QP-CSMA-CA: A Modified CSMA-CA-based Cognitive Channel Access Mechanism with Testbed Implementation

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***Abstract*—In this paper, a *modified* carrier sense multiple access-collision avoidance (CSMA-CA) mechanism, termed as quiet period-CSMA-CA (QP-CSMA-CA) is proposed, for the purposes of coexistence in a cognitive networking set-up with secondary clients that seek access using 802.11. In work to date, *dedicated* quiet periods have been defined for this purpose, as a *synchronized* duration wherein all clients are prohibited from uplink transmissions; this interval is intended for sensing channel status so as to detect out-of-network transmissions. However, such dedicated periods may adversely impact system throughput as the price for coexistence. In QP-CSMA-CA, the Wi-Fi nodes perform channel sensing during an *extended back-off phase*; thereby bypassing the need for separate dedicated sensing interval. The proposed QP-CSMA-CA protocol is implemented on the universal software radio peripheral (USRP)-based software defined radio platform and configured in a small network for measuring throughput and latency. Experimental and simulation results show the efficacy of the proposed algorithm over the dedicated sensing-based mechanism when compared in terms of system throughput and medium access latency.**

***Index Terms*—sensing, quiet period, CSMA-CA, USRP, TV White Space**

I. Introduction

The desire to improve utilization of previously licensed bands that have been shown to be under-used, has led to the new policy of allowing use of such spectrum by secondary or unlicensed users, as long as they do not interfere with the primary or licensed users [1]. The resulting proliferation of unlicensed wireless networks will increasingly lead to scenarios where multiple such secondary networks overlap due to co-location, contributing to what is expected to become *the* major challenge in the future [2] - that of coexistence among *heterogeneous* unlicensed networks, *i.e.*, those with different PHY and MAC layers. This is already an issue in the so-called 700 MHz TV White Space (TVWS) band, where IEEE 802.22 Wireless Regional Area Networks (WRAN) will co-exist with the currently emerging IEEE 802.11af Wi-Fi networks.

IEEE 802.22 is designed for point-to-point access between a base station (that may operate upto a maximum of 4 W equivalent isotropically radiated power (EIRP)) and fixed customer premise equipment (CPE) with 1.5 Mbps/384 Kbps on downlink/uplink, respectively [3]. On the other hand, 802.11af Wi-Fi network is intended for extended range internet access of portable devices. The PHY/MAC layers of these two potentially co-located networks are thus very different by design; 802.22 has adopted orthogonal frequency division multiple access (OFDMA) and a centralized, connection-oriented MAC, where the base station controls resource allocation on the uplink among all its connected users. On the other hand, the 802.11af MAC supports the usual contention-based medium access with restrictions on operation only within channels 21 to 62 in the TVWS. Since these Wi-Fi devices will operate in the TVWS, they need to transmit with a spectral mask of -55 dBm below the maximum transmit power on channels adjacent to channels with active TV broadcasting. The PHY layer of 802.11af is based on the same principles as 802.11ac and will support multiple bandwidths, *e.g.*, 5, 10, and 20MHz. The 802.11af devices need to coexist with heterogeneous bandwidths of operation within a homogeneous Wi-Fi network, as well as with 802.22 networks, and primarily with TV broadcasting networks.

Clearly, coexistence enhancing mechanisms are desirable in all such PHY/MAC designs to protect incumbents and mutual interference, utilizing primitives such as spectrum sensing, geolocation, and frequency agility. In general, nodes within a network transmit beacons [1] that could facilitate discovery of network identity by other networks that are equipped with out-of-band sensing capability [3]. In 802.22, the base station schedules *quiet periods for sensing* by all nodes during which no transmission takes place, to enable (self) network status estimation. Since 802.11af will access medium using distributed MAC, any such synchronized listening must be achieved via a different manner. The primary purpose of this work is to suggest a new MAC algorithm - Quiet period carrier sense multiple access - collision avoidance (QP-CSMA-CA) - that enables such a feature, by exploiting inherent opportunities within distributed coordination function (DCF) in 802.11. Further, we implement the QP-CSMA-CA protocol

[1]For example, 802.22 base station transmits regular super-frame Control Header (SCH). Similarly, 802.11af APs could also transmit quiet period schedules for sensing in periodic beacon frames during which the active nodes are prohibited from data transmissions.

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in a lab-scale universal software radio peripherals (USRPs) test-bed to validate the performance of our proposed algorithm. In summary, following are our major contributions:

- Propose QP-CSMA-CA protocol for sensing and detection of coexisting networks;
- Implementation of USRP-based heterogeneous network of secondary and primary users, where QP-CSMA-CA algorithm is applied at the secondary nodes.

The paper is organized as follows. Section II gives a brief discussion on dedicated sensing in conventional CSMA-CA based mechanism and existing 802.22 Standard. In Section III, we provide a detailed description of our proposed QP-CSMA-CA mechanism. The USRP test-bed implementation of our proposed algorithm is detailed in Section IV while the algorithm and process flow are illustrated in Section V. The results obtained from our USRP test-bed and corresponding simulation results are presented in Section VI. Finally, Section VII draws the conclusion.

II. Related Work

In order to detect interfering networks, a Wi-Fi network needs to have a coordinated sensing period without activity in the own network. Currently proposed schemes [4] - [5] for coordinated sensing introduce periodic sensing intervals within the data transmission phase that result in reduced network performance.

The *intermittent DCF (I-DCF)* scheme [4], illustrated in Fig. 1, introduces dedicated and periodic sensing duration, τ in order to detect presence of incumbents. Due to these predefined durations, the authors propose to fragment data packets (Fig. 1(a)) in order to accommodate periodic sensing. *However, the control packets namely, RTS, CTS, and ACK packets are not fragmented*. Additionally, a successful data fragment should have a minimum of $DATA_{min}$ bits. So the I-DCF scheme leads to three serious drawbacks:

- If the remaining time t_r between SIFS and initiation of sensing is not sufficient for an RTS, CTS, or ACK packet, then a control packet, if scheduled, is not transmitted and can be a potential cause of inefficient spectral usage. However, a fragment of $DATA_{min}$ bits with duration less than t_r can be transmitted until the initiation of the sensing duration as depicted in Fig. 1(a);
- If t_r is smaller than the transmission duration of $DATA_{min}$ bits, no data fragment is sent and this t_r interval is wasted as depicted in Fig. 1(b);
- Significant overhead due to the need for transmitting multiple PPDU containing the packet fragments.

In [5], the base station within the IEEE 802.22 network defines specific sensing intervals namely, intra-frame sensing (IFS) and inter-frame sensing (IRFS) durations. These durations are typically around 25 and 50 ms, respectively. During these sensing periods, all the CPEs are prohibited from data transmission and are required to sense collaboratively for idle channels, not occupied by incumbents.

In a Wi-Fi basic service set (BSS), a *Quiet element* [6] is used in order to obtain measurements on occupancy of one or multiple channels, except for the one it is currently operating in. The *Quiet element* is defined by an access point (AP) in *Beacon* or *Probe Response* frame in order to request the nodes to collect and report measurements on designated channels. However, it should be noted that this *Quiet element* demands for a dedicated time duration, similar to *I-DCF*, of at least one time unit (TU) of 1ms during which no transmissions are permitted from the nodes in the BSS on the current channel. Multiple such *Quiet elements* can be transmitted by the AP in order to schedule various quiet intervals. These dedicated sensing intervals on multiple channels result in inefficient bandwidth utilization, since STAs are prohibited from data transmissions simultaneously.

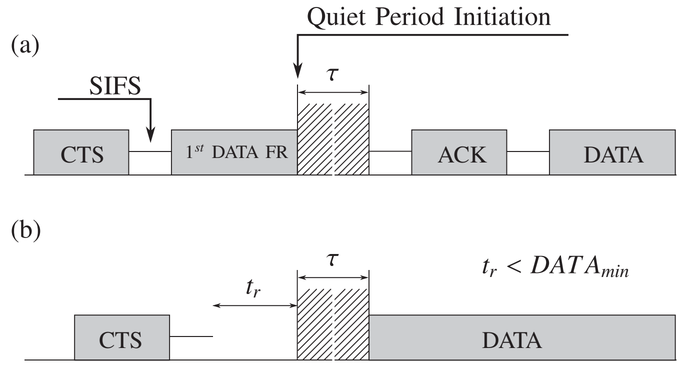

Figure 1. Intermittent DCF Scheme illustration

Our proposed QP-CSMA-CA does not involve dedicated sensing since we intend to exploit existing back-off period in conventional CSMA-CA mechanism for sensing of out-of-network interference. Since carrier sensing (CS) is already performed during the back-off phase, QP-CSMA-CA extends this CS procedure to sense multiple other channels for future occupancy. By incorporating sensing within back-off, QP-CSMA-CA intends to improve short-term unfairness among network nodes and enhance aggregated throughput of the BSS as illustrated later in Section VI.

III. QP-CSMA-CA Mechanism

In DCF, contention-based access adopts the CSMA-CA mechanism, where the active nodes in the network perform the following actions: *(i)* sense the channel if it is idle for a fixed distributed inter frame spacing (DIFS) period, *(ii)* if the medium is still idle, the nodes enter a *back-off phase* and choose a random value for their back-off counters between 0 and minimum contention window (CW_{min}), while sensing simultaneously its operating channel for possible occupancy, *(iii)* if medium is sensed occupied, they set their network allocation vectors (NAV) corresponding to the fixed duration specified by either an uplink or a downlink packet transmission, *(iv)* if medium is sensed idle, the nodes start decrementing their existing counter values in every time slot, and *(v)* when counter value of a single node reaches zero, and the medium is still idle, this specific node wins the contention and starts data transmissions.

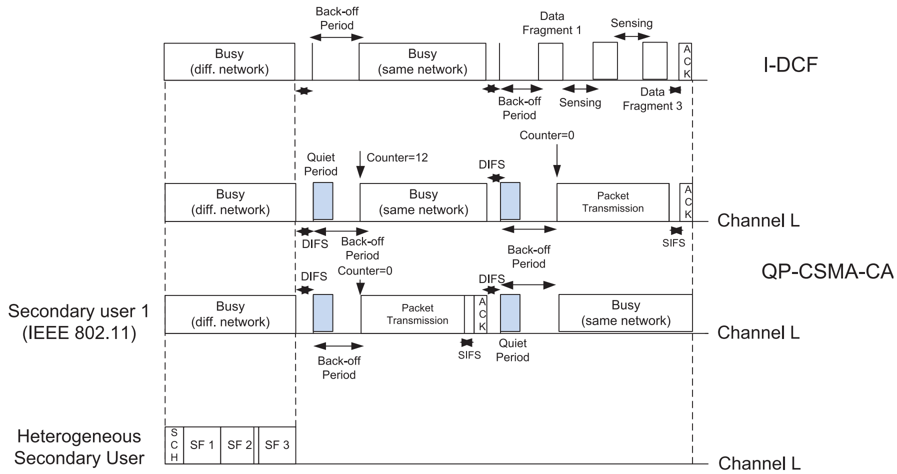

Figure 2. Comparison of timing diagram between QP-CSMA-CA and I-DCF

In QP-CSMA-CA, we propose to introduce quiet periods within the contention period prior to gaining access to the medium. The purpose of such quiet periods is to sense and detect other coexisting network (*e.g.*, 802.22, Zigbee networks) operation either on the current channel of contention or in one of its adjacent channels. Detection of such operation would either allow the Wi-Fi network to coexist using interference mitigation techniques or switch to a different channel for interference avoidance. Quiet periods ensure perfect detection of coexisting heterogeneous networks, since transmissions from the similar network are prohibited during this interval. The major difference between QP-CSMA-CA and conventional CSMA-CA (for instance, *I-DCF*) is in the scheduling of quiet periods. Dedicated sensing periods [4] are scheduled in CSMA-CA mechanism as illustrated in Fig. 1, while quiet periods in QP-CSMA-CA are scheduled during the contention phase.

For QP-CSMA-CA, step *(ii)* in conventional CSMA-CA illustrated above is modified to an *extended back-off* phase. This phase is initiated with the scheduled quiet period of fixed duration followed by the back-off phase as shown in Fig. 2. However, the quiet periods are scheduled periodically by the AP after sensing the medium to be idle for DIFS period. The reason for scheduling quiet periods within the back-off phase is two-fold:

- During back-off phase, nodes are in sensing mode and hence, not transmitting data packets (unless one of its counter value reaches zero). Therefore, quiet period is, in essence, already established.
- In back-off phase, since nodes are already in sensing mode, QP-CSMA-CA extends this sensing behavior not just restricting to its own channel, but also to its adjacent channels; therefore, no state change (from transmission mode to sensing mode as in dedicated sensing) is required in the transreceiving circuitry.

The potential benefits behind this new MAC proposal are the following:

- Fragmentation of data packets prior to dedicated sensing periods in *I-DCF*, while sensing during the contention phase leads to no packet fragmentation since nodes are in sensing mode after the DIFS period;
- Exploit the back-off phase that is essentially a sensing phase with inherent quiet periods;

Quiet periods, when scheduled, may initiate after synchronization at the DIFS period. The extended back-off phase starts with the quiet period, followed by back-off counter setting, and then medium access. Each of these steps are illustrated in depth in the following sub-sections.

A. Quiet Period Scheduling

In QP-CSMA-CA, as stated earlier, sensing shall be performed during the back-off phase. However, the network nodes need to be informed by the AP about scheduled sensing either in a *Beacon* or a *Probe Response* frame. We utilize the existing *Quiet element* in *Beacon* and *Probe Response* frames but with new interpretations of the fields in terms of DIFS periods. The Quiet element frame format is depicted in Fig. 3.

The *Element ID* is a specific value assigned for the *Quiet element*.

The *Length* field is set by the AP based on the length of the six fields namely, *Quiet Count*, *Quiet Period*, *Quiet Duration*, *Number of Channels*, *Switch Decision*, and *Channel ID*.

The *Quiet Count* field is set to the number of DIFS intervals after the current Beacon or Probe Response frame interval when the quiet period is initiated. A value of 1 indicates that the quiet interval starts immediately after the DIFS period following the current *Beacon* or *Probe Response* frame interval. Alternatively, a target time can also be advertised along with this field such that the nodes may initiate scheduled quiet period after the DIFS period following the expiration of the target time.

The *Quiet Period* field is set to the number of DIFS periods between the start of regularly scheduled quiet durations. A value of 0 indicates that no periodic quiet interval is defined. A

Element ID	Length	Quiet Count	Quiet Period	Quiet Duration	Number of Channels	Switch Decision	Channel ID

Figure 3. *Quiet element* frame format in *Beacon* and *Probe Response* frames

value of 2 implies that the nodes are required to perform sensing every alternate DIFS period. This scenario is illustrated in Fig. 4. The periodicity can be changed by the AP in the BSS based on measurement reports received from the nodes. Higher rate of occupancy by coexisting networks shall result in reduced periodicity (values between 1 and 3 DIFS period) and frequent sensing schedules, while lower occupancy rates shall result in increased periodicity (values between 6 and 10 DIFS period and value 0).

The *Quiet Duration* field is set to the duration of the quiet interval required for sensing M channels. This duration is a function of the channel sensing time, T_{sen} and channel switching time, T_{sw} per channel. The parameter T_{sen} for energy detection is the time incurred in the integration of the received signal power over N samples per channel bandwidth B. It should be mentioned here that N is a function of target detection probability, P_d and false alarm probability, P_{fa}. A lower bound on sensing time T^*_{sen} for M channels is expressed in terms of received signal-to-noise ratio ζ and P_d based on [2]:

$$T^*_{sen} = M \times \frac{N}{B}\left(-Q^{-1}(P_d)\left(1+(\frac{1}{\zeta})\right)\right)^2, \qquad (1)$$

where $Q(.)$ is the Q-function. Settling time, T_{sw}, also known as the switching time, is the time incurred by the phase locked loop circuit to switch from the current channel and lock into the next desired channel for sensing. Usually, the phased locked loop bandwidth is increased in order to reduce the settling time during the frequency switching transient. After the transient has subsided (indicated by acquisition of phase lock), the loop bandwidth is reduced. This mechanism allows fast settling with low phase noise and low power dissipation. This technique is used as an illustrative technique that can be used by the nodes for faster switching between channels to be sensed.

As evident from Eq. 1, the sensing time after each DIFS period is a function of the number of channels (M) to be sensed, samples per channel (N), and the current traffic load requested by the network nodes in the BSS. The AP may run an algorithm using T^*_{sen}, a fixed T_{sw}, traffic load in the BSS, P_d, and P_{fa} in order to obtain an optimal number of channels to be sensed. The detail of the algorithm is out of scope of this paper. Based on the *Quiet Duration* field in the *Quiet element*, the recipient nodes are aware of the next quiet duration.

The *Quiet Duration* field in a *Quiet element* can be varied within a beacon interval. After initiation of contention phase after the beacon interval, the nodes perform quiet periods of durations specified in the *Quiet Duration* field in a *Beacon* frame. However, the *Channel Usage* field in *Probe Request* frame can be utilized by the nodes to indicate to the AP about occupancy decisions on channels defined by the field *Number of Channels*. If no variations in sensing decisions are observed from nodes for some sensed channels, the AP uses the *Quiet Duration* field in the *Quiet element* of a *Probe Response* frame to indicate variations in quiet period scheduling for ONLY the channels that require revised sensing durations. In such a scenario, the *Quiet Count* element is now revised and all other previous values of *Quiet Count* shall be ignored by the nodes. The reference is now based on the *Probe Response* frame, instead of the last received *Beacon* frame. The *Quiet Duration* and *Channel ID* fields are replicated for each of the channels that require modified quiet periods in QP-CSMA-CA. For the channels not mentioned in the *Probe Response* frame, the *Quiet Duration* value defined in the last *Beacon* frame shall still be maintained by the nodes. Finally, if the AP decides on no variability in sensing durations based on sensing reports from the nodes, the AP transmits an unchanged *Quiet element* in *Probe Response* or in *Beacon* frame.

The *Channel ID* field contains a variable number of octets, where each octet describes a single channel ID. Based on the algorithm executed at the AP, it should decide on the number of channels to be sensed and enlists the IDs in this field.

B. Extended Back-off Phase for Quiet Period

As stated earlier, in order to schedule quiet periods (QPs) within the contention phase, the AP broadcasts the *Quiet element* with all the pertinent parameters. For instance, based on the fields in the *Quiet element*, the AP may schedule QPs with *Quiet Period* of 5 DIFS if it detects operation from heterogeneous networks on a specific channel of interest (from measurement reports sent in regular intervals), or *Quiet Period* of 20 DIFS when no other networks are detected on this desired channel. Since the QP is scheduled in terms of DIFS intervals, it is apparent that the distributed Wi-Fi network has to synchronize at the scheduled DIFS period. Moreover, an extended back-off phase is initiated at this scheduled DIFS, where sensing shall be performed by all active (with uplink data to transmit) nodes in the network.

In order for the QP sensing to be effective, each node must enter the scheduled DIFS periods (*i.e.*, based on the *Quiet Count* field in received *Beacon* or *Probe Response* frame) simultaneously as all the other nodes. If all packets during the data transmission phase (*i.e.*, RTS, CTS, DATA, and ACK) are received successfully, then the DIFS period will be initiated by each node concurrently when the NAV expires and the medium is sensed idle. Since the hidden node problem is reduced with virtual carrier sensing, the medium is sensed idle by each node simultaneously. The NAV, being set by a successfully detected packet, also expires at the same time for each node. In case of detected errors in packet reception (*i.e.*, no ACK received from the AP after uplink data transmission),

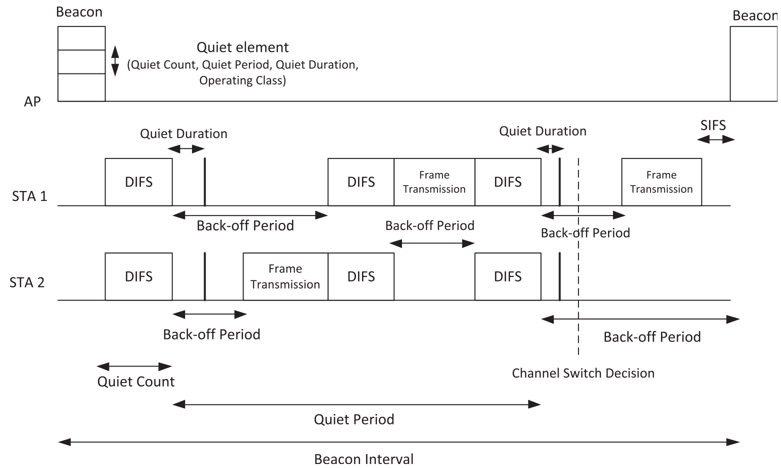

Figure 4. Illustration of the fields in Quiet element for sensing in back-off phase

and if the following DIFS is where the QP is scheduled, then, instead of sensing the channel for ($Extended\ IFS$ - $DIFS$) period shall just sense for DIFS period in order to synchronize with the other nodes in the network. In all other scenarios of detected packet reception errors and no QP scheduling at the following DIFS, the conventional CSMA-CA protocol is executed by the nodes. *It should be emphasized here that none of the contending nodes shall be allowed to decrement their counters during the scheduled QP in order to ensure no packet transmission within the network.*

C. NAV Setting and Medium Access

Following the extended back-off phase, the nodes resume normal operation with their existing values of back-off counters from the preceding contention period. During the preceding contention phase, the nodes contended for the channel with their respective back-off counter values. While decrementing the counter values, one of these nodes gained access to the medium when its counter value decremented to zero. When the medium is occupied by this node, all other active nodes set their NAVs to the value of RTS-NAV or CTS-NAV and freeze their counters at their respective back-off counter values. After the schedule QP, all these nodes resume their counter values from the previous contention phase.

IV. USRP Based Experimental Set-Up for QP-CSMA-CA Evaluation

An experimental set-up to assess the performance of the QP-CSMA-CA algorithm was designed using the USRP [7] test-bed, which provides a radio front-end to a General Purpose processor (GPP) as depicted in Fig. 5. Basic filtering, tuning, down-sampling, and interpolation occur on the USRP; complex valued samples are streamed over Ethernet to and from the GPP, where all other signal processing necessary for demodulation are accomplished, using the open source GnuRadio software library [2]. GnuRadio blocks are connected

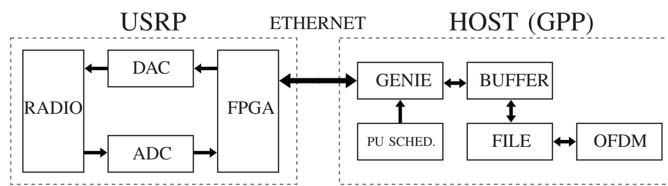

Figure 5. Separation of USRP and Host functions.

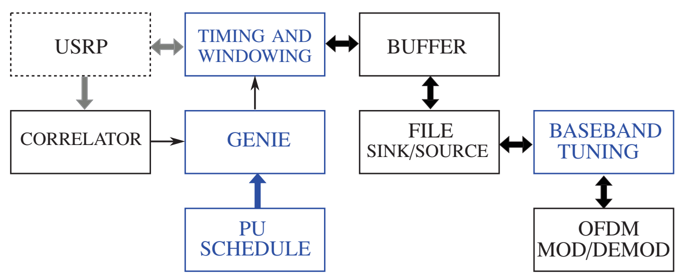

Figure 6. A detailed view of the GPP implementation. Blue blocks indicate custom written GnuRadio blocks used for implementation. Small arrows indicate control signals.

into a flow graph that allow for data passing between blocks in a thread-safe manner. Our experiment relies heavily on the included OFDM modulation and demodulation blocks provided [8].

The performance of QP-CSMA-CA is explored with respect to three key parameters:

a) Per-channel arrival rate λ of primary user (PU) frames

b) *Quiet Period D* between sensing intervals (varying QP sensing frequency)

c) Exponent variable L that determines the *Quiet Duration*.

Prior to the start of an experiment, the values for D and L are preset at each node. After each packet is transmitted, the back-off procedure begins. If sensing is not scheduled, a random back-off between 0 and 15 ($= CW_{min}$) is selected. In the case when QP is scheduled after the completion of a packet transmission, the countdown length is selected at random in the range $[2^L, 2^{L+1} - 1]$, measured in number of slots.

[2]GnuRadio includes a set of signal processing blocks that perform the digital transceiver functionalities on a host computer.

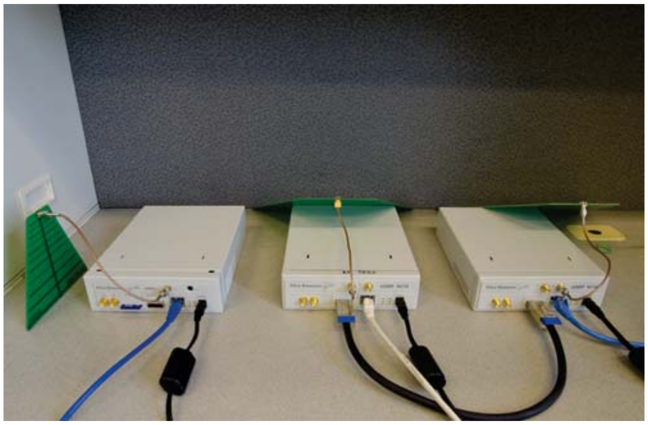

Figure 7. Left:PU (USRP2), Middle: Receiver (N210), Right: Transmitter (N210)

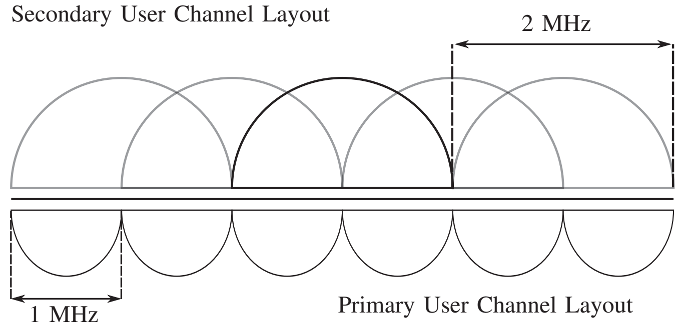

Figure 8. Channel layout selected to simplify detection and relocation strategy

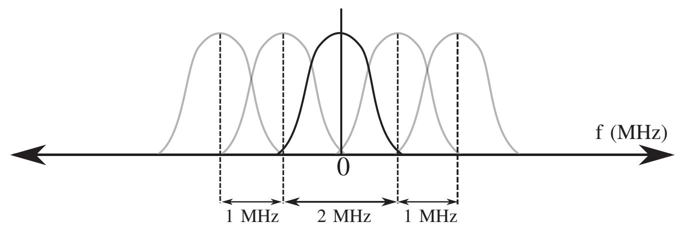

Figure 9. For each channel, a packet is shifted to the appropriate frequency at complex baseband.OFDM sub-carriers not shown.

Three USRPs were used in the set-up; a pair of USRP N210 devices serve as nodes in the secondary network, while a USRP2 is used to simulate the primary user (PU) [3]. The nodes used for the secondary network are synchronized through a common clock using a cable as show in Fig. 7. The antennas used were PCB directional Log Periodic with a gain of 5-6dBi (Ettus LP0410) [7].

1) The nodes in the secondary network are set to a sample rate of 12.5 MS/s with antennas located 1 meter apart. Each node is set up as a dedicated transmitter or receiver.
2) The secondary network uses an OFDM signal with a bandwidth of 1.5MHz located in one of 5 partially overlapping 2MHz channels (Fig. 8).
3) A fixed packet length of 1536 bits and a preamble length of 128 is chosen for the secondary network.
4) The PU node is set to a sample rate of 7 MS/s located 10 meters away from the secondary network transmitting an OFDM modulated signal occupying 875KHz. The PU can operate in one of six non-overlapping 1 MHz channels.
5) The activity schedule for the primary, including channel dwell times and hopping sequence, are generated in advance using Matlab. The primary is modeled as a Poisson process with arrival rate λ that dwells on a channel for an exponentially distributed duration before relocating to a uniformly distributed randomly selected channel in the range of [1,6]. A minimum dwell time of 10ms is enforced by re-generating samples that are too small.
6) Modulation and demodulation are performed off-line using the OFDM blocks included as part of the Gnuradio toolkit (Fig. 6).

A. Retuning

The challenge faced when the local oscillator frequency on the USRP is changed to a new channel is the lack of control on timing of the retuning. Specifically, it is not possible to ensure the USRP re-tunes at a specific time leading to uncertainties when attempting to transmit in a new channel. The timing of tuning is influenced by control signal latency that is governed by that of Ethernet [9]; often times a tuning operation can take more than 1 millisecond, orders of magnitude longer than the typical DIFS. Our solution relies on digital tuning on the GPP (Fig. 6). Using multiplication by a complex exponential with frequencies ranging from -2 through +2 MHz in increments of 1 MHz, data packets are pre-shifted at baseband and placed at the correct frequency offsets for each channel (Fig. 9). Then, switching channels is simply a matter of streaming the correct data to the USRP slightly in advance of their intended transmission. Appending timing information to the samples ensures that the USRP switches to a new channel at the desired time.

B. Sensing and the Genie Block

The duration required to stream samples from the USRP to the GPP, compute energy, and make a decision regarding the presence of the PU far exceeds the allowed time proposed by QP-CSMA-CA. Therefore, in addition to the new GPP re-tuning, a Genie block is implemented (please refer to Figs. 5 and 6) to simulate sensing. The genie block has access to perfect knowledge of the PU's actions. Parameters such as P_{fa} and P_d are used to mimic real sensing as closely as possible. While the inclusion of the genie block is undoubtedly a simplification, it is justified since realistic implementations would avoid heavy latency penalties when compared to the USRP.

[3] The selection of USRP models has no significance other than availability - none of their functional differences were exploited during the experiment.

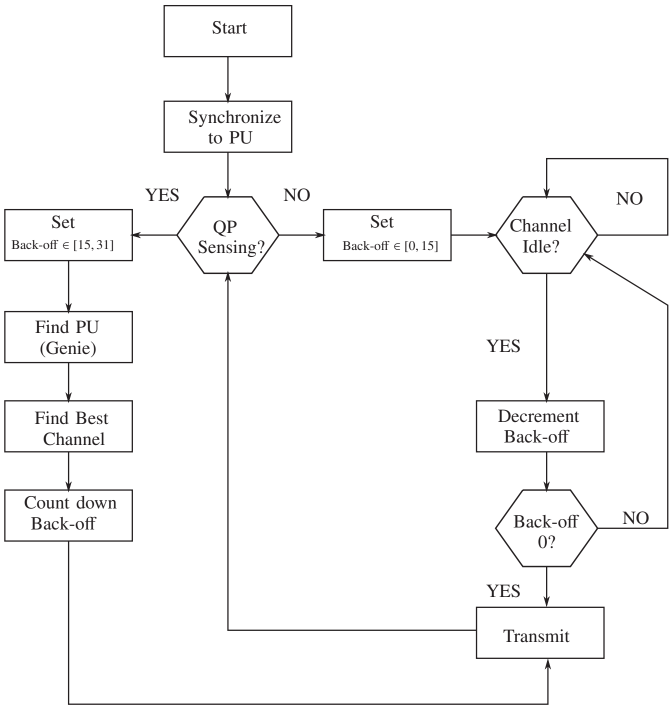

Figure 10. Flowchart for the QP-CSMA-CA USRP based implementation

```
1: packetcount ← 0 {number of packets transmitted}
2: period ← D {sensing frequency parameter}
3: L ← 4 {quiet period length}
4: while more packets remain do
5:    if packetcount mod period then {QP Sensing}
6:       backoff ← rand(2^L,2^(L+1) − 1)
7:       while backoff> 0 do
8:          backoff ← backoff−1
9:          wait(20 µs)
10:      end while
11:      tune_best_channel()
12:      transmit()
13:      packetcount ← packetcount+1
14:   else {Default Carrier Sensing}
15:      if channel is idle then
16:         while backoff> 0 do
17:            backoff ← backoff−1
18:            wait(20 µs)
19:         end while
20:         transmit()
21:         packetcount ← packetcount+1
22:      else
23:         backoff ← rand(0,15)
24:         go to 17 {continue checking for idle channel}
25:      end if
26:   end if
27: end while
```

Figure 11. Algorithm implementing QP-CSMA-CA on the USRP

The Genie block maintains a running timer used to determine the timing of the sensing operations. When sensing is scheduled to occur, the Genie consults the PU activity schedule and simulates a sensing decision. The best channel is then chosen by scanning all channels and selecting the one furthest away from the location of the PU. When the genie selects the appropriate channel for transmission, it streams the baseband shifted (Fig. 9) packet for the channel to the USRP. In order to ensure accurate timing, a Time Tag is appended to the stream which is later used by the USRP to transmit samples at the desired time. It is important to note that employing a Genie necessitates a common reference time for the primary and secondary networks.

V. QP-CSMA-CA Implementation

The general flow of the QP-CSMA-CA algorithm as implemented for the experiment is shown in Fig. 10. There are two basic flows described and the base case occurs when QP sensing is not scheduled. In such a case, the algorithm executes conventional CSMA/CA MAC. On the other hand, when QP sensing is scheduled, the algorithm takes the opportunity to scan and locate the best available channel. Due to simulated sensing (the Genie block), synchronization between the PU and secondary networks is crucial, as such, the algorithm begins by synchronizing the networks. Thus, channel idleness and best channel decisions can be made by the Genie consulting the PU schedule.

As the algorithm executes, it maintains a count for the number of packets transmitted. The packet count is then used to establish when QP sensing takes place using the parameter D (Fig. 11, lines 1-5). If QP sensing is to occur, the extended back-off is randomly generated and counted down (each slot is $20\mu s$). At the end of the countdown, the secondary user relocates to the best channel as selected by the Genie and a packet is transmitted (Fig. 11, lines 12-13). On the other hand, if QP sensing is not scheduled, the algorithm (once again using the Genie) senses the medium until it is detected to be free. Subsequently, a random back-off between 0 and 15 is selected and counted down ultimately leading to a packet transmission. In either the QP or non QP case, once transmission is complete, the packet count is incremented and the next iteration begins. The algorithm continues the process until all packets have been transmitted. The *Quiet Period* (parameter D) is varied in each experiment while *Quiet Duration* (L) is kept constant.

VI. Performance Evaluation of QP-CSMA-CA

Broadly, there are two sets of parameters available for modification to explore the performance of QP-CSMA-CA. The secondary network parameters govern the frequency of the extended back-off periods used for sensing (D) and the duration of sensing periods (L) while the mean dwell time of the PU (λ) are modified to evaluate the throughput of the secondary network when coexisting with varying PU activity.

A simulation based on the experimental set-up is created using MATLAB in order to establish expectations for each scenario. For the purposes of the simulation, a collision channel [10] model was used.

A. Dedicated Sensing

As a point of comparison, measurements were made using a conventional CSMA-CA type algorithm with a dedicated sensing periodicity of 50 milliseconds and duration of 25 time slots. Packets generated just prior to the scheduled (dedicated) sensing period would be delayed till sensing is executed. In other words, the packet is not fragmented (as proposed in *I-DCF*) but delayed until sensing is complete. This modification has negligible impact given our setup.

B. Experimental Timing Diagram

At first, the node simulating the PU transmits a 13-bit Barker sequence so that both networks are synchronized to a common time reference. The experiment begins 1 second after the networks have been successfully synchronized. The PU node transmits its signal as indicated by the pre-generated activity schedule. When the secondary network begins transmission, a timer is initiated. The timer is incremented based on the number of samples streamed to or from the USRP. The timer is then used by the GPP to locate the sensing windows as directed by QP-CSMA-CA. During a sensing window, the Genie makes a decision about the preferred channel to operate. The receiver simply records the complex samples provided by the USRP to a file. Once the preset experiment duration has elapsed, the experiment terminates. An off-line demodulation of the recorded data is performed to compute the number of corrupted and dropped packets. Subsequently, the nodes are re-initialized and wait for the synchronization signal from the PU node to initiate the next experiment.

C. Simulation Set-up

The Matlab based simulation is done in two steps. First, the algorithm in Fig. 11 is executed to generate a full trace (a fully simulated experimental time-line) of the secondary user's activities based on the QP algorithm. Next, the secondary user trace is compared to the PU activity schedule allowing detection of all packet collisions.

During the simulation, no detailed channel model is implemented and no samples are transmitted, instead, the collision channel model [10] is used to determine whether a packet is successfully received; once the number of collisions is tallied, it is used to compute throughput of the secondary user. Each simulation run represents a 10 second long experiment with a single PU and a pair of secondary nodes, repeated for 300 iterations. Channel set-up, packet length, and other key parameters in the simulation exactly match the experimental set-up.

D. QP-CSMA-CA Throughput

Fig. 12 shows that throughput increases sharply at first when sensing becomes less frequent. In the case of frequent sensing, throughput is dominated by the overhead of the newly introduced quiet periods. However, as sensing becomes more infrequent, experimental results do not match simulations as closely. In the event of a collision, the simulation assumes a packet drop. In contrast, packets are frequently successfully decoded even in the presence of interference, potentially accounting for the throughput discrepancy as the number of such events increases due to less frequent sensing.

When evaluating the performance of QP-CSMA-CA, throughput must be compared to that of dedicated sensing. Specifically, Fig. 13 clearly shows the benefits of QP-CSMA-CA when compared to the dedicated sensing strategy. Dedicated sensing is comparable to QP-CSMA-CA when QP sensing is scheduled with *Quiet Period* of 75 DIFS. As a result, in cases where the PU exhibits a short mean dwell time, dedicated sensing performs significantly worse when compared with QP-CSMA-CA. On the other hand, as mean dwell time of the PU

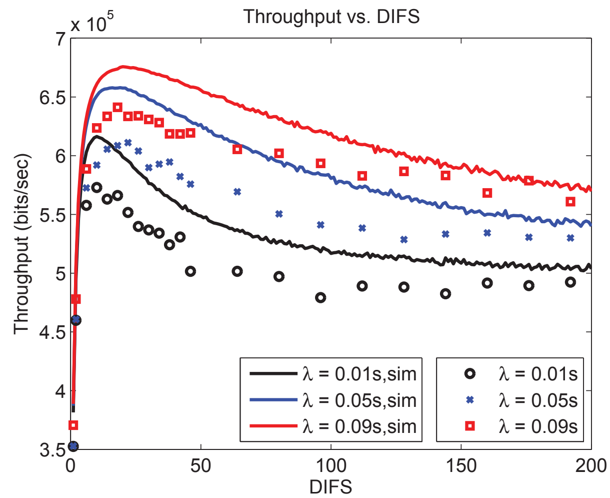

Figure 12. An optimal selection for number of DIFS between sensing exists

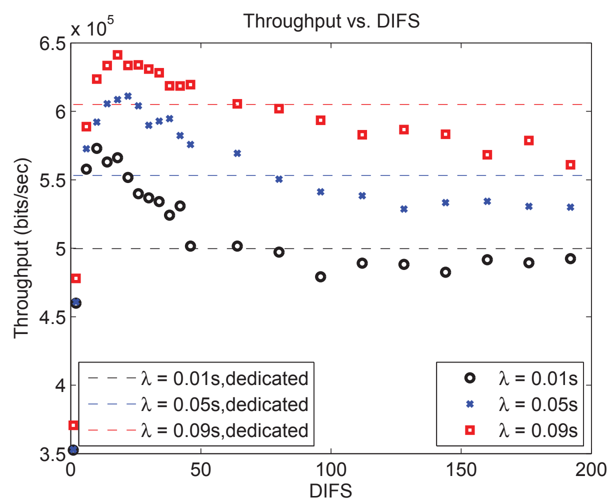

Figure 13. Throughput of dedicated sensing compared to QP-CSMA-CA

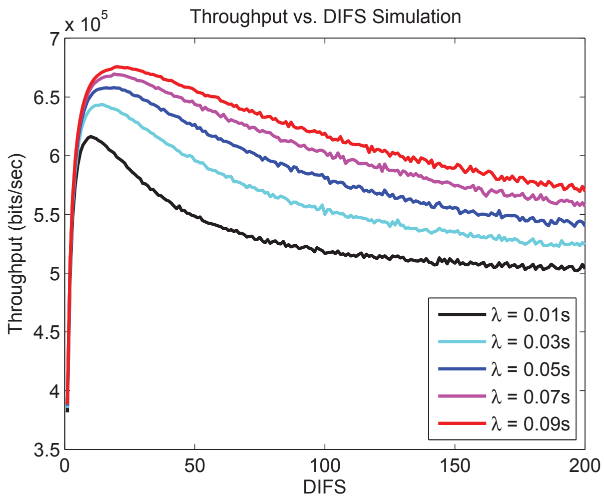

Figure 14. Optimal sensing frequency is stable regardless of PU dwell time

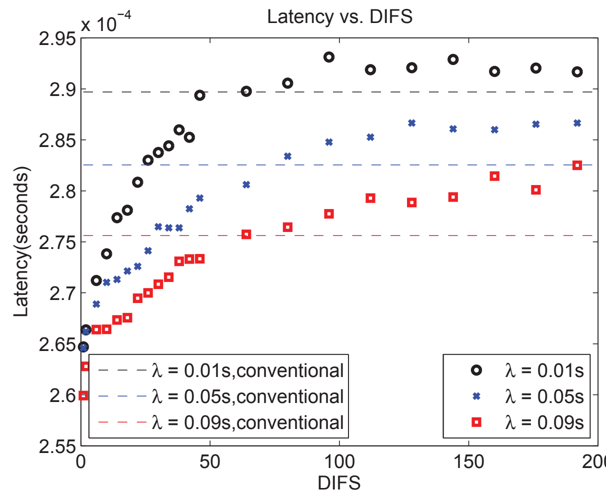

Figure 15. Comparison of medium access latency between conventional CSMA-CA and QP-CSMA-CA mechanisms

increases, the performance gap is reduced.

Regardless of the mean dwell time of the PU, optimal throughput is achieved when the secondary network is programmed to sense approximately with *Quiet Period* of 20 DIFS. Remarkably, the *Quiet Period* range of 20-40 DIFS remains close to the optimal point (Fig. 14) as dwell time is increased. Note that as the dwell time of the PU increases, throughput is less affected by reducing sensing frequency. As expected, frequent sensing of a slow-moving PU is a poor strategy to achieve enhanced throughput.

E. QP-CSMA-CA Medium Access Latency

The medium access latency results indicate that QP-CSMA-CA yields an improvement over the dedicated sensing mechanism. Fig. 15 illustrates the performance of QP-CSMA-CA with various values of *Quiet Periods*. Note that lowest latency does not coincide with optimal throughput, indicating a trade-off between the two performance metrics. When sensing is most frequent, the secondary network is aware of the location of the PU at all times and therefore exhibits lowest latency for medium access. Furthermore, when the PU has faster switching behavior, latency to access the medium is correspondingly higher. Once again, when compared to dedicated sensing, QP-CSMA-CA allows for significantly lower latency with *Quiet Period* values lower than 40.

VII. Conclusion

Dedicated sensing intervals within DCF are introduced in Wi-Fi networks in order to detect presence of licensed users while operating on a channel opportunistically. In this paper, we have proposed a modified CSMA-CA-based medium access mechanism termed here as QP-CSMA-CA, which enables sensing and detection of heterogeneous wireless networks during the back-off phase, while contending for the medium simultaneously. In QP-CSMA-CA, the nodes execute quiet periods during an extended back-off phase, where the nodes sense not only the operating channel but also adjacent channels in order to detect transmissions from other wireless networks. Additionally, our proposed QP-CSMA-CA mechanism is exhaustively implemented in the USRP-based SDR platform. Experimental and simulation results proved efficiency of our proposed medium access mechanism over the dedicated sensing-based CSMA-CA mechanism when compared in terms of system throughput and medium access latency.

Acknowledgement

The authors acknowledge genuine efforts from colleagues at FUNLAB, University of Washington (notably Colby Boyer and Linda Bai) and Nokia Research Center at Berkeley, CA.

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