A Case Study of QoS Provisioning in TV-band Cognitive Radio Networks

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Abstract—**Dynamic Spectrum Access (DSA) MAC protocols allow a Cognitive Radio (CR) device to opportunistically access unused or less crowded spectrum while ensuring protection for the incumbents. Though DSA shows great potential to enhance spectrum efficiency, the associated constraints on QoS may limit its usefulness. QoS support in a DSA-based network is not trivial due to the fact that in addition to unfavorable characteristics of the wireless medium, the secondary devices are subject to additional interference and interruption from incumbents. In this paper, we present a case-study of key QoS provisioning techniques in DSA protocol design that facilitate the required application QoS. Specifically, we consider a CR system that supports high quality multimedia (including HDTV) streaming over UHF frequency bands. We model and evaluate the QoS-oriented CR system together with the underlying QoS-Provisioned DSA Protocol (referred as QPDP) through extensive simulations. The results show the effectiveness of DSA coupled with QoS provisioning, in supporting QoS-demanding consumer-oriented network applications in TV bands. This outcome is significant as FCC has recently approved UHF bands for unlicensed operations in the second Report and Order in the USA, and various DSA-based personal/portable CR systems are being actively considered by the consumer wireless industry.**

***Keywords*—QoS provisioning, DSA, cognitive radio**

I. INTRODUCTION

Dynamic Spectrum Access (DSA) [2][3] is characterized by opportunistic access to licensed channels with no or very limited (hence acceptable) interference to the authorized devices. Thus, DSA improves network performance by minimizing spectrum-usage inefficiency. Advances in Cognitive Radio (CR) technologies [1] have made DSA technically feasible in wireless systems.

The DSA MAC is one of the most important components in providing the DSA functionality. Researchers have proposed several DSA MAC protocols and their associated procedures [5][6][9][10]. The DSA MAC protocols proposed thus far are aimed at improving throughput via opportunistic spectrum utilization. Nevertheless, the high throughput gained from DSA does not necessarily translate into better perceived application QoS. This is due to the higher degree of wireless resource fluctuations possibly experienced in DSA.

On the other hand, modern consumer wireless networks are being increasingly dominated by different types of multimedia traffic that require stricter QoS guarantees (in terms of sustainable data-rates, delay bounds, and so on) as opposed to simple best-effort service. Examples of such applications include multimedia streaming and video-based telephony.

Consequently, whether and how (in terms of complexity and cost) a DSA MAC protocol and the overall CR system can provide adequate QoS support, is a major test for the viability and success of consumer-oriented DSA-based wireless systems. In this paper, we attempt to characterize the key characteristics needed for a CR communication system to meet application-level QoS requirements. In particular, we consider a CR system which must support high quality multimedia streaming over UHF frequency channels.

The main contributions of this paper are two-fold. We first present the important QoS provisioning features in the context of DSA MAC design. To provide a concrete illustration of incorporating such QoS features, we derive the *QoS-Provisioned DSA Protocol (QPDP)* from the WiMedia MAC [4]. QPDP is designed for indoor CR systems operating in UHF channels. QPDP can serve as a model for QoS provisioning in design of other DSA protocols. Second, we provide the proof-of-concept of our ideas inherent in QPDP via simulations—illustrating full quality HDTV streaming in home environments. The simulation results show the effectiveness of QPDP in QoS provisioning, and reveals the impact of key QoS-impacting design components like sensing schedule and channel switching mechanism.

The paper is organized as follows. Section II provides the motivation for this work while Section III discusses the prior related efforts. Section IV presents the system and QoS model. Section V briefly illustrates the QoS-centric cognitive MAC, namely QPDP. Details on QPDP's key QoS provisioning schemes are provided in Sections VI and VII, while we discuss the evaluation results in Section VIII. Section IX concludes the paper.

II. MOTIVATION

This work is motivated by both commercial necessity as well as technical challenges.

From a commercial point of view, QoS support in CR systems is critical to ensure its success in consumer wireless market. UHF spectrum block has already been approved for unlicensed operations by the FCC [11] in the second Report

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and Order. This ruling allows unlicensed operation in TV bands for both fixed and personal/portable devices with DSA capabilities.

From a technical perspective, the effort is motivated by the challenges of designing QoS-provisioning schemes in DSA. Disruptions from DSA operations can make deployment of QoS-sensitive applications questionable. For example, to maintain the viability of DSA (with incumbent protection), the CR system must sense the channels frequently. This involves quiet periods, which suspends the ongoing communication traffic and may lead to violation of QoS requirements. Further, supporting high throughput data-traffic in narrow TV bands (6 MHz) is a significant challenge in itself. This problem is further exacerbated by stringent QoS demands of new-generation multimedia data-traffic in indoor networks. For example, HDTV streams require 19.3 Mbps bandwidth with PER less than two MPEG transport stream packets per second, or 376 bytes/sec.

III. RELATED WORK

IEEE 802.22 draft [7] is the first world-wide standard for cognitive radio networks. The 802.22 MAC operates in a point-to-multipoint networking model. Though 802.22 MAC provides certain mechanisms to support QoS in infrastructure-based networks, they are unsuitable for decentralized networks.

There also have been several other proposals for ad-hoc MAC protocols [9][10][12][13] in literature for generic CR networks. Notions like control channel and backup channel are used in many of these proposals.

In this paper, a UHF-based distributed CR system is considered, where the behavior of incumbents is relatively stable. There have been some studies done recently in similar operating environments (where the behavior of incumbents is stable). In [14], KNOWS prototype was presented, which dynamically accesses TV broadcast bands in a distributed personal environment. However, the KNOWS prototype uses separate sensing and data interfaces. It also assumes that a control channel in ISM band is always available for handshake and coordination. Additionally, a GPS receiver is incorporated in the hardware board for performing time synchronization.

The aforementioned prior efforts do not consider QoS provisioning as a primary design objective for the DSA protocol, which is incorporated in our design and investigation through QPDP. The objective of this case-study is to evaluate the feasibility of DSA-based QoS-sensitive multimedia communication over UHF channels with single-radio CR hardware.

IV. SYSTEM & QOS MODEL

We consider a secondary device which is equipped with only one CR, ensuring its simplicity and cost-effectiveness. The CR system operates in 512– 698 MHz frequency range, or UHF channels 21-51, excluding channel 37. A secondary device operates on one 6-MHz UHF channel at any given time.

The incumbents on UHF band are TV broadcasting services and wireless microphones. The secondary CR systems must meet a set of performance parameters to protect incumbents according to regulatory requirements. It must be able to detect the presence of an incumbent signal stronger than the Incumbent Detection Threshold (IDT) within the Channel Detection Time (CDT).

Furthermore, the Channel Move Time (CMT) defines the amount of time within which the secondary system has to vacate the channel once an incumbent is detected, and the Channel Closing Transmission Time (CCTT) limits the amount of transmission time allowed to the secondary system once an incumbent is detected. Actual values for these parameters depend on regulatory directives and system design. Following the guidelines defined in [8], we assume CDT = 10s, CMT = 2s, CCTT = 200ms, IDT= -114dBm (for wireless microphones and TV broadcasting).

As mentioned earlier, we consider QoS provisioning for high quality multimedia traffic (e.g., HDTV streaming) in this work. To support such application traffic, the goal is to provide *better-than-best-effort QoS* [16]. The underlying observation behind following this approach is that multimedia applications, despite being QoS-sensitive, are flexible and adaptive to short-term network variations and degradations. Hence, they can perform optimally with better-than-best-effort QoS provisioning. Note that guaranteed real-time QoS is extremely difficult to provide in wireless communications [15][16], and even more so in DSA (as discussed in Section II).

V. QPDP OVERVIEW

The design philosophy behind QPDP is not to develop a completely new DSA MAC protocol, but rather to adapt a suitable MAC protocol to easily provide the functionality of DSA with QoS provisioning in order to facilitate our case-study. We chose WiMedia MAC [4] as our base MAC protocol platform to design QPDP. Apart from being a popular WPAN MAC standard, WiMedia already contains rudimentary QoS support, including aspects of mobility and coexistence support.

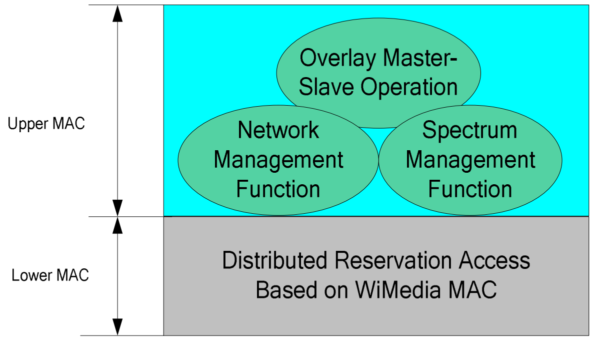

Figure 1. QPDP MAC architecture

As shown in Fig. 1, QPDP is logically divided into *lower MAC* and *upper MAC* functionalities. The *lower MAC* is a modified version of WiMedia MAC, and is characterized by distributed reservation-based channel access. The *lower MAC* is mostly responsible for routine MAC operations, such as superframe synchronization and frame processing. The *upper MAC* coordinates high level on-demand management of the channels as well as the network for incumbent protection and fair secondary device coexistence.

To make network management consistent and simple, we propose an overlay *Master-Slave* operation in QPDP. The basic idea is to designate one of the secondary devices as a master--either through user configuration, using any existing mechanism for selecting a leader node, or any other external technique. The master device assists network entry, sensing, channel classification and channel switching.

Note that the overlay Master-Slave operation over the distributed lower MAC in QPDP is different from how a purely centralized MAC operates. In the pure centralized MAC, the master acts as the only device coordinating the beaconing, synchronization, and channel reservation functions. If the master device fails, the whole network fails, suffering the single-point-of-failure problem. In contrast, the overlay Master-Slave operation allows devices to maintain peer-to-peer communications even when the master device is temporarily down, since the lower MAC is coordinated in a distributed fashion. Such a loosely coupled design allows sufficient time for the master device to recover, or to be re-established gracefully. Details are discussed in the following sections.

VI. DISTRIBUTED RESERVATION AND CHANNEL ACCESS

This section presents basic QPDP details and key *lower MAC* mechanisms in QPDP with respect to QoS provisioning.

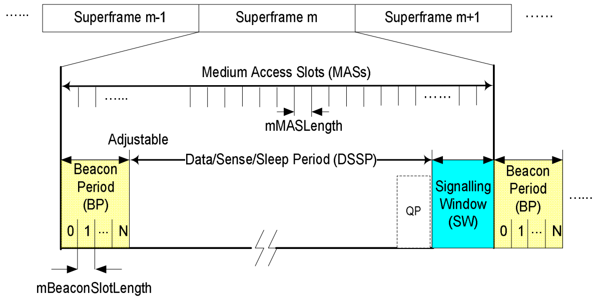

Figure 2. QPDP MAC structure

A. *QPDP MAC structure and distributed beaconing*

As shown in Fig. 2, the MAC structure (adapted from WiMedia MAC) follows a time-recurring superframe structure. Each superframe consists of a Beacon Period (BP), a Data/Sense/Sleep Period (DSSP), and a Signaling Window (SW). The SW and the BP are used for broadcast and exchange of control and management information, and their sizes (in units of time slots) are dynamically adjustable.

Each superframe consists of 256 equal-interval Medium Access Slots (MASs). A MAS represents a unit of time that can be accessed by either reservation or contention, or utilized for sensing Quiet Period (or QP - needed for incumbent detection). The beginning of a superframe is the BP, and is used to transmit (and receive) special control packets called beacons. During BP, each device in the network transmits a beacon in its Beacon Slot. The number of beacon slots, i.e., BP length, is adjustable according to the number of devices in the network. Beacons (consisting of Information Elements or IEs) are used for coordination among member devices as well as for negotiating and informing DSA decisions.

Additionally, there are a few specialized MASs at the end of superframe for exchanging control and management information, such as network entry, sensing report and channel request. This window is called the Signaling Window (SW). In contrast to the BP, the SW is shared by all devices opportunistically, thus improving channel efficiency for signaling.

B. *Distributed channel reservation*

Reserving the medium for a particular communication stream is a standard technique used in networking (e.g., circuit-switched networks) to ensure continuous QoS guarantees in both wired and wireless domains.

In QPDP MAC, channel reservation/release is achieved through the use of beacons. By default, all the MASs in a DSSP are available for contention-based access by all the devices in the DSA network. However, they can also be reserved for sole transmission by any participating device. Each device includes Reservation Availability IE in its beacon, indicating the device's view about channel reservation status of the MASs in the upcoming superframe. A special IE called the Reservation Request IE is included by a device in order to reserve a specific range of MASs in the superframe. On receiving a beacon containing a reservation request, other devices update their MAS availability map, and their own transmissions during the reserved MASs are disallowed. Reservation Relinquish IE can be included by a device to request the release of certain reserved MASs by another device. This ensures fairness in the reservation mechanism. Reservation is secured in a FCFS fashion, even when there is a conflict in the process during the same superframe.

VII. NETWORK AND SPECTRUM MANAGEMENT

In this section, we discuss important *upper MAC* functionalities of QPDP, in conjunction with the overlay Master-Slave approach mentioned earlier.

A. *Network entry and association*

Automatic device discovery and association is an essential component of providing complete QoS provisioning support for real-world consumer wireless systems. In QPDP, when the master powers up, it automatically performs an initial channel scan of all channels. After the initial scan, the master chooses one of the clean channels as the operating channel, and other clean channels as backup channels. The master then starts beaconing on the selected operating channel.

When a slave (i.e., a device not configured as the master device) powers up, it also automatically performs an initial channel scan. In this process, the slave should discover the master device through beacons if the master powered up earlier. In case the master is not found, the slave device can either start another round of channel scan or wait for user command to resume the bootstrapping process.

After locating the master device, the slave device starts association with the master device by sending a join request message in the SW of a superframe. On receiving the join request message, the master device starts the association process. A new device may be denied by the master either due to authentication failure or traffic congestion. This provides network admission control—an important aspect of QoS provisioning.

B. *Spectrum sensing*

Spectrum sensing consists of two major components: the PHY sensing algorithm and the associated MAC sensing schedule (or QP schedule).

There are two basic types of sensing schemes—fine sensing and fast sensing (or simple energy detection). Fine sensing is mandatory and should be able to detect incumbent signal as low as -114dBm [8]. Since fine sensing requires large QP duration, it cannot be scheduled by MAC frequently.

Energy detection is optional, and can detect incumbents when incumbent signal is higher than -85dBm, at which level secondary devices are subject to severe service interruption. Due to a much shorter detection time, energy detection can be scheduled more often, thus reducing the service interruption when incumbent signal is strong. As suggested in our evaluation results (Section VIII), a combination of fine sensing and energy detection schemes performs much better in terms of QoS support.

There are two types of sensing tasks: detecting incumbents in the current operating channel, and monitoring backup channels. The former, also called in-service monitoring, requires highly reliable sensing, and thus regular QPs with fine sensing are needed. Further, to ensure effective in-service monitoring, all secondary devices are required to participate in each collaborative spectrum sensing. Backup channel scans, on the other hand, can be scheduled less frequently and are accomplished individually or with few secondary devices. In QPDP, the master can schedule backup channel scan for slave secondary devices, according to their traffic demands, so that service interruptions are minimized.

QP requires all traffic to be suspended, causing interruptions to QoS-sensitive applications. Therefore, in a multimedia system, long QPs should be avoided. For this, we propose scheduling of multiple short QPs throughout CDT, with the QP scheduling frequency confirming to regulatory requirements. To ensure that each device follows the same QP schedule, the master and other nodes advertise the QP schedule within their beacons. In addition to regular QPs, on-demand QPs can always be scheduled whenever some abnormal channel behavior is observed.

C. *Channel switching*

If incumbent signal above the IDT threshold is found on the operating channel, the secondary network must switch to another channel within the CMT, in order to avoid interfering with the incumbent.

The QoS-degradation associated with a channel-switch can be significantly reduced if the next channel to be used is already known to the communicating SU devices. Usage of backup channels (BCs) prevents reactive sensing or probing in order to search for a new channel. Further, since BCs are negotiated between devices prior to an actual channel switch, it minimizes the coordination control overhead involved at the beginning of utilizing a new channel. The master is responsible for designating backup channels, ordered by channel utilization metric. The master uses its own spectrum sensing results as well as spectrum sensing reports collected from other nodes to build the ordered list of BCs.

After moving to the new channel and re-synchronization with the master device, all devices continue to keep the same channel reservation schedule for beaconing and data transmission, as used in the previous channel. We call this *channel imaging*. The benefit of channel imaging is to resume transmission as fast as possible by avoiding the time-consuming channel reservation re-negotiation. As a result, any QoS violation due to channel-switching is further minimized.

D. *Other mechanisms and remarks*

QPDP *upper MAC* incorporates several additional mechanisms and optimizations for meeting stringent QoS demands. For instance, two closely located secondary networks may choose to merge (by merging superframes) in order to use the medium fairly and eliminate mutual interference. Also, QPDP includes packet aggregation for small size frames leading to improve channel-usage efficiency. This simple optimization is crucial to supporting high data-rate multimedia traffic that are usually characterized by smaller size frames (<200 bytes) on narrow-band channels. We omit discussion on other QoS provisioning techniques due to lack of space.

VIII. EVALUTION

In this section, we analyze the performance of QPDP using simulations. We are particularly interested in two aspects of QPDP w.r.t. QoS provisioning: 1) MAC efficiency in supporting high data-rate, low delay, and small error-rate in a typical indoor environment; 2) MAC robustness in response to incumbent disruptions.

We simulate QPDP in a home network setting using the OPNET Modeler [17]. We use HDTV streaming for evaluation because it requires extremely high-level of QoS, making it close to the worst-case usage scenario for a consumer network QoS provisioning model. HDTV requires high data-rate (19.3Mbps), small end-to-end delay (less than 100ms), small delay variation (less than 50ms), and very low bit error rate (less than 5%).

A. *Simulation setup*

The setup consists of a single-house home network (range of up to 30-40m). The channel is modeled with Exponential Rayleigh multipath fading. The transmission power is 30dBm and path loss factor is set to 3.

The PHY of the CR system is based on OFDM with a total 128 FFT size. The subcarrier space is 50 kHz. The guard interval is set to 1/16 of and therefore, the OFDM symbol duration is 21.25us. In other words, it allows the system to mitigate inter symbol interference (ISI) when delay spread is less than 100ns, typical in home environments. The modulation for data payload is 64-QAM at 5/6, while default modulation used (beacons and headers) is 16-QAM at 1/2. The size of preamble is 4 symbols and PLCP is 1 symbol long.

Each MAC superframe consists of 256 MASs, each of 432 microsecond duration. The maximum BP length is designated as 5. The channel-switch repetition (N) is 3. The sender and receiver nodes power up within 1 second of the start of the simulation, unless mentioned otherwise. HDTV sender and receiver are designated as the master and the slave node respectively. They automatically associate with each other to form the DSA network, through the QPDP mechanisms (described in Section VII.A). HDTV streaming is started once the network is formed.

Also, we test 6 fine sensing (FS-1 to FS-6) schemes, each with same long-term average sensing overhead, but with different schedules. FS-1 involves QP of 5ms duration scheduled every 3 superframes, FS-2 has QP of 10ms duration scheduled every 6 superframes and so on.

B. Simulation results

While the incumbent services are afforded all the protection required by the FCC, the QoS of secondary application may be impacted, the severity of which depends upon the sensing schedule. Fig. 3 shows the throughput performance in presence of a low power incumbent. We observe that the sensing mechanism does detect the incumbent by aggregating multiple sensing samples, and the devices switch to a BC. The incumbent signal power received (or *iRxPr*) is found to be -100.25dbm. It can be noticed that the incumbent transmission power is low enough to allow secondary HDTV communication to continue without introducing any perceivable degradation to QoS level, as seen from throughput values. The observation is consistent through various fine sensing schemes, as seen from the graph.

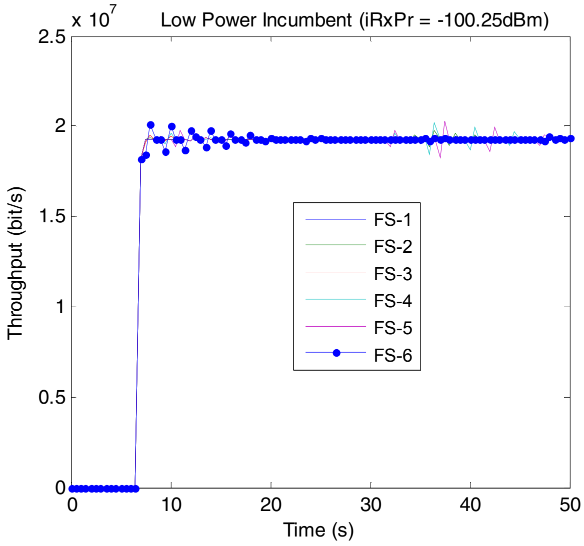

Figure 3. Throughput vs. impact of QP schedule - low power incumbent

Fig. 4 shows the impact of a high power incumbent on throughput performance. Since the incumbent now transmits at high power, it affects the reception of the HDTV stream resulting in a higher percentage of packets received in error. Thus, the required QoS level for throughput cannot be maintained and the throughput drops as seen in the graph.

Fig. 4 also shows the relative degree of impact on application throughput depending on the delay in incumbent detection of various sensing schedules. If the QP is frequent (5ms every 3 superframes), the impact on application QoS is much less than the case when sensing is less frequent (e.g., 30ms every 18 superframes). Note that in all the sensing schemes, the average sensing rate (hence average sensing overhead) is same. Thus, difference in the sensing schedule can influence how quickly QoS-degradation can be detected.

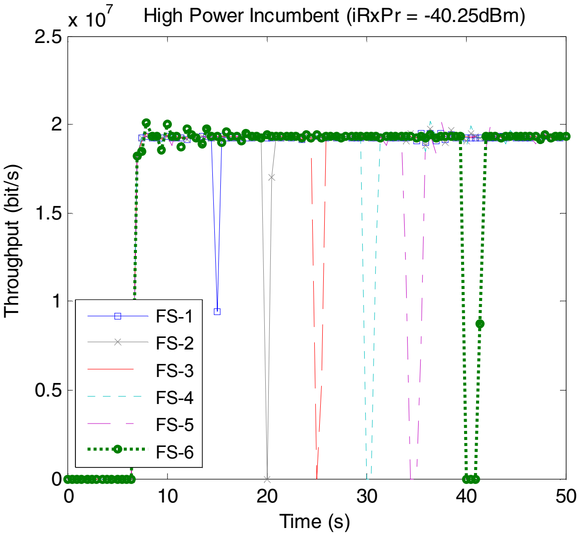

Figure 4. Throughput vs. impact of QP schedule - high power incumbent

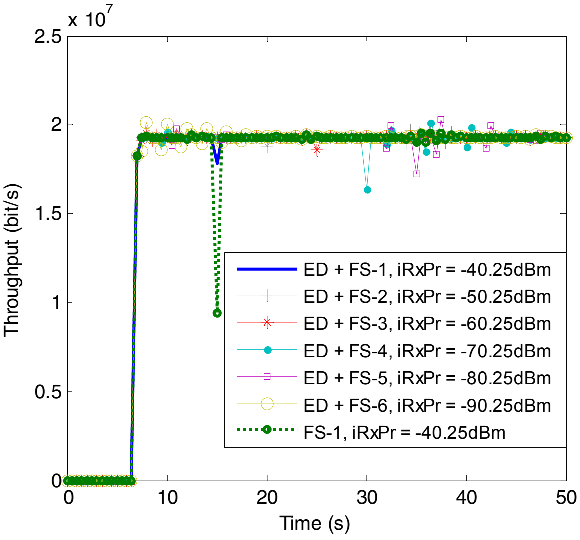

Figure 5. Combined fast sensing (energy detection) and fine sensing

For previous results (Figs. 3 and 4), only fine sensing was used. Fig. 5 shows the throughput performance when both fast sensing and fine sensing are incorporated. As received incumbent signal increases from -100.25dBm to -40.25dBm, the throughput does not drop significantly as compared to the case when only fine sensing is applied. Note that the energy detection is scheduled in every superframe (for 1 MAS).

Fig. 6 shows the delay performance in presence of a high power incumbent. As expected, the sensing schemes significantly affect the delay experienced. The primary reason for this is the suspension of transmission during QPs.

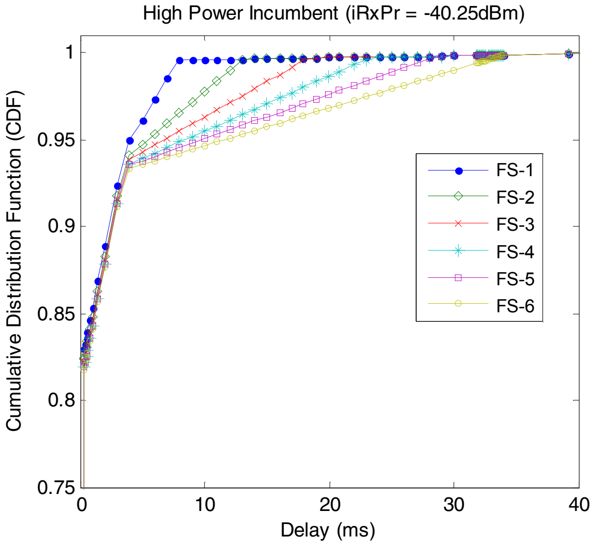

Figure 6. Delay vs. impact of QP schedule

Many other results have been omitted due to lack of space. We briefly mention few important observations. In all of the simulation scenarios, quick incumbent detection and fast channel switches play a significant role in sustaining the required application QoS levels. Moreover, channel imaging was found to further reduces the impact of disruptions to the HDTV application when transitioning to a new channel. The narrow spectrum-width (6 MHz) of TV channels necessitates designing extremely efficient DSA protocols in order to sustain stringent multimedia QoS. The techniques of channel reservation and frame aggregation play a key role in ensuring protocol efficiency. The resultant spectrum efficiency, represented by goodput divided by signal bandwidth, was found to be as high as 3.7 bit/s/Hz.

IX. CONCLUSION AND FUTURE WORK

In this paper, we have provided a case study of DSA QoS provisioning through QoS-Provisioned DSA protocol (QPDP) for multimedia streaming in indoor home/office networks. QPDP incorporates both fine-grained and coarse-grained QoS provisioning mechanisms. Fine-grained (packet-level) QoS support is provided primarily via slot-based channel reservation. Coarse-grained QoS support ensures QoS at stream (or connection) level and is provided through intelligent network and spectrum management. QPDP supports stringent QoS while ensuring efficient and distributed communication through the proposed overlay Master-Slave design. QPDP evaluation is done by simulating HDTV streaming in a single home network. The simulation results show the effectiveness of QPDP in DSA QoS provisioning and reveal the impact of key design components in minimizing incumbent disruption. It is shown that a high level of protocol efficiency, as achieved by QPDP through various intelligent optimizations, is critical to supporting QoS in narrow-band TV channels. Our next step is to study the behavior of QPDP in multi-dwelling unit environments such as an apartment complex. Open research topics for future work include adjacent channel operation, channel bonding and power control in conjunction with DSA.

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