On the Energy Efficiency of Opportunistic Access in Wireless Home Networks

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***Abstract*—In this paper, we evaluate the energy efficiency of opportunistic channel access when used in wireless home networking applications. The main idea is to prioritize the access rights of the wireless home applications sharing a given IEEE 802.11 channel. A low priority network can opportunistically access the channel during the inactive periods of a high priority network. We empirically show that such opportunistic access does not only improve the channel utilization but also reduces the energy consumption by up to 25% and 40% compared to legacy IEEE 802.11 channel access that is widely adopted in wireless home networks. Our results also show that opportunistic access provides protection to the access right of the high priority network with outages as low as 6.4% to 0.5%.**

***Index Terms*—opportunistic access; energy-efficient; IEEE 802.11; home networking**

I. Introduction

The number of home devices with IEEE 802.11 interfaces in 2014 exceeded one billion devices – not including PC computers and mobile devices [1]. Typically, wireless home networks (WHNs) are managed manually in a static way (i.e., a fixed IEEE 802.11 channel per WHN application). Alternatively, WHN applications may periodically change their operating channels after predefined time intervals [1]. Either way, several home wireless systems will operate over the same channel and compete for channel access using legacy IEEE 802.11 medium access control (MAC) protocol.

Opportunistic access has the wireless device continually sensing different frequency channels to determine the one(s) that are not currently used by a primary network [2]. A secondary network opportunistically uses a chosen channel until its primary owner is willing to use it back. Hence, the secondary network searches for a new channel to use. Given its autonomous channel selection, opportunistic access strongly presents itself as an efficient solution for the WHN management problem. It allows the coexisting WHN applications to autonomously identify the most appropriate IEEE 802.11 channels to use. The literature of opportunistic access is affluent covering its various aspects. Furthermore, several standards are being developed to exploit opportunistic access and incorporate such a concept in widely used wireless systems such as the IEEE 802.11 [3]–[5].

In this paper, our goal is to evaluate the gains of opportunistic spectrum in WHNs. Unlike the related literature, we focus on assessing the energy efficiency of the basic opportunistic access if used in its simplest form in WHNs without any peculiarities inherited from specific energy-efficient enhancements such as those presented in [6], [7]. Furthermore, we do not consider a specific channel selection process and consider the operation over a single unlicensed channel. We aim at answering the following questions: if two WHNs are to operate on a given IEEE 802.11 channel, what are the energy gains of *prioritizing* their access rights to a high-priority (primary) network and a low-priority (secondary) network and employing opportunistic access? How would the improved channel utilization available through opportunistic access relate to its energy efficiency? Our benchmark is legacy IEEE 802.11 access which will have the different WHNs *fairly* competing for channel access.

Our results show that opportunistic access has an energy saving that increases to up to 25% as the secondary network becomes less aggressive in accessing the channel. A less aggressive secondary network also adheres to the priority of the primary network and causes significantly less performance degradation to the primary throughput (outages below 6.4% and can be as low as 0.5%). This contrasts with contention-based access that causes 50% degradation of the primary throughput. We conclude that there is a trade-off between the energy efficiency of opportunistic access and the primary network protection on one hand, and the channel utilization and the secondary network throughput on the other hand.

The remainder of the paper is organized as follows. In Section II, we motivate our work. We explain our experimental methodology in Section III. Section IV presents an extensive set of experiments that illustrate the energy efficiency of opportunistic access. We conclude the paper in Section V.

II. Is Opportunistic Access Energy-Efficient?

Information and Communications Technologies (ICT) have been shown to contribute with approximately 3% of the worldwide energy consumption and 2% of the global carbon dioxide (CO_2) emission [8]. Recently, the energy efficiency of ICT became of paramount importance in the move towards green world. In this paper, we aim at evaluating the energy efficiency of opportunistic access if used in the widely deployed WHNs. Would it be energy-efficient to prioritize different WHN applications and have them *opportunistically* coexisting over the same channel. Given the channel utilization gain provided by opportunistic access, how does such utilization gain relate to the energy consumption? Our goal in this paper is to experimentally answer such questions.

There exists several works that aim at reducing the energy consumption of opportunistic access protocols [6], [7]. Our objective here is different as we are not proposing any energy efficient techniques nor evaluating the energy efficiency of a particular opportunistic access scheme. Instead, we aim at evaluating the energy efficiency of the concept of opportunistic spectrum access in its simplest form if used in commodity IEEE 802.11 WHNs.

A. Energy Consumption of Radio Transceivers

In order to answer the above questions, we need to examine the energy consumption profile of a radio transceiver during the different states in which the transceiver operate. A radio transceiver can be either transmitting a packet, receiving a packet, idle listening to the channel, or operating in a lower power (sleep) mode. Figure 1 depicts a typical architecture of a wireless transceiver chipset. The power consumed in the transmit mode, P_{TX}, and the receive mode, P_{RX}, depend on several factors such as the modulation scheme, the coding rate, the antenna configuration in multi-antenna systems, etc. However, P_{TX} and P_{RX} are comparable to each other although their absolute values differ from one transceiver implementation to another [9], [10].

Intuitively, the power consumption of a radio transceiver operating in the idle listening mode, P_{IL}, is expected to be much less than P_{TX} and P_{RX} as it is not actively processing (transmitting or receiving) packets. However, this is not true in many transceivers. Different measurement studies have shown that the idle listening power consumption P_{IL} is still comparable to the transmit and receive powers [9], [10]. Even when the transceiver is not involved in packet processing activities when in the idle mode, it still down-converts the RF signal received at the antenna to the baseband. The down-converted signal is then sampled to either determine the start of a newly incoming packet or determine the channel occupancy state for upcoming transmissions. The sampling and processing of the RF signal is carried out by the analog to digital converter (ADC) and the baseband processor, respectively. The ADC and the baseband processor are the two most power-hungry components in most of the existing wireless transceivers. Therefore, the idle listening power consumption is still comparable to the transmit and receive power consumption. The contrasts with the sleep power P_{sleep} which is orders of magnitude less than P_{TX} and P_{RX} since most of the transceiver components are switched off when operating in this mode.

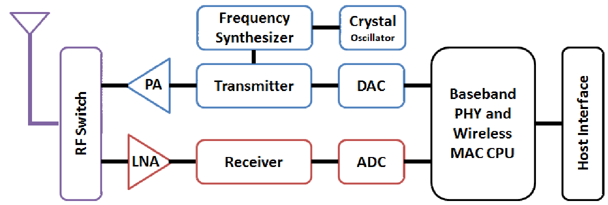

Fig. 1. Typical transceiver architecture of a wireless chipset.

III. Experimental Methodology

We consider the scenario in which there exists a wireless home application that is considered as a primary network operating over a given IEEE 802.11 channel in the unlicensed 2.4 GHz ISM. The primary network represents a wireless application which data is of high priority (e.g., the network responsible for home energy, temperature and light control). Another wireless home application (e.g., a network presenting a video streaming service) which data is of less priority represents a secondary network. The secondary network will opportunistically access the channel whenever the primary network is not using the channel. The above scenario is widely encountered in WHN environments wherein two different wireless services operate over the same channel either due to manual configuration, periodic channel hopping or any other channel sharing mechanism. Other related examples include wireless sensor networks operating on the same channel used by IEEE 802.11 Wi-Fi devices and the Internet of Everything (IoE) applications [1].

A. Primary Network Implementation

We model the primary WHN application transmissions via a single ON/OFF periodic source. During the ON portion of the period, the primary transmitter will always have packets to transmit back-to-back unlike the OFF period in which the transmitter will not have any packets to transmit. The activity factor of the primary network is defined as the fraction of time the source in ON. Such a model is widely used to model primary networks in the context of cognitive radio research. We implement such an ON/OFF traffic source on a single transmitter with a respective single receiver. We use *iperf* to originate a UDP flow at the primary transmitter and collect the UDP flow statistics at the receiver.

B. Secondary Network Implementation

For the secondary network, we also use a single transmitter and a single receiver. Unlike the primary network, we assume that the secondary network always have packets to be transmitted, i.e., fully backlogged. Our goal is to assess the worst-case energy consumption when opportunistic access is exploited at its full potential. Hence, we generate a fully backlogged *iperf* UDP flow at the secondary transmitter and collect its statistics at its receiver.

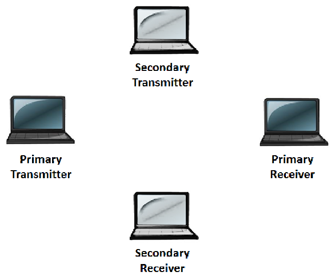

Fig. 2. Illustration of the experiment setup.

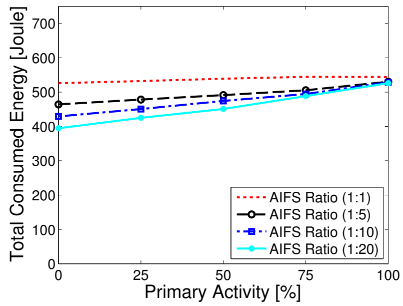

Fig. 3. The total energy consumption.

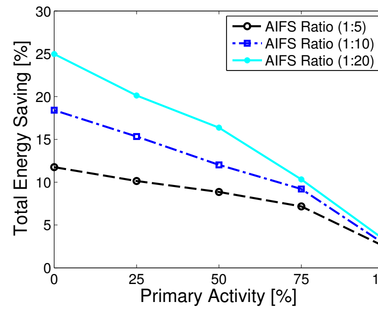

Fig. 4. Energy saving w.r.t. IEEE 802.11.

TABLE I
EXPERIMENT PARAMETERS

Parameter	**Value**
Simulation Time	120 sec
Transport Protocol	UDP
Packet Size	1470 Byte
Chipset	AR9285
PHY Rate	54 Mbps
SIFS	16 μsec
AIFS	34 μsec
Slot time	9 μsec
(CW_{min}, CW_{max})	(15, 1023)
Chipset Voltage	3.3 Volts
Chipset TX Power Consumption	1531.2 mW
Chipset RX Power Consumption	1551 mW
Chipset IDLE Power Consumption	696.3 mW
Chipset SLEEP Power Consumption	23.1 mW

Originally, IEEE 802.11 chipsets had a node sensing the channel for a DCF Inter-Frame Spacing (DIFS) period. The DIFS period is defined by the IEEE 802.11 standard as $DIFS = SIFS + 2 \times Slot\ time$, where the Short Inter-Frame Spacing (SIFS) is the turn-around time of the transceiver hardware. Meanwhile, contemporary IEEE 802.11 chipsets – such as those deployed in WHN devices – have a node sensing the channel for an Arbitration Inter-Frame Spacing (AIFS) period. The AIFS period is equal to $AIFS = SIFS + AIFS_{number} \times Slot\ time$. Through the proper choice of the $AIFS_{number}$, the secondary network aggressiveness in accessing the channel is controlled. We accordingly modify the open source *Ath9k* driver developed for all Atheros IEEE 802.11 chipsets [11].

IV. EXPERIMENTAL RESULTS

We experimentally assess the energy efficiency of opportunistic channel access with respect to traditional contention-based access when used in wireless home applications. Figure 2 depicts the experimental setup which is composed 4 nodes: 2 of which resemble the primary network and the other 2 resemble the secondary network as explained in Section III. All nodes are equipped with IEEE 802.11n PCI wireless cards that use Atheros AR9285 chipsets [12] widely used in WHN devices. We use *iperf* to generate and collect the statistics of the periodic ON/OFF primary traffic as well as the fully backlogged secondary traffic. The primary network activity is varied from no activity at all up to fully utilizing the channel (i.e., 100 % utilization) in 25% steps. We configure the $AIFS_{number}$ of the secondary sender to be 5, 10 and 20 times the $AIFS_{number}$ of the primary sender in order to control the aggressiveness of the secondary network in opportunistically accessing the shared channel. We set all nodes to operate over channel 10 of the 2.4 GHz ISM band. Channel 10 was identified as the least interfered channel at the time and location where the experiments were conducted using a spectrum analyzer. All our experiments were conducted in the early hours of morning to further minimize the potential uncontrolled transmission activities over the used channel. The reported results are averaged over at least five independent runs, each of 120 seconds length. Table I summarizes the experiment parameters.

A. *Energy Consumption*

We start by examining the total energy consumed in both opportunistic and contention-based access scenarios. As shown in Figure 3, having the two networks fairly competing for channel access consumes more energy compared to having the least priority network opportunistically accessing the channel *only* when it is not used. The total energy consumption decreases as the secondary network becomes less aggressive in accessing the channel (i.e., having a higher $AIFS_{number}$). The energy saving percentage of opportunistic access is shown in Figure 4. When the secondary $AIFS_{number}$ is 5 times the primary $AIFS_{number}$, the energy saving goes from 25 % to 3.7 % as the primary activity goes from idle to fully utilizing the channel. The energy saving decreases with increasing the secondary $AIFS_{number}$ (i.e., less aggressive opportunistic access). This is because larger AIFS implies that the secondary sender spends more time listening to the channel before transmitting its packets. Spending longer time assessing whether or not the channel is used reduces the energy consumption of the secondary network. Furthermore, it also provides protection to the channel access priority of the transmissions of the primary

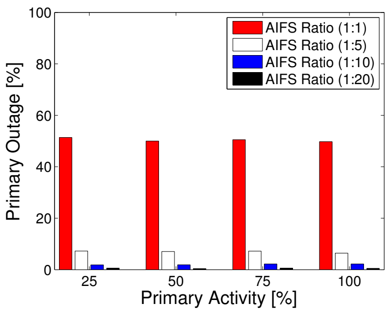

Fig. 5. The outage percentage of the primary home network packets due to the secondary home network packets.

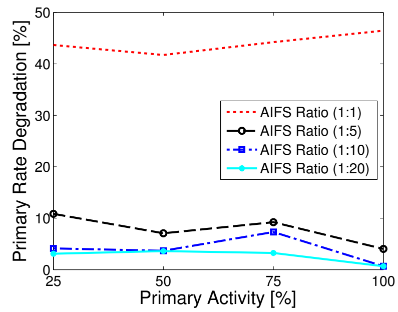

Fig. 6. The primary transmission degradation percentage relative to the case of the absence of any secondary transmissions.

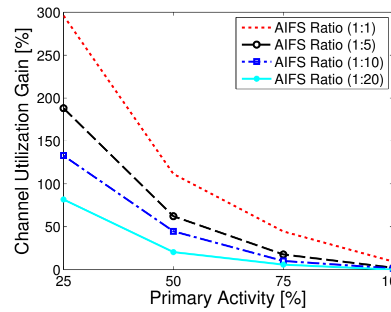

Fig. 7. The channel utilization gain of different coexistence schemes relative to using a separate channel per WHN application.

network which is essential in the context of cognitive radio networking as we shall demonstrate.

It is worth mentioning that we repeated our experiments using the Qualcomm-Atheros QCA4002 and QCA4004 green Wi-Fi families developed for low-power IoE applications [13]. Our results showed that the energy saving of using opportunistic access with the energy-efficient QCA4004 chipset has further increased to be up to 40% instead of 25% with the AR9285 chipset. We omit such result due to space limitations. We conclude that opportunistic access will provide further energy saving as more energy-efficient techniques are developed at the transceiver hardware level.

B. *Impact on Primary Network Performance*

We use another laptop equipped with *Wireshark* packet sniffer to identify the identity of the sender of each transmitted packet. Figure 5 depicts the percentage of the primary network outages which is the percentage of packets that were denied access due to the transmission of packets belonging the secondary network. Two observations are made: First, contention-based access results in almost 50% outages since it allows the fully backlogged secondary network to fairly compete with the primary network. On the other hand, opportunistic access results in significantly less outages. The primary network outages go from 6.4% to 0.5% as the AIFS ratio increases and the secondary network is less aggressive. Second, the activity of the primary network does not impact the above outage percentages. This is because the secondary network always have packets to transmit. Hence, it is either always attempting to transmit (in contention-based access) or always waiting for the primary network to finish its transmissions (in opportunistic access). Therefore, our conclusions are not limited to the case in which the primary network is using contention-based access. Similar performance will occur if the primary network is using other access mechanism such as scheduled access.

We also assess the primary network throughput degradation when solely using the channel compared to the cases in which it shares the channel with the secondary network. Figure 6 depicts the percentage of the primary network throughput degradation. When the secondary network uses contention-based access (i.e., AIFS ratio 1:1), the primary network losses between 41.73% to 46.46% of its maximum achievable throughput. In opportunistic access, the primary network throughput degradation falls below 10% of maximum achievable throughput. As the AIFS ratio increases, the secondary network becomes more conservative in accessing the channel, and hence, the primary throughput degradation further decreases. For example, the primary throughput degradation varies from 3.6% to 0.67% at 1:20 AIFS ratio.

C. *Channel Utilization*

Finally, we examine the tradeoff between energy efficiency and the channel utilization improvement of opportunistic access. As shown in Figure 7, contention-based access achieves the maximum possible improvement since no channel time is wasted in channel sensing. However, opportunistic access still achieves a very high channel utilization improvement that decreases with the increase of the AIFS ratio (i.e., less aggressive secondary network). Such a utilization improvement deterioration is the price paid to provide better protection to the primary network as explained earlier. It is up to the WHN administrator to choose the best tradeoff between energy saving/primary protection and the desired secondary network throughput/channel utilization depending on the requirements of the coexisting WHN applications.

V. Conclusions

This paper has presented an experimental study of the energy efficiency of opportunistic access if used in wireless home networks. Our goal has been to assess whether it is more energy efficient to allow two different wireless applications in a WHN to coexist in a shared unlicensed channel using opportunistic access as compared to using traditional contention-based access. Our experiments have shown that opportunistic access does not only improve the channel utilization and provide protect to the higher priority primary network but also achieves significant energy saving (up to 25% and 40% depending on the used chipset) compared to contention-based access. Such energy saving is expected to be further improved by developing energy-efficient enhancements to the basic opportunistic access.

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