Experimental Evaluation of Opportunistic Access in Shared Contention-based Channels

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***Abstract*—In this paper, we experimentally evaluate the gains of applying the concept of opportunistic channel access to the traditional contention-based access widely used in unlicensed channels. We consider the scenario in which multiple IEEE 802.11 networks coexist in a given channel and pose the following question: should all networks fairly compete for channel access or should they be prioritized in terms of channel access rights, and use opportunistic access to regulate their transmission? We implement a simple modification to the IEEE 802.11 medium access module of the wireless interface driver to allow opportunistic access of the shared channel. Then, we configure a secondary IEEE 802.11 network to opportunistically access the channel only when a primary network is not using it. Our empirical results show that such opportunistic channel access achieves high channel utilization (up to 188 % utilization gain) while respecting the prioritized access rights of the primary network with primary network outages below 7 %. In contrast, legacy contention-based access achieves higher channel utilization. However, it does not provide prioritized access and causes half the primary network packets to be denied transmission, which is not suitable for the targeted application scenarios.**

***Index Terms*—Opportunistic Spectrum Access, Experimental Evaluation, IEEE 802.11, Ath9k.**

I. Introduction

In this paper, our goal is to experimentally evaluate the performance of different channel coexistence techniques. More specifically, we are interested in the case in which two wireless networks are sharing a given channel. This scenario is encountered in different cases wherein different IEEE 802.11 networks coexist on the same channel as in the recently growing wireless home networking applications. In 2014, the number of devices with IEEE 802.11 interfaces was estimated to be over one million devices, not including PC computers and mobile devices [1]. Another example is the Internet of Things (IoT) scenarios in which WiFi networks share the channels with wireless sensor networks. In both examples, the traffic of some applications is of higher importance compared to others. Legacy medium access control (MAC) protocols will allow the different networks to fairly compete for channel access. Instead, we aim at evaluating the gain of having the lower priority network (i.e., the secondary network) opportunistically accessing the shared channel only when the high priority network (i.e., the primary network) is not using it. This requires incorporating prioritized channel access and opportunistic channel access to the IEEE 802.11 MAC implementation.

The concept of opportunistic access arose when Mitola first defined the Software Defined Radio (SDR) and Cognitive Radio (CR) concepts [2]. In the CR/SDR context, secondary networks continually sense different frequency bands before determining the one(s) that are not currently used by a primary network. The secondary network opportunistically uses a channel until the primary network is active again. Consequently, the secondary network searches for a new channel to use [3]. There exist several ongoing efforts that incorporate opportunistic channel access into IEEE 802.11 devices [4], [5], [6], [7], [8], [9], [10]. Those studies mainly focus on sensing the spectrum holes (also referred to as white spaces) and the channel selection mechanism. Examples include [7] where OSA is implemented using the IEEE 802.11 standard and OSA is based on observing the PHY errors and received signal strength indicator (RSSI). Alternatively, [8] has OSA implemented through a modified MAC protocol with dynamic spectrum allocation capability.

In contrast, we aim at studying the gain of using opportunistic spectrum access considering a single channel where primary and secondary networks coexist on an IEEE 802.11 channel. We are not interested in evaluating the multiplexing gain of having different channels to choose from. Channel switching is a complex process which requires hardware/software with complex specification this will add significant protocol overhead, packet loss and delay in the transmission process. Our experimental results show a significant improvement in the channel utilization (up to 188 %) with insignificant harm to the primary network with outages below 7 % depending on how aggressive the secondary network is configured. In contrast, legacy IEEE 802.11 contention-based MAC results in higher channel utilization at the expense of 50 % outages of the primary network.

The remainder of the paper is organized as follows. In Section II, we motivate our work. Section III explains our experimentation methodology. We present our main findings in Section IV and conclude the paper in Section V.

II. Motivation

Our objective is to experimentally evaluate the gains of using an opportunistic channel access approach instead of the traditional competition-based CSMA/CA if two networks are to share the same channel. Opportunistic access is applicable to the scenarios in which one of the two networks has a higher priority (will be referred to as the primary network) in terms of channel access as compared to the other network (will be referred to as the secondary network). Having multiple networks sharing the same channel is frequently encountered especially in the unlicensed Industrial Scientific and Medical (ISM) band as it is available for use without the need to purchase a license. For example, two IEEE 802.11 home networking applications configured on the same channel: one is used for streaming and the other is used for room ambiance control. Another example is a wireless sensor network sharing the channel with an IEEE 802.11 network. We aim at studying the pros and cons of the following coexistence scenarios.

1) Contention-based Coexistence: Both networks will compete on seizing the channel using the legacy CSMA/CA listen-before-talk MAC. Since contention-based access does not differentiate between the two networks, the two networks will have the same channel access right. However, if one of the two networks is of more importance or if one network is not using the channel frequently, contention-based access is not the best way to allow both networks to coexist. Under fully backlogged traffic conditions (i.e., there are always packets to transmit), the two networks will share the medium equally between them and the spectrum is expected to be fully utilized. However, the primary network performance will be negatively impacted due to the transmissions of the secondary network.

2) Opportunistic Access Coexistence: Unlike contention-based coexistence, opportunistic access adheres to the fact that the secondary network has a lower priority compared to the primary network. Hence, the secondary network should not compete with the primary network for channel access. Instead, the secondary network should only access the channel whenever the primary network is not using it. This way employing opportunistic spectrum access does not only improve the channel utilization (compared to having the primary network accessing the channel while having the other network using a different channel), but also the primary network performance is barely affected even though another network is sharing its channel.

Fig. 1 depicts the difference between the contention-based channel access [11] typically used in wireless systems operating over the unlicensed ISM channels and opportunistic access. The main difference is that while both the primary and secondary networks fairly share the channel in contention-based access (Fig. 1 (a)), the secondary network accesses the channel only when the primary network is not transmitting as shown in Fig. 1 (b).

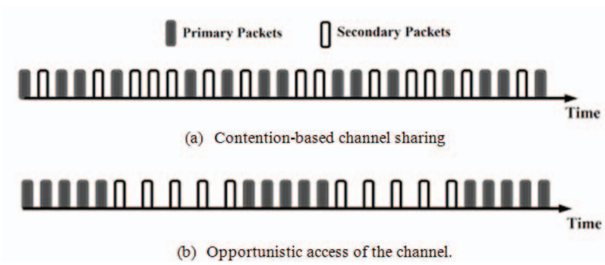

Fig. 1. OSA concept of using unused portion of the band.

III. Experimental Methodology

Here, we explain the methodology used for our experimental study.

A. Primary Network Implementation

For our experiments, we established one primary network that consists of a single sender and a single receiver. This single flow resembles the activities of N in ranges flows since the transmissions of N in range CSMA/CA transmitters is equivalent to the transmission of a single CSMA/CA transmitter with the traffic equal to the total of the N transmitters. Two laptops equipped with IEEE 802.11n wireless cards that are based on Atheros AR9285 chipset [12] were used to create the primary network. The primary network will use the IEEE 802.11 CSMA/CA MAC unchanged. We use *iperf* [13] to generate UDP traffic from the client side (the primary sender). At the other end of the data transfer (the primary receiver) we have an *iperf* server reporting the traffic throughput and packet loss statistics. We control the activity pattern of the primary network by having *iperf* generating the UDP packets in an ON/OFF periodic fashion. In the ON part of the period, the primary sender transmits back-to-back packets. In the OFF part of the period, the primary sender does not transmit any packets at all. We define the activity factor of the primary network as the ratio of the ON time to the entire period duration.

B. Secondary Network Implementation

Likewise, we established one secondary network that consists of a single sender and a single receiver. The secondary network operates over the same channel as the primary network. Another *iperf* UDP flow was generated in the secondary network. However, the secondary UDP flow is fully backlogged (i.e., the secondary transmitter always has packets to transmit if it can access the channel). This allows us to determine the maximum throughput the secondary network can get as well as the worst-case harm to the primary network due to the secondary network. Another two laptops equipped also with the Atheros AR9285 IEEE 802.11n PCI/PCI wireless were used to implement the secondary network.

Unlike the primary network, we need to change the channel access mechanism of the secondary network to have lower priority compared to the primary network. Our main idea to implement prioritized access is to change the sensing mechanism of the secondary network by increasing its sensing time.

1) OSA Implementation Using Ath9k Driver: The best way to achieve this purpose is by increasing the secondary network's Arbitration Inter-Frame Spacing (AIFS) value. AIFS is the time a node waits before it transmits its next frame. The AIFS time is defined as

$$AIFS = SIFS + AIFSnumber * Slottime \tag{1}$$

where SIFS is the Short Inter-Frame Spacing time needed for a node to switch from the transmit mode to the receive mode, or vice versa, and the AIFS number depends on the Access Category (AC). Nodes that have higher AIFS have lower probability of transmitting. Increasing the sensing time will force the secondary network to have lower priority than primary network and it will also decrease its maximum throughput. We increase the AIFS time by only increasing the AIFS number in (1). Increasing the SIFS number would have added latency to the control packets which will severely affect the throughput. Likewise, increasing the slot time will add huge delay in the contention resolution in the backoff mechanism since the contention window is a function of the slot time.

We implement opportunistic channel access by modifying the MAC parameters of the IEEE 802.11 protocol using the ath9k open-source driver for all Atheros IEEE 802.11n WLAN based chipsets such as the used AR9285 chipset. In order to avoid re-building the whole kernel every time we make a modification to the ath9k driver, we use the compat-wireless package [14]. Compat-wireless is a package which contains versions of the in-kernel wireless drivers. It is considered as a sized-down version of the kernel tree which contains only the source codes of the wireless drivers. In the file "Linux/net/mac80211/util.c", we change the default queuing parameter (i.e., AIFS number) to be 2, 3 or 7 depending on the packet priority through multiplying those numbers by a factor of 1, 5, 10, and 20.

C. Performance Metrics

For our performance evaluation, we use three metrics: throughput, primary network outage, and the percentage improvement in channel utilization.

- A flow throughput is defined as the total size of successfully delivered data over the used channel.
- The primary network outage is defined as the percentage of the primary packets that were not carried out due to the use of the channel by secondary transmissions during the ON time of the primary network relative to the total number of packets transmitted by both the primary network and the secondary network in the ON time of the primary network.

$$\textbf{Primary Outage} = \frac{\#\,\textbf{SN pkts (PN ON)}}{\#\,\textbf{PN pkts} + \#\,\textbf{SN pkts (PN ON)}}\%$$

- The percentage utilization improvement is defined as the ratio of the gained channel utilization when both the primary and secondary networks coexist on the channel and the channel utilization when only the primary network uses the channel, that is:

$$\textbf{Improvement} = \frac{\textbf{Utilization(PN+SN)} - \textbf{Utilization(PN)}}{\textbf{Utilization(PN)}}\%$$

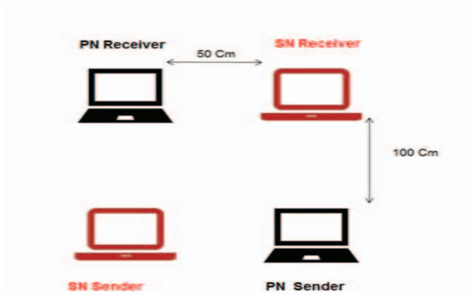

Fig. 2. Illustration of the experimental setup.

TABLE I: Experiment Parameters Summary.

Parameter	Value
SIFS Time	16 μs
Slot Time	9 μs
DIFS Time	34 μs
PHY Rate	54 Mbps
Min Contention Window	15
Max Contention Window	1023
Packet Length	1470 bytes
Transport Protocol	UDP
Simulation Time	120 s

IV. Performance Evaluation

In this section, we experimentally evaluate the performance of opportunistic access compared to contention-based channel access.

A. Experimental Setup

The primary and secondary networks (two laptops representing the primary network and the other two laptops representing the secondary network) are configured with the distances shown in Figure 2. Table I summarizes the experiment parameters. We used a spectrum analyzer to determine the least crowded and most appropriate channel to be used by the primary network. Consequently, we configured both the primary and the secondary networks to operate on channel 10 (with frequency equal to 2457 MHz) of the 2.4 GHz ISM band which is the least interfered channel at the location where the experiments were performed. We run the experiments after midnight and before dawn to minimize the potential uncontrolled transmission activities over the used channel. The following results are the average of several runs (at least five times), each of 120 seconds length.

We measured the backlogged throughput of the primary network in the absence of any secondary network activity and found it to be 21.5 Mbps which is the maximum achievable throughput of the channel. For all our experiments discussed next, we vary the primary network activity from 0% (the primary network is not using the channel at all) to 100% (the primary network is fully using the channel) in 25% steps. The experiments were repeated for the secondary AIFS number is multiplied by a factor of 5, 10 and 20 of the primary network AIFS.

B. Experimental Results

1) Channel Utilization: We start our experimental evaluation of the relative performance of opportunistic access as compared to contention-based access by studying the effect of both coexistence mechanisms on the channel utilization. More specifically, our goal is to assess how much OSA improves the channel utilization without degrading the performance of the higher priority primary network. Fig 3. depicts the size of data sent in Mbytes by the primary network only in the absence of secondary network with the size of total data sent by both networks (i.e. when the two networks share the band).

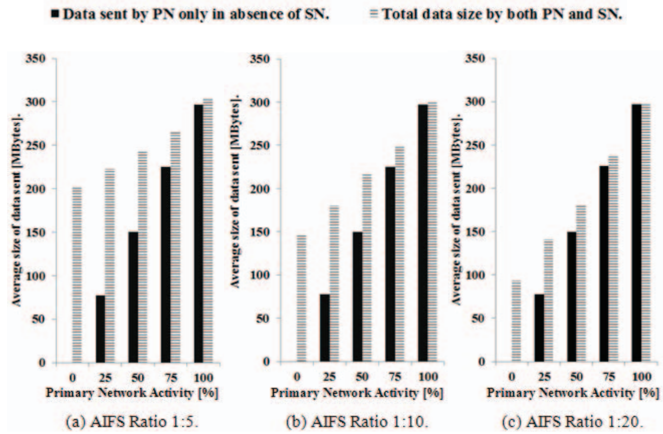

Fig. 3. The total transmitted data size when only the primary network uses the channel, and when both networks opportunistically coexist.

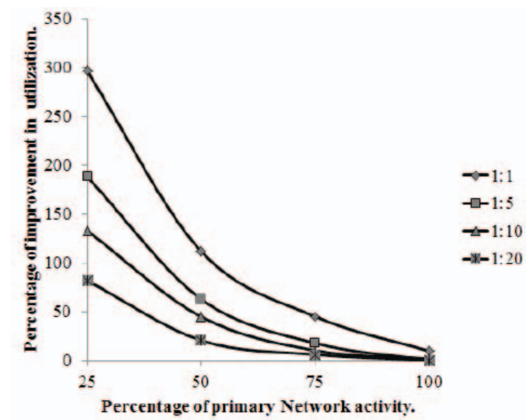

Fig. 4. Percentage of improvement in the channel utilization.

Fig. 3 shows the significant gain in the channel utilization when the secondary network opportunistically shares the channel with the primary network as compared to the case wherein only the primary network is using the channel. However, two observations can be made regarding Fig. 3. First, the size of data sent by the secondary network decreases as the AIFS number increases due to the long sensing time. Consequently, the total size of data sent by both the primary and secondary networks will decrease for lower primary network activity. The second observation is that the size of data sent by the primary network increases and that of the secondary network decreases as the primary network activity increases. However, the total size of data sent by the primary and secondary networks will increase.

Fig. 4 shows the percentage of the improvement in channel utilization for different AIFS values. At AIFS ratio 1:5, the channel improvement percentage can go up to188% for low primary network activity. As the primary network activity increases, the improvement percentage decreases until it reaches almost zero when the primary network is fully using the channel. While opportunistic coexistence over the channel improves its utilization, the achieved utilization improvement is still below the gain of contention-based (depicted by the curve labelled 1:1). When the AIFS value of the secondary

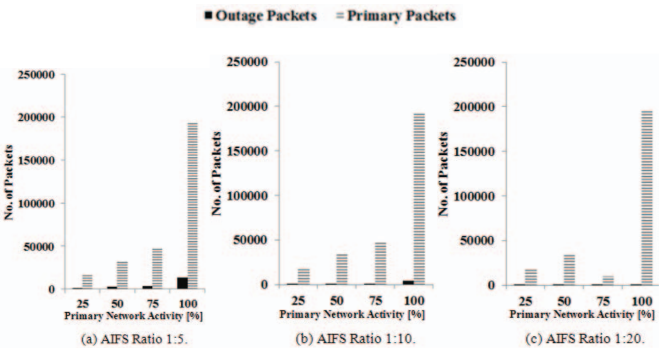

Fig. 5. The number of outage packets and the primary packets for opportunistic sharing scenarios.

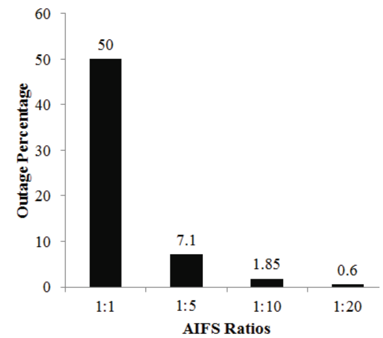

Fig. 6. Primary packets outage percentage for all scenarios.

network is equal to that of the primary network, they fairly compete for channel access. However, contention-based access does not provide protection to the transmission of the primary network, and hence, such improvement in the channel utilization is misleading as will be evaluated next.

2) Primary Network Outage Performance: Next, we evaluate the number of packets that belong to the secondary network that will use the channel during the ON period of the primary network. We refer to such packets as the outage packets as they give us an indication of how much did the secondary network interfere with the primary one. We use Wireshark [15] to identify the presence of outage packets from the secondary network during the active interval of the primary network. We compare the number of outage packets of secondary network with the total number of packets of the primary network when the primary network is ON for both coexistence scenarios.

Fig. 5 shows the number of outage packets as well as the number of primary packets for different opportunistic coexistence scenarios. As the AIFS number increases, the number of outage packets decreases. This is due to the long sensing time of the secondary network. The outage packets percentage goes down to zero at AIFS ratio equal to 1:20 (or at high AIFS ratios in general). Furthermore, the number of outage packets increases as the primary network activity increases because the collision probability between the two networks increases. We also found that the outage percentage will be almost the same for a given AIFS ratio regardless of the primary network activity. We omit this result due to space limitation.

Fig. 6 depicts the outage percentage of both coexistence scenarios. In contention-based access, half the primary network packets will be not transmitted – regardless its activity factor – because of transmission of the secondary network. This is because contention-based access does not give any priority to the primary network transmissions. Fig. 6 shows that outages due to opportunistic sharing is insignificant compared to contention-based access, especially at high AIFS ratios. We conclude that opportunistic channel access will make the most of the unused portions of the band, and utilize it without adverse impact on the primary network. The trade-off between channel utilization and primary outage packets can be easily controlled by choosing the appropriate AIFS.

V. Concluding Remarks

In this paper, we have experimentally studied the scenario in which different IEEE 802.11 networks will share the channel in the case in which some networks have higher priority compared to others. Our results have shown that even though contention-based access have higher overall channel utilization, it is not suitable for scenarios wherein one network has high priority in accessing the channel. The performance of contention-based access will be severely degraded as the outage rate will be almost 50%. In contrast, opportunistic channel access achieves relatively high channel utilization (slightly less than contention-based access) but achieves very low outage to the primary network packets. The trade-off between channel utilization and outage packets can be easily controlled by choosing the appropriate AIFS value to determine how aggressive the secondary network can be in exploiting the shared channel.

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