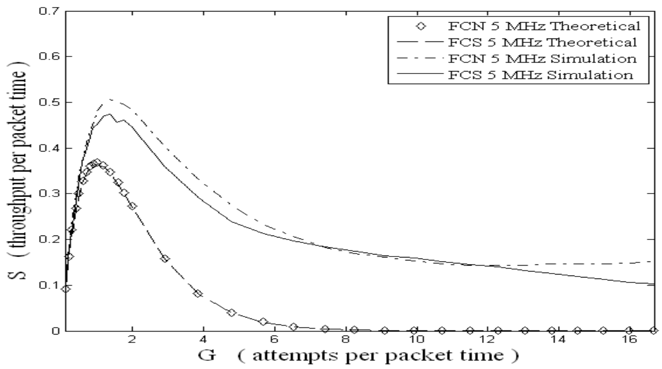

Fig -3: Throughput vs traffic for slotted Aloha on a 5 MHz TV channel

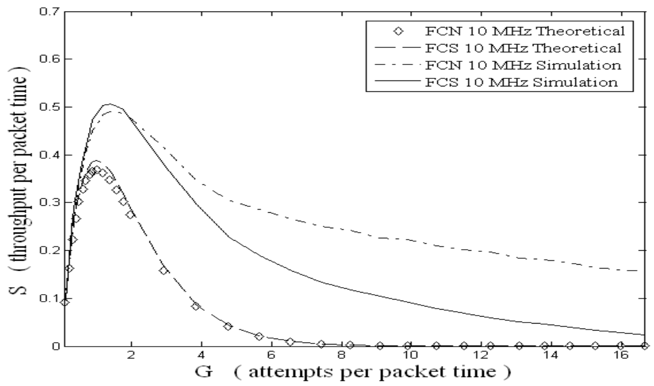

Fig -4: Throughput vs traffic for slotted Aloha on two contiguous 10 MHz TV channel

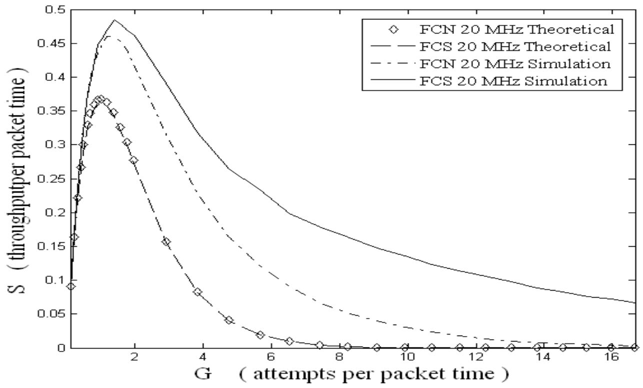

Fig -5: Throughput vs traffic for slotted Aloha on four contiguous 20 MHz TV channel

3.2 Throughput Analysis of np-CSMA

The np-CSMA throughput depends on the value of the normalized propagation delay. The normalized propagation delay α was chosen to be 0.1 for np-CSMA. The simulation results for ideal channels and for channels affected by shadowing and capture effects are shown in Figs. 6 through 8.

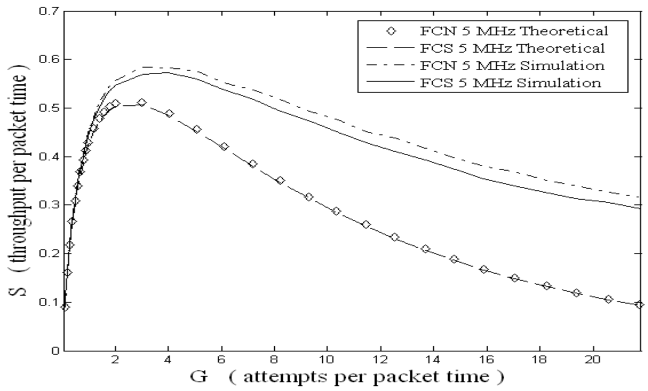

Fig.-6: Throughput vs traffic for np-CSMA on a 5 MHz TV channel

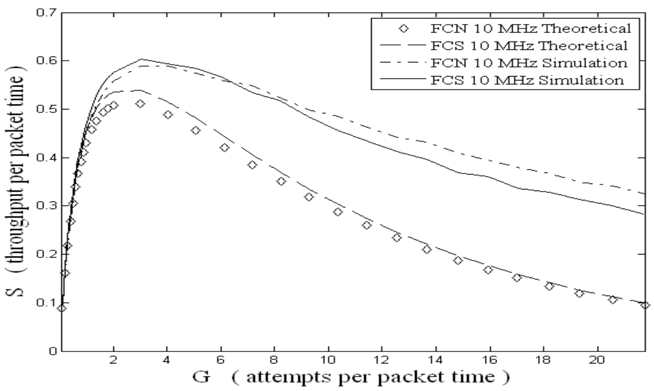

Fig. -7: Throughput vs traffic for np-CSMA on two contiguous 10 MHz TV channel

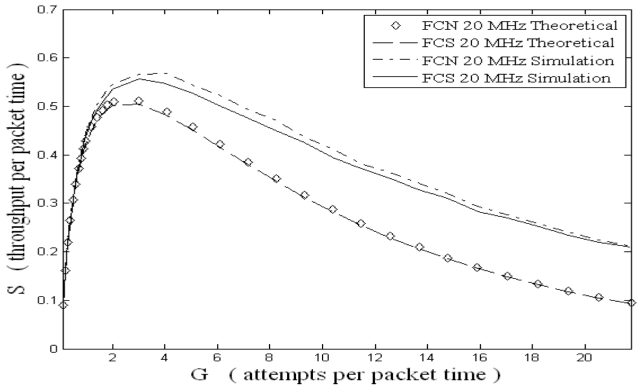

Fig. -8: Throughput vs traffic for np-CSMA on four contiguous 20MHz TV channel

The FCN and FCS OFDM schemes under ideal channel conditions were matched with the analytical results that were discussed in the previous section. However, the capture effect is very active in the channel. When shadowing and capture effects exist on the channel, the peak throughput is shifted by around three traffic values. Peak throughput values for np-CSMA are given in Table 3.

Table -3: Peak throughput for np-CSMA

OFDM Scheme	Bandwidth	Peak Throughput
FCN	5 MHz	0,5847
	10 MHz	0,5884
	20 MHz	0,5674
FCS	5 MHz	0,5731
	10 MHz	0,6039
	20 MHz	0,5563

It is observed that for channel bandwidths of 5 and 20 MHz (Figs. 6 and 8), the FCN throughput is slightly higher than that of FCS. The reason is again the fragmentation capability that is missing from our simulation. In contrast, FCS outperforms FCN for the 10 MHz channel by a slight margin, as shown in Fig. 7.

Our study was valid under the assumption that all nodes are in line-of-sight (LOS) and within range of each other. The analytical throughput for the model was designed in a perfect channel case with an indefinite call source assumption without any hidden node or exposed terminal, which causes another source of fluctuation between the analytical and simulated throughput results.

4. CONCLUSIONS

The analysis and simulation framework presented in this paper can be used to test the performance of FCN/FCS OFDM schemes for various channel bandwidths in contiguous and non-contiguous TV bands. The throughputs of slotted aloha and np-CSMA are quite different, but the capture effect is very effective for the FCN and FCS OFDM schemes. Also, np-CSMA performs better than the slotted Aloha protocol with channel bonding on TV bands.

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