QoS Aware Overlay MAC Layer for Coexistence of Heterogeneous Networks over White Spaces

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Abstract— **Several nations have approved the unlicensed use of TV white spaces (TVWS), under the condition that secondary (unlicensed) users do not interfere with incumbent primary (licensed) users. As a result parallel efforts are on in several different standardization groups (for IEEE 802.11, IEEE 802.16, IEEE 802.22, Weightless etc.) to develop wireless standards for secondary TVWS usage. A key challenge which we address in this paper is the coexistence of different secondary wireless technologies in TVWS. While some technologies such as WiFi (IEEE 802.11) are designed for unlicensed usage, others such as WiMAX (IEEE 802.16) are designed assuming exclusive use of spectrum. WiFi communications coexisting in the same TVWS with WiMAX (or WRAN (IEEE 802.22)) will potentially disrupt the latter's ability to provide QoS in terms of latency or bandwidth guarantees. In this paper we present a minimal overlay Medium Access Control (MAC) protocol that can serve as a wrapper over heterogeneous MAC layers and allow them to coexist while reducing mutual interference. We show that our MAC layer wrapper is *spectrum aware* in the sense that it promotes the use of disjoint TV channels by different wireless networks if several unused channels are available; is *coexistence aware* in the sense that it enables non-disruptive communication if more than one network occupies the same TV channel; is *QoS aware* in the sense that it can distinguish between networks with varied QoS requirements and promotes channel sharing likewise. In this paper we describe our overlay MAC layer design and present evaluation results obtained from simulating our MAC protocol. We give experiments to support our choice of design parameters. We analyze trends for our protocol based on a new metric "Error in Distribution" and show the feasibility of prioritized Coexistence.**

Keywords- Spectrum Sensing, TV Spectrum Sharing and Access, White Spaces, White space device (WSD), Overlay MAC layer, Distributed Coexistence Protocol

I. INTRODUCTION

Wireless regulators in several countries have permitted the use of TV white spaces (TVWS) for unlicensed use, under the condition that secondary (unlicensed) users do not interfere with incumbent primary (licensed) users. Various standardization efforts such as IEEE 802.11af, IEEE 802.22, IEEE 802.16h and those from the White Spaces Coalition, are underway to develop secondary wireless technologies for TVWS. While all standards for secondary technologies address the problem of avoiding interference to primary users, several challenges remain regarding coexistence of different secondary users in the same TVWS.

The problem of coexistence among secondary users can be sub-divided into *self-coexistence* and *cross-coexistence* issues. Self-coexistence refers to different secondary white space devices (WSD) using the same wireless technology coexisting with each other. Standards such as Weightless and IEEE 802.22 address this issue. For example, in IEEE 802.22 a particular WSD wanting exclusive use of a TVWS channel can broadcast beacons in that frequency channel. Other WSDs which overhear these beacons will avoid transmitting in that TVWS channel.

Cross-coexistence refers to WSDs of *different* wireless technologies coexisting in the same TVWS channel. Avoiding interference in a cross-coexistence scenario is particularly challenging for the following reasons.

(i) *No common language*: Since the devices trying to use TVWS use different air-interface protocols they cannot communicate with each other using beacons to avoid interference as in IEEE 802.22.

(ii) *Asymmetric Ranges*: Different secondary WSDs can have very different transmit powers and transmission ranges. Thus high-power WSDs which are far away from low-powered ones may be oblivious to their presence, even if they follow a carrier-sensing approach, and thereby significantly interfere with them.

(iii) *Quality of Service*: Certain technologies, such as WiMAX, ensure quality of service to their users. To guarantee such QoS in TVWS, they need to ideally be allocated appropriate time and frequency channel resources, which is non-trivial to accomplish in a cross-coexistence scenario.

(iv) *Arbitrary density of deployment*: The density of WSDs will vary largely with geo-location. For example an urban area is likely to have a high density thus exacerbating the cross-coexistence problem, whereas a rural region has fewer WSDs per unit area. Hence any cross-coexistence solution must automatically adapt to the density of WSDs.

In this paper, we present a distributed solution for cross-coexistence with the following key features.

(i) Our solution uses a common overlay MAC layer which acts as a wrapper over existing MAC layers of WSDs.

(ii) The overlay MAC is protocol agnostic. It presumes nothing about the physical layer modulation used by the WSD and avoids making changes to existing air-interface PHY and MAC layer protocols. Existing standards (WiFi, WiMAX, etc.) can run as-is on the WSDs.

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(iii) The overlay MAC gives priority to technologies such as WiMAX which attempt to give QoS to users. Thus interference from technologies that typically do not guarantee QoS to users (such as WiFi) on technologies providing QoS is reduced.

(iv) The overlay MAC layer has a frequency selection scheme that promotes allocation of different networks to different TVWS channels.

(v) Minimal additional hardware is needed on the WSDs. All devices must be capable of generating a blocking signal which can be as simple as a sinusoid with frequency located at the center of the TVWS in question, and also be capable of detecting the presence of the blocking signal. These are easily accomplished with the help of a voltage controlled oscillator and a narrow-band filter respectively.

In Section II we briefly give an overview of related work. Section III gives a brief overview on aspects of FCC TVWS regulations which we exploit in our design. Section IV describes the distributed overlay MAC protocol we have proposed. Section V details our experiments and the results obtained. Section VI presents our concluding remarks.

II. RELATED WORK

Gollakota et al. discuss physical layer MIMO antenna techniques to avoid cross-technology interference of 802.11n by signal nulling and selective channel ratio estimates [1]. This idea could be utilized in other MIMO based wireless technologies for coexistence but would be limited only to MIMO based technologies. Kondo et al. [2] solve the WiFi and WiMAX coexistence problems by taking advantage of WiFi inter-frame space idle sensing period and suggesting suitable changes in the WiMAX protocol. Their solution, however, addresses only the problem of WiFi and WiMAX coexistence and cannot be extended to generic scenarios. Esense [3] is an approach to address the cross-technology communication barrier through energy sensing, wherein energy profiling of wireless transmissions helps in cross-technology communication. Unlike our protocol, Esense allows explicit communication across technologies and requires knowledge of typical packet sizes of technologies etc. to communicate. It has also not been specifically designed to handle various challenges of cross-coexistence in TVWS listed in Section I.

Various standards address the problem of self-coexistence such as IEEE 802.22 [5] and Weightless [16]. Weightless addresses cross-coexistence partially through the use of frequency hopping.

Centralized approaches have been proposed to address coexistence. In DIMSUMnet [6], spectrum brokers coordinate spectrum usage in relatively large geographic regions; in DSAP [7], the centralized controller manages the spectrum access by offering long-term leases to secondary users. The shortcoming of a centralized approach is the cost of installation and maintenance of the infrastructure associated which also puts a bound on the scalability.

Among distributed approaches, several MAC protocols have been proposed to better utilize the overall spectrum. For example, SSCH [8], MMAC [9] use a single radio to exploit multiple fixed channels. DCA [10], HMCP [11], KNOWS [12] are proposed to use multiple channels in parallel with multiple radios. However, all of them propose a completely new MAC layer and do not provide a protocol agnostic coexistence mechanism. One exception is the IEEE 802.19 Task Group 1 [4], which is dedicated to proposing a MAC layer for TVWS coexistence but is still in a nascent stage of development.

III. FCC REGULATIONS AND BENEFITS

We use the capabilities mandated by FCC regulations on the nature of devices that will use TVWS, to our benefit, to overcome the issues in coexistence.

Frequency Agility: Typically WSD's would have frequency agile radios i.e. cognitive radios able to change frequency of operation. The TVWS may span across a large bandwidth (depending on the geo-location), consisting of several unused TVWS channels each 6 MHz wide. We employ this frequency agility in the form of a hopping scheme in our protocol discussed in Section IV.

Central Database: A device that wants to initiate a network has to first look up the central database based on its geo-location, get the list of available channels and poll the database periodically. This ability will be used in our distributed approach to maintain a feasible list of TVWS channels for each network initiator.

IV. DISTRIBUTED APPROACH

In our distributed approach we present a generic MAC layer as a wrapper over the MAC/PHY layer of a device adhering to any wireless technology. This overlay MAC layer is minimal in nature and serves as a medium of coordination between different TVWS based networks and hence enables non-disruptive communication even if two different kinds of networks are in the same channel, this we term as *coexistence awareness*. Our approach also helps networks occupy disjoint channels in the available TV white spaces which we term as *spectrum awareness*. Also our approach distinguishes the needs of a high priority network as against a low priority network and promotes channel sharing likewise which we term as *QoS awareness*.

The overlay MAC layer operates in two phases that serve different purposes. The first phase is the Joining Phase which helps a network to initially start using a particular TVWS channel from all the available ones, and is responsible to distribute networks to different TVWS channels. This helps overcome the issue of *Arbitrary Density of Deployment* (described in Section I) to some extent as crowding in a single channel is avoided. After the Joining Phase a network switches to the second phase - the Coexistence Phase. This phase helps in the non-disruptive communication of various heterogeneous networks, if at all present in the same TVWS channel and facilitates priority based channel sharing.

In our design of the overlay MAC layer we assume that the maximum distances over which communication takes place i.e. the diameter of a single secondary network is 20km. By each TVWS channel we mean a particular TV channel which is available for license-exempt use by secondary users. We do not fragment or combine TVWS channels for use by any particular secondary network.

We make use of blocking signals in our protocol. The blocking signals serve multiple purposes with minimum additional hardware required (as explained in Section I):

(i) In our protocol, the blocking signal serves as a means of reservation of a TVWS channel. It indicates to all other networks in the same TVWS channel the reservation of that channel for a fixed amount of time (channel occupancy time (COT)) and hence helps overcome the *No Common Language* barrier.

(ii) It also helps overcome the *Asymmetric Ranges* barrier as in our protocol the reach of the blocking signal decides the extent of the region within which coexistence is possible and this can easily be extended with the additional hardware required for the blocking signal, without interfering with the inherent hardware or modulation schemes in a low-range device. Note that an unmodulated sinusoid can be easily detected at long distances because after filtering with a narrow-band filter the SNR is very high. We hence recommend this as a blocking signal.

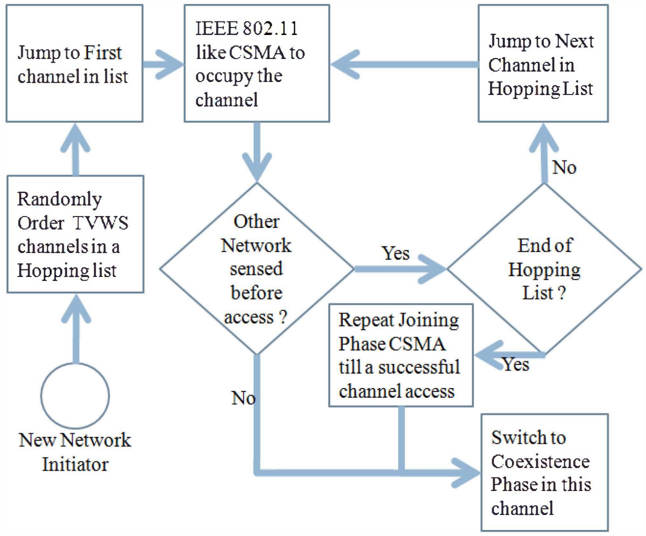

Figure 1: Joining Phase Flow Diagram

We assume each network to consist of a network initiator, i.e. a master node such as the Base Station in case of WiMAX or the Access Point in case of WiFi network, and network followers, i.e. clients such as the Subscriber Stations in case of WiMAX or clients in case of WiFi.

Our overlay MAC layer behaves differently for network initiators and network followers, the distinction being that the network initiators of varied networks are responsible for blocking signal based contention of a particular TVWS channel. Once a particular network gets access to this channel it informs its followers to switch to the underlay MAC layer via a beacon signal and then itself switches to the underlay MAC layer to resume communication within the network. We now give a detailed phase-by-phase description of our overlay MAC layer followed by a discussion about various aspects of the protocol.

A. *Joining Phase*

The joining phase is the initial phase when a particular network wants to start using any TVWS channel. The network initiator, by virtue of the mandatory FCC regulations, has the list of TVWS channels from the central database. The network initiator initializes a frequency hopping list which is a random ordering of all the TVWS channels. The network initiator now performs what we term as “Dynamic Frequency Selection”. The network initiator selects the first channel in the hopping list, initializes its backoff counter to a random value between 0 to CW (Contention Window size) and starts carrier sensing that channel for blocking signal (henceforth referred simply to as carrier sensing) in an IEEE 802.11 like manner which consists of first blocking signal based idle sensing (henceforth referred simply to as idle sensing) of the channel for Idle Sense Time (IST) followed by slotted countdown of the backoff counter. If it senses the presence of another network via the blocking signal sent by another network initiator during this period, it hops to the next TVWS channel in the hopping list, re-initializes its backoff counter and continues the same carrier sensing process. Otherwise if the network initiator counts down the backoff counter to zero it first sends a blocking signal for 1 slot duration followed by a beacon signal for Channel Occupancy Time (COT) intended for its network followers and then switches to the Coexistence Phase. We assume the switching delay to hop from one channel to the other, which is governed by the settling time of Voltage Control Oscillator, to be 80μsec [13]. If at all during a frequency hop the network initiator reaches the end of the list, the network initiator continues to stay in this channel and switches to the coexistence phase only after a successful IEEE 802.11 like joining phase CSMA, wherein the backoff counter is freezed and not re-initialized whenever other network is sensed. The description of the Joining Phase flow diagram and the exact CSMA breakup for a network initiator is given in Figure 1 and Figure 2.

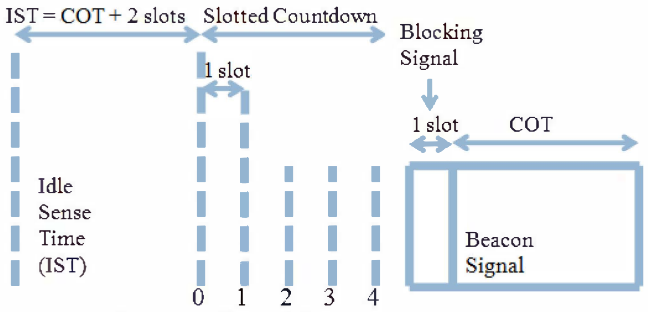

Figure 2: Joining Phase CSMA breakup

In the joining phase, the network followers listen on all the TV channels for the presence of its network initiators beacon signal so that the network followers know which particular TV channel to join. This enables synchronization of the complete network with respect to joining a particular channel and switching to the Coexistence Phase. The reasoning behind the protocol design decisions and the exact timing values given to the various parameters for the joining phase is discussed at length in Section IV-C.

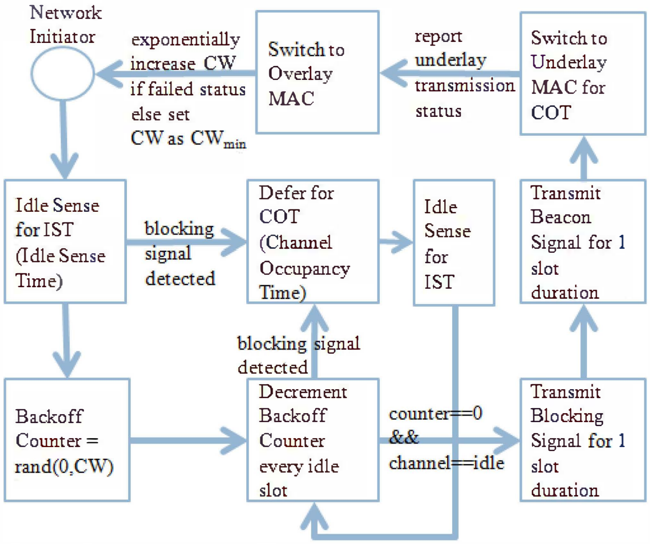

Figure 3: Coexistence Phase State Diagram

B. *Coexistence Phase*

The second phase of the overlay MAC layer is the Coexistence Phase. This phase helps in facilitating coexistence among different networks. The state diagram for this phase is given in Figure 3. Any network initiator on switching to this phase first initializes the backoff counter to a random value between 0 to CW (Contention Window size) and then starts carrier sensing the medium in an IEEE 802.11 like manner. CW for this phase is variable and varies between CW_{min} and CW_{max}, by default the CW value is set as CW_{min}. The network initiator first idle senses the channel for Idle Sense Time (IST), followed by counting down its backoff counter in slots. If during this period the network initiator detects a blocking signal, it defers for Channel Occupancy Time (COT). If the counter counts down to zero and the channel is still idle it first transmits the blocking signal for 1 slot duration followed by the beacon signal intended for its followers and then switches to the underlay MAC layer for COT. The network followers sense the channel for the beacon signal from its initiator and switch to the underlying MAC layer for COT once they receive the same. Figure 4 gives the exact breakup of CSMA for a network initiator in Coexistence Phase. It may so happen that more than one network initiator count down their backoff counters to zero at the same time and as a result start sending the blocking signal at the same time. In such a case the transmissions in the underlay MAC layer will be disrupted. This is reported to the overlay MAC layer after COT when the network initiator reverts to the overlay MAC layer with a status message. In response to a failed status message the overlay MAC layer increases its CW value exponentially (unless it is CW_{max}). In case of a success response CW is set as CW_{min}.

Additionally a network initiator in the Coexistence phase also performs periodic QoS checks to see if QoS satisfaction is being achieved. If not the network initiator re-enters the Joining Phase after informing all the network followers of the same in the last successful coexistence phase channel access. Such QoS checks will help in waning overcrowded channels, help in reclaiming channels that now has dormant networks in them or help in exploring unused channels with the added benefit of maintaining QoS guarantees. Any remaining reasoning behind the protocol design decisions and the exact timing values given to various parameters for the coexistence phase is discussed in Section IV-C.

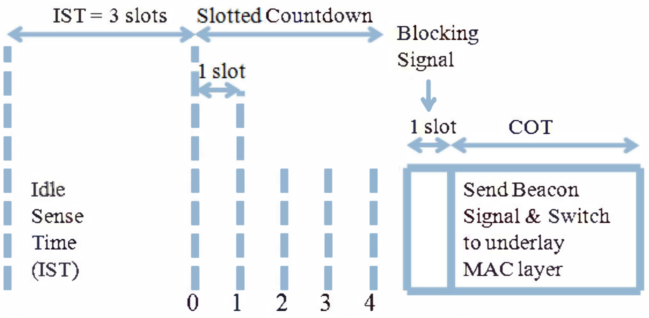

Figure 4: Coexistence Phase CSMA breakup

Parameter	Joining Phase	Coexistence Phase	
		High Priority	Low Priority
IST	COT+2 slots	3 slots	
CW	CW_{min}	CW_{min}, exponential increase on failure at underlay MAC layer	
CWmin	6	3	7
CWmax	6	7	31
Backoff Counter	rand(0,CW)		
Slot Duration	70 µsec		

Table 1: Values for Protocol Parameters

C. *Explanation of Protocol Design Decisions*

Table 1 gives the various overlay MAC layer protocol parameters. The decision process behind each is discussed in this subsection.

(i) *Slot Duration:* The slot time depends on four key delays – the time to carrier sense, Rx-Tx switching time, speed of light propagation, and MAC processing delay. Since the distances under assumption here are of the order of 20km the dominating factor here is the speed of light propagation which is 66µsec. The other delays can be accounted for in 4µsec as is also recommended for CSMA in IEEE 802.11. Thus the total slot time is 70µsec.

(ii) *Idle Sense Time (IST):* The IST for coexistence phase is kept as 3 slots to serve as a padding that accounts for variability in Channel Occupancy Time (COT) as the COT time is an approximate amount of time spent in the underlay MAC layer and can be subject to slight variability as time spent in underlay MAC layer may overshoot time COT to complete an ongoing event/transmission of the underlay MAC layer. IST for coexistence phase is more of a failsafe than a necessity as will be clear from the discussion for COT.

The IST for joining phase is equal to the Channel Occupancy Time (COT) plus time for 2 slots. The purpose of an IST in the joining phase is to decrease the chances of a joining phase network to join a channel that already has a coexistence phase network (one belonging to high priority class to be more specific) occupying it. It may so happen that a joining phase network initiator just misses the blocking signal sent by a coexistence phase network initiator. Since the blocking signal is missed by the joining phase network it means that time of the order of propagation delay i.e. 1 slot has already passed since the switch to the underlay MAC layer, which means the coexistence phase network initiator has time of the order of COT – 1 slot left before it itself reverts to the overlay MAC layer and starts its own IST idle sensing. Now, while the joining phase network initiator idle senses for IST time, i.e. waiting for COT + 2 slots, the coexistence phase network initiator would have completed its own IST idle sensing as well (because COT -1 slot + 3 slots = COT + 2 slots). This ensures that both the network initiators start their slotted countdown phase at the same time. Since the value of CW is smaller for high priority coexistence phase network, most likely the joining phase network will lose the channel access to the coexistence phase network and will hop to the next channel. However if it were a low priority coexistence phase network, the joining phase network would have a high chance of occupying this channel. Again the joining phase networks' chances of winning channel access will reduce if even in the absence of a high priority coexistence network, the number of contending low priority coexistence networks is large.

Thus this promotes individual channel access for a high-priority-coexistence-phase-network even in a worst case scenario, promotes joining phase network to join only a less crowded channel consisting solely of low-priority-coexistence-phase-networks that too in this limited borderline scenario. In normal circumstances the joining phase network would occupy an uncontested channel, or in case of overcrowding of all the TVWS channels would end up occupying the channel occurring last in it's randomly ordered hopping list. In the overcrowded scenario all the incoming joining phase networks would invariably occupy the last channel in its random hopping list, which essentially is a random channel, thus ensuring the incoming new networks would distribute equally to all the TVWS channels. This is ascertained in Section V-A via Error in Distribution analysis.

(iii) *CW, CW_{min} & CW_{max}:* The backoff counter is set to a random number between 0 and CW, the contention window size. The value of CW varies from CW_{min} to CW_{max} and the exact nature of variation or none thereof has already been discussed in light of both the phases. Here we discuss CW, CW_{min} & CW_{max} in the context of ascertaining QoS awareness.

In our protocol we ensure basic QoS guarantees for a particular network by controlling CW_{min} & CW_{max}. We support two classes of networks – high priority networks and low priority networks. As illustrated in Table 1 high priority networks have CW_{min} & CW_{max} as 3 & 7 respectively whereas low priority networks have CW_{min} & CW_{max} as 7 & 31 respectively for the coexistence phase. The the choice of these values has been determined through experimental results in Section V-C. More refined Contention Window based QoS differentiation schemes for IEEE 802.11 exist and have already been explored in research attempts as [14], [15]. Adaptation or exploration of a much better QoS differentiation scheme for our case lies within the future scope of this research.

(iv) *Channel Occupancy Time (COT):* The choice of COT has two sources of constraints on it. The first constraint on the choice of COT comes from the Coexistence phase. Carrying forward from the discussion on COT in the IST section, COT should essentially be enough so that atleast one event/transmission can successfully take place so as to avoid any spillover to the idle sensing phase of other network initiators. Moreover implementation specific care needs to be taken at the underlay MAC layer to maintain timers for time left to COT timeout and forgo transmission of frames that will exceed the COT time limit.

The second constraint comes from the nature of joining phase protocol. In the joining phase, the network followers may want to search for the beacon signal of its network initiator in all the TV channels. This is only to expedite the association of a network follower with its initiator and may as well spill over to the coexistence phase wherein the network follower will then have to scan all the channels for transmissions corresponding to its network initiator. In case we want to achieve this association in the joining phase COT should be sufficient for followers to be able to scan all channels for the beacon signal in that amount of time. For our experiments we assume network followers capable of sensing multiple channels at the same time thus giving free choice for COT which we fix as 8 slots unless specified.

V. EXPERIMENTS AND RESULTS

We implemented the overlay MAC layer in the Qualnet network simulator [17] as an independent module to demonstrate qualitative aspects of the same. We also plugged in our implementation of our overlay MAC layer for WiFi and WiMAX networks to demonstrate feasibility of priority based coexistence. We chose WiFi and WiMAX as the former does not give specific QoS guarantees while the latter does. Also if TVWS are unlicensed these would be strong contenders to switch to the same. We now present our results and analysis.

A. Analyzing Error in Distribution for Joining Phase

The experimental setup for analyzing the Joining Phase consisted of a variable number of network initiators adhering to the overlay MAC layer, trying to occupy 13 available channels in the sub-GHz TV frequency range. To show the effectiveness of the Dynamic Frequency Selection (DFS) scheme of the Joining Phase we compared the final distribution of the networks in all the available channels with an ideal situation wherein all the networks are evenly distributed in all the available 13 TV channels.

For this purpose we define a new metric we refer to simply by "Error in Distribution". The "Error in Distribution" is a metric to quantify the degree to which the achieved distribution of networks in the TVWS channels differs from an ideal one wherein each channel has equal number of networks.

$$x(i) = \text{number of networks in channel } i$$

$$A = \text{average number of networks per channel}$$

$$\text{Error in Distribution} = \sum (\delta(x(i) - A) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where,

$$\delta(x) = (\delta(x) > 0)\ ?\ x:0$$

Thus the ideal scenario has each TVWS channel containing networks equal to the ratio of total contending networks to total available channels. In this light, we defined the "Error in Distribution" quantitatively as in Eq. (1). Using this definition we found the total Error in Distribution for our Dynamic Frequency Selection (DFS) implementation. Moreover for the experiments we changed the number of networks in the joining phase simultaneously and kept the number of available TV channels fixed. We averaged our results over 20 simulations. We present our result for this analysis in Figure 5. We found that though error increases with increase in number of networks but the magnitude of error observed is small, for example, with 26 high prioritized networks vying for 13 channels we found our error to be approximately 4 on average which means that in the average case there are 4 misplaced networks highlighting that our DFS scheme is deviating by a very small magnitude from the ideal scenario. We experimented for high prioritized networks as their misplacement is more detrimental as they need QoS guarantees. For the above simulation of the joining phase we chose COT time as equal to 8 slots. We chose the Contention Window size (CW) as 6 slots for the joining phase, the reason for which will be justified in the next experiment.

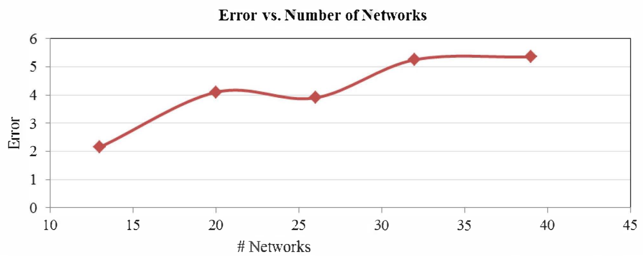

Figure 5: Error in Distribution of networks for DFS scheme with increasing number of networks

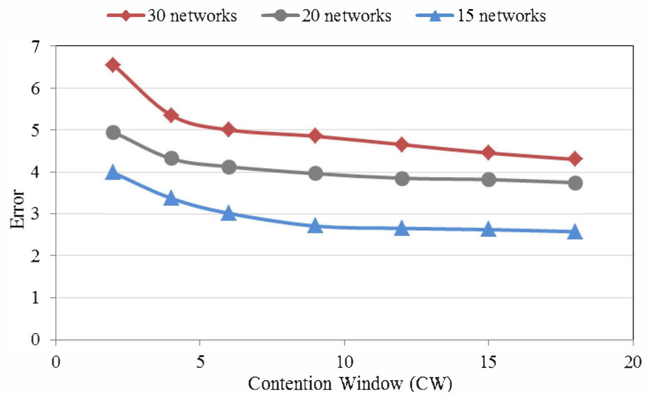

Figure 6: Variation of Error in Distribution with Contention Window size of the Joining Phase

B. *Determining Contention Window for Joining Phase*

We perform another experiment to find the minimum possible but feasible contention window size for the Joining Phase of the overlay MAC layer. We did this by analyzing the trend of error in distribution with varying contention window sizes. We increased the contention window size and observed the deviation from ideal distribution by averaging over 20 simulations for each data point. We repeated the same experiment by varying the number of networks. We considered the case of 15, 20 and 30 high prioritized networks and found the same trend across all these cases. Again we experimented over high prioritized networks as error in distribution over high prioritized networks is really our concern as these are the networks that need QoS guarantees.

We present the results in Figure 6. We found that as we increase the contention window the error decreases rapidly until the contention window size approaches 6 slots and the error decrement rate is very small thereafter. A large contention window results in more time required for networks to wait before transmission, decreasing overall throughput in the channel. Hence we propose to use contention window of 6 slots for the joining phase. The possible reason behind the nature of the graph is that for a very small contention window size the number of initial collisions for Joining Phase network initiators is large and hence they end up in the same channel. However once a network initiator ends up in the Coexistence Phase this channel is more difficult (and the difficulty increases with increasing number of Coexistence Phase network initiators in that channel) for a Joining Phase network initiator to join due to the design decisions made with respect to the choice of the CSMA schemas for both the phases (explained clearly in Section IV-C), making that channel less susceptible to an error. Hence the major contributing factor for the error is the initial collisions which rapidly decreases with increase in contention window size initially and thereafter plateaus.

C. Determining Contention Window for Coexistence Phase

Our next series of experiments was to deduce the Contention Window sizes for Coexistence Phase of the overlay MAC layer. For QoS awareness we support two classes of networks – High Priority that guarantee QoS to users (such as WiMAX) and Low Priority that typically do not guarantee QoS to users (such as WiFi). To achieve QoS differentiation we have different CW_{min}, CW_{max} pairs for High Priority and Low Priority networks which we determine through a series of experiments in this section.

In the next set of experiments two networks vied for the same channel in the Coexistence phase with varying contention window range (CW_{min}, CW_{max}) values. Each data point was obtained by averaging over 20 simulations. We first analyze the effect of Overlapping and Non Overlapping contention window ranges.

From Figure 7 we observe that the ratio of time spent decreases with increasing overlap and from Figure 8 we observe that the collision probability increases with increasing overlap. Hence we conclude that High Priority and Low Priority networks should have non-overlapping contention windows with lower set of CW values for High Priority networks as this will promote higher channel access for high priority networkS and also reduce time wastage due to overlay MAC layer blocking signal collisions.

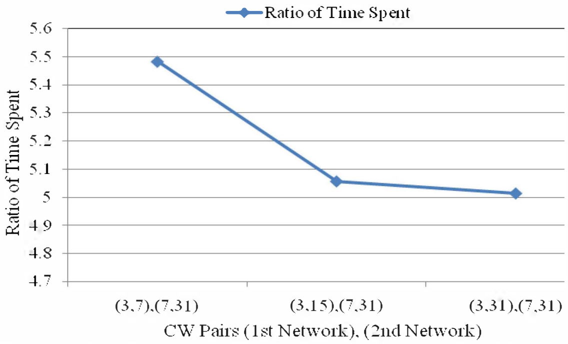

Figure 7: Ratio of Time Spent trend for Overlapping and Non Overlapping Contention Window Pairs

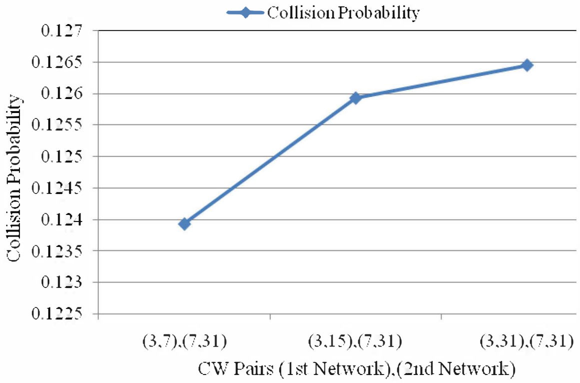

Figure 8: Collision Probability trend for Overlapping and Non Overlapping Contention Window pairs

We now analyze the effect of CW_{min} on the nature of channel sharing between two networks. We have two networks with the same CW_{min}, CW_{max} values vying for the same channel in the coexistence phase.

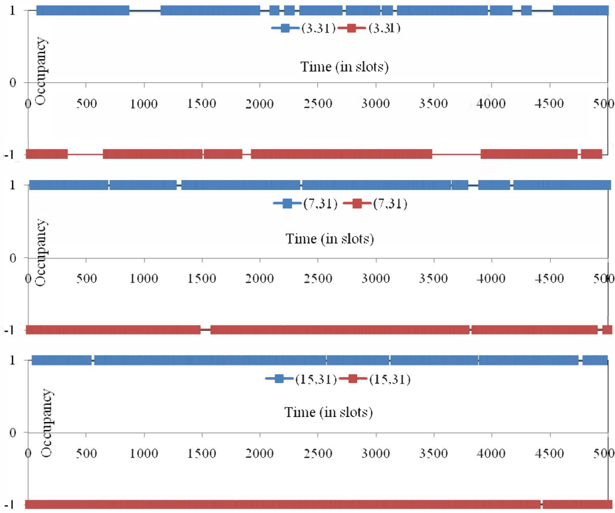

Figure 9: Nature of Channel Access with varying CW_{min}

Figure 9 shows channel access as coalesced filled boxes for a network on y=1 line and for the other network on y=-1 line with varying CW_{min} values. From Figure 9 we observe that the channel access occurs in bursts for lower CW_{min} value. Moreover this burstiness reduces as we increase CW_{min}. Since in our protocol the High Priority nodes should have lower CW_{min} values, we fix the CW_{min} value for our High Priority networks as 3. This offers an advantage in the form of bursty channel access. To illustrate in case two High Priority networks occupy the same channel one will starve the other during one of these bursts (i.e. sole access to channel for prolonged period), and due to the failed QoS check in the Coexistence phase, the starved High Priority network will vacate the channel. This ensures that High Priority networks will ultimately occupy distinct channels irrespective of the starting distribution (reducing the error in distribution). Hence the final (CW_{min}, CW_{max}) values for High Priority and Low Priority networks was chosen as (3,7) and (7,31) respectively due to advantages offered by non-overlapping windows and a low CW_{min} for high priority networks. CW_{max} was capped at 31 overall as the slot durations involved in our case is of the order of hundreds of µsecs (70 µsec) which is quite high.

D. Prioritized Coexistence of WiFi with WiMAX

For the Coexistence phase we demonstrate coexistence of a Whitespace (WS) enabled WiFi network and a WS enabled WiMAX network. The setup consists of a basic functional IEEE 802.16 single cell network consisting of 5 nodes with one of the nodes as the base station and a UDP CBR flow with packet size as 512 bytes and packet interval of 50 µsec between a pair of subscriber stations. Also present is a 54Mbps IEEE 802.11a network in the same channel consisting of 3 nodes, one being the access point and the other two having a UDP CBR flow with the same credentials as stated above. This flow is a max rate flow for the WiFi network so as to create a scenario with maximum possible hindrance to the WiMAX network. Here we assume the both the networks are in the Coexistence phase.

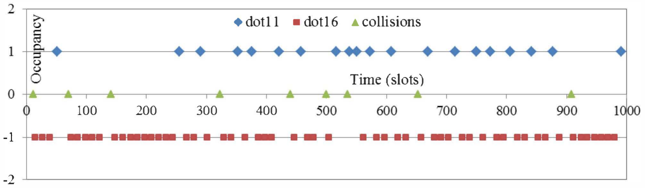

Figure 10: QoS differentiation between 802.11 and 802.16 Network via prioritized channel sharing

WiMAX has overlay CW_{min} and CW_{max} as 3 and 7 whereas WiFi has the same as 7 and 31. We present a much magnified snapshot (of the order of slots) of the time sharing achieved between WiFi and WiMAX networks in Figure 10, which shows that prioritized coexistence is possible in our protocol with regular and higher time share given to WiMAX.

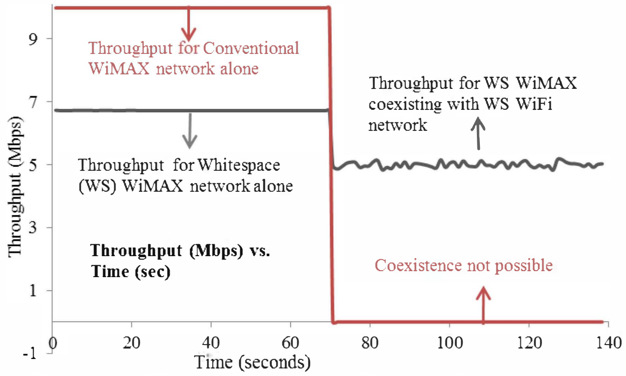

Figure 11: Throughput variation for 802.16 network

In Figure 11 we present the variation of throughput achieved by WiMAX network before and after the introduction of our overlay MAC layer and in the presence of a WiFi network. The initial half of Figure 11 gives baseline throughputs for conventional WiMAX and WS enabled WiMAX network (with reduced throughput due to overlay MAC layer overheads) existing as sole occupant of the channel. The right half of Figure 11 gives throughput observed for WS enabled WiMAX in presence of WS enabled WiFi otherwise not feasible for conventional WiMAX with conventional WiFi.

VI. CONCLUSIONS

We have discussed in detail the issues that may arise once many technologies start using TV white spaces and proposed a distributed protocol that uses FCC Regulations to our benefit. Our generic minimal overlay MAC layer is spectrum aware, coexistence aware and QoS aware. The modifications of this protocol for a much refined QoS differentiation scheme as well as its modification for multi-hop mesh networks are potential avenues for future work.

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