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Analysis of QoS Provisioning in Cognitive Radio Networks: A Case Study

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Abstract Dynamic Spectrum Access (DSA) is a promising solution to the problem of spectrum inefficiency. Based on Cognitive Radio (CR) technology, DSA allows a CR device to opportunistically access unused or less crowded spectrum while ensuring protection for the incumbents. Though DSA shows great potential to enhance network performance, its adverse side-effects on application 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 must face additional interference and interruption from incumbents that have to be protected. In this paper, we present a case study of key DSA protocol characteristics necessary for QoS provisioning. Specifically, we consider a personal/portable 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 (called QPDP) through extensive simulations. The results show the effectiveness of the proposed DSA QoS provisioning approach in sustaining high levels of QoS, e.g., supporting HDTV streaming in TV bands. This outcome is significant as FCC has recently approved UHF bands for unlicensed operations in the USA, and various DSA-based CR systems are being actively designed by the wireless industry. The techniques outlined in this work can be generalized to be applicable to generic DSA design in various spectrum bands.

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1 Introduction

Dynamic Spectrum Access (DSA) [1] has the potential to effectively address the problem of spectrum usage inefficiency, as it allows opportunistic access to licensed channels with very limited interference to the authorized devices on such channels. Thus, DSA can result in significantly improved network and end-user performance. Advances in Cognitive Radio (CR) and Software Defined Radio (SDR) technologies [16,19] have made DSA technically feasible in wireless systems.

Regulatory bodies like FCC are actively involved in formalizing guidelines and rules for unlicensed wireless operations [7]. Considering the soon-to-come switch over to entirely digital TV transmission standard in 2009, FCC has recently approved the UHF spectrum region for DSA [8].

Many researchers have proposed MAC/PHY protocols for DSA [2,4,10,11], and its component mechanisms, like spectrum sensing [5,9,14,15]. The DSA protocols proposed thus far are focused on improving throughput via opportunistic spectrum utilization. Nevertheless, the high throughput gained from DSA does not translate into better perceived QoS at user level. This is primarily due to the fact that DSA is inherently disruptive in nature. It causes high degree of wireless resource fluctuations and traffic interruptions.

In designing DSA protocols, it is important to consider the evolution of consumer networking applications, which are becoming 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, video-based telephony, real-time traffic mapping and updates, etc.

Consequently, whether and how (in terms of complexity and cost) a DSA protocol and the overall CR system[1] can provide adequate QoS support is a major test for the viability and success of DSA, especially in consumer-oriented wireless systems. In this paper, we attempt to characterize the key characteristics needed for a CR communication system to meet its QoS requirements. Specifically, we consider a personal/portable CR system supporting high quality multimedia streaming over UHF frequency channels.

The main contributions of this paper are two-fold.

1. We first present the fundamental MAC features for supporting stringent application QoS requirements in DSA through the design of *QoS-Provisioned DSA Protocol (QPDP)*. QPDP is designed for indoor CR systems operating in UHF channels. QPDP can serve as a model for QoS provisioning of any DSA MAC.
2. Second, we provide the proof-of-concept of our ideas inherent in QPDP via simulation, 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 design components like sensing schedule and channel switching mechanism in minimizing QoS impacts from incumbent disruption.

[1] CR system refers to the complete set of technologies, including MAC/PHY protocols, involved in realizing the CR function—DSA in this case.

The paper is organized as follows. Section 2 provides the motivation for this work while Sect. 3 presents the prior related efforts. Section 4 describes the system model, while Sect. 5 provides the type of QoS considered. Section 6 briefly illustrates our proposed QoS-centric cognitive MAC, namely QPDP. Details on QPDP's key QoS provisioning schemes are provided in Sects. 7 and 8, while we discuss the evaluation results in Sect. 9. Section 10 concludes the paper.

2 Motivation

This work is motivated by commercial necessities, 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. From a technical perspective, the effort is motivated by the challenges of designing QoS-provisioning schemes in DSA.

2.1 Design of QoS Provisioning Schemes

In general, it is difficult to provide reliable QoS in wireless networks due to high degree of variability in wireless medium. However, it is even more challenging for a CR system to provide QoS due to the additional interference from incumbents as well as the side-effects introduced by the underlying DSA protocol. Disruptions from fundamental operations involved in DSA protocols can make deployment of QoS-sensitive applications infeasible. For example, to maintain viability of DSA (including incumbent protection), the CR system must sense the channels frequently. This involves quiet periods, which disrupt the ongoing communication traffic and may lead to violation of QoS requirements.

It should be noted that DSA, by virtue of its ability to dynamically select and utilize better channels has a key advantage in providing sufficient resources for sustainable QoS in wireless systems. However, DSA operations must be properly scheduled and managed in conjunction with suitable safeguard mechanisms in order to provide reliable QoS. QPDP incorporates features to achieve this very goal (see Sects. 6, 7, 8).

2.2 Realizing QoS in a CR System

In addition to proposing generic design schemes, this work also aims to investigate the practical viability of DSA QoS provisioning in realistic deployment environments. For this, we consider indoor wireless networks operating in UHF (TV) spectrum band. UHF channels are characterized by incumbents with stable and relatively long-term transmissions, which is ideal for deployment of DSA. Moreover, TV bands have very good propagation characteristics, thus making it ideal for wireless home/office setting. Also, it has been the first and only spectrum block so far to be approved for unlicensed operations by FCC [8].

However, TV channels have very narrow spectrum-width—only 6 MHz. Thus, supporting high bandwidth data-traffic in narrow TV bands is a significant challenge in itself. This problem is further exacerbated by increasingly stringent QoS demands of new-generation multimedia data-traffic in indoor networks. For example, full HDTV streams require around 20 Mbps bandwidth with PER less than 188 bytes/s. Such QoS-sensitive multimedia traffic is expected to dominate indoor wireless networks.

Therefore, DSA QoS design must also take a practical and context-oriented view of the specific CR system under consideration. Such a system-oriented QoS provisioning approach will show substantial QoS benefits when deployed. This work illustrates this conclusion through the proposed DSA protocol—QPDP (see Sect. 6) and its evaluation (see Sect. 9).

3 Related Work Television White Space (TVWS)

IEEE 802.22 [11] draft is the first world-wide standard for cognitive radio networks. 802.22 MAC operates in a point-to-multipoint networking model, which is comparatively simpler than the decentralized networking scenarios. Though 802.22 MAC provides a few mechanisms to support QoS in infrastructure-based networks, they are unsuitable for peer-to-peer or decentralized networks. Different from the IEEE 802.22 standard which focuses primarily on high power fixed applications, Ecma 392 [6] mainly targets personal and portable wireless devices. The Ecma 392 standard aims to serve the robust delivery of high definition video inside home and across multiple walls, among a broad range of applications. The challenges for enabling whole-home High Definition Television (HDTV) video streaming using Television White Space (TVWS) can be three-fold: (a) to access TVWS, incumbent services using these bands must be robustly detected and protected; (b) to efficiently fit an HDTV stream within a single television channel, QoS provisioning with respect to limited bandwidth must be supported; and (c) to ensure co-located or neighboring networks co-exist, self-coexistence and interference mitigation in personal/portable environments must be designed-in. This main purpose of this paper is to investigate QoS support in a decentralized networking model similar to Ecma 392.

There also have been several research proposals for ad-hoc MAC protocols [2–4,10] for CR networks. Most of them target operating environments in which incumbent presence is fast changing (based on transmission duration), and the time needed to sense spectrum is small compared to the transmission duration. Further, the notion of common control channel to is used to simplify design. In [20], backup channels were utilized in order to minimize disruptions when an incumbent is detected. However, sensing-before-transmission is applied for every frame, which is inefficient.

In this paper, the CR system considered is a UHF-based distributed cognitive communication system, 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 [21], 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. Further, it 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 study through QPDP. Moreover, no simplifying assumptions like control channel are used.

4 System Model

We consider a secondary device which is equipped with only one CR for simplicity and cost-effectiveness. The CR system operates in 512–698 MHz frequency range, or UHF channels 21–51, excluding channel 37. Based on channel availability, a secondary device dynamically chooses one 6-MHz UHF channel for its operation.

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) with a success probability greater than or equal to the Probability of Detection (PD), and with probability of false alarm lower than or equal to the maximum Probability of False Alarm (PFA).

Furthermore, the Channel Move Time (CMT) defines the amount of time 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. Following the guidelines defined in FCC's first-rule-and-order for personal/portable devices [7], we assume CDT = 10 s, CMT = 2 s, CCTT = 200 ms, IDT = -107 dBm (for wireless microphones), IDT = -116 dBm (for TV broadcasts), PD = 90% and PFA = 10%. Clearly, these hardware constraints and DSA regulation requirements, together with application QoS demands, impose significant challenges on overall CR system design, especially on the underlying DSA MAC/PHY protocol.

5 QoS Model

As mentioned earlier, we consider QoS provisioning for high quality multimedia traffic (e.g., HDTV streaming) in this work. To support such a QoS-demanding application traffic, the goal is to provide *better-than-best-effort* QoS [12].

Note that *absolute* (or *guaranteed*) real-time QoS is extremely difficult to provide in wireless communications [12,13], and even more so in DSA (as discussed in Sect. 2). Further, multimedia applications, despite being highly QoS-sensitive, are flexible and adaptive to short-term network degradations. Hence, such tolerant and adaptive applications perform optimally with better-than-best-effort QoS provisioning which is relatively simpler to provide.

Still, such QoS support must accept diversity of QoS demands, and also ensure adequate long-term resources (e.g., application bandwidth, delay-bounds) for the most stringent QoS requirements expected in operational settings—HDTV streaming in this case. QPDP design attempts to meet this goal by providing adaptive better-than-best-effort type of QoS through mechanisms like channel reservation and intelligent sensing schedule

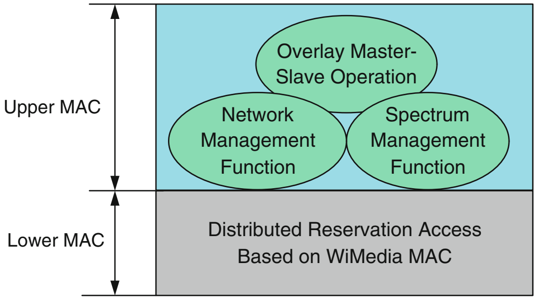
6 QPDP Overview

In this section, we provide a brief insight into the proposed DSA protocol, called the *QoS-Provisioned DSA Protocol (QPDP).*

The design philosophy of QPDP is not to invent a totally new DSA MAC protocol, but rather to adapt an existing MAC protocol to incorporate features in order to provide DSA with adequate QoS support. Such an approach allows us to exploit existing developments and innovations in this area. We choose WiMedia [17] as our base MAC protocol due to its salient features for QoS provisioning, as well as, mobility and coexistence support.

In order to provide adequate QoS support for DSA, protocol enhancements targeting both fine (low-level) and coarse (high-level) granularity communication aspects are necessary. For instance, reservation-based medium access provides QoS support at fine granularity (i.e., at

Fig. 1 QPDP MAC architecture



packet level). On the other hand, network and spectrum management protects the overall connection stream.

As shown in Fig. 1, QPDP is logically divided into *lower MAC* and *upper MAC* functions. The lower MAC is adapted from 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 over a channel. The upper MAC, on the other hand, coordinates high level on-demand management of channels and overall 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 or any other external mechanism. The master device assists network entry, sensing, channel classification and channel switching.

Note that the overlay Master-Slave operation over distributed lower MAC is different from how a purely centralized MAC operates. In a pure centralized MAC, the master acts as the only device performing coordination of beaconing, synchronization, and channel reservation. If the master device fails, the whole network fails, suffering the single-point-of-failure problem. In contrast, the overlay Master-Slave operation will allow 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.

7 Distributed Reservation and Channel Access

We now detail some key lower MAC mechanisms in QPDP with respect to QoS provisioning. Note that many low-level details have been omitted as they are not the primary focus of this paper.

7.1 MAC Structure and Distributed Beaconing

As shown in Fig. 2, the MAC structure (adapted from WiMedia MAC) follows a recurring superframe structure, which consists of a Beacon Period (BP), Data/Sense/Sleep Period (DSSP), and a Signaling Window (SW). The signaling window and the beacon period are used for broadcast or 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) numbered 0–255. A MAS represents a unit of time that can be accessed by either reservation or

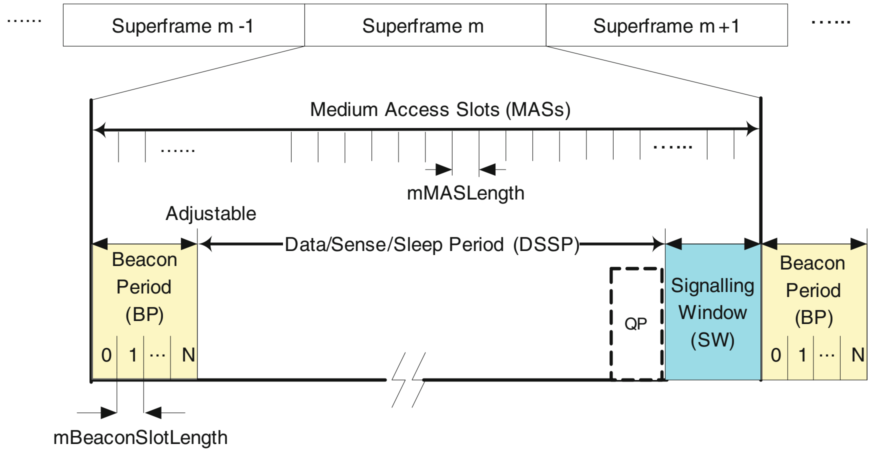


Fig. 2 QPDP MAC superframe structure

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 are used for coordination among member devices as well as for negotiating and informing DSA decisions.

Apart from self-identification data, beacons consist of a variable number of Information Elements (IEs) corresponding to various aspects of MAC operations. For example, an IE requesting reservation of MASs can be included in a device's beacon. Compared with centralized beaconing, distributed beaconing can effectively avoid the hidden terminal problem, which not only causes collisions but also makes DSA spectrum sensing unreliable. Moreover, distributed beaconing allows the overall system to be more reliable and avoid the single point-of-failure problem.

The remaining MASs (those not included in the BP) in a superframe can be used for data transmission, spectrum sensing activities, or remain un-utilized. This portion of a superframe is collectively called as the DSSP. DSSP MASs can be reserved beforehand by any device for data transmission, or be shared among all nodes through contention-based access. Further, certain MASs can be reserved as QPs for spectrum sensing.

Additionally, there are 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). Any device may use the SW to send control/management information on demand. In contrast to the BP, the SW is shared by all devices opportunistically, thus improving channel efficiency for signaling.

7.2 Distributed Channel Reservation

Reserving the medium for a particular communication stream is a standard technique used in networking to ensure QoS guarantees in both wired and wireless scenarios. In contrast to contention-based channel access, channel reservation based access allows a stream to maintain steady bandwidth resource, as well as, ensure low jitter. Moreover, it improves spectrum efficiency, since it avoids the overhead of collisions in contention-based access.

Therefore, the DSA protocol should incorporate low-overhead channel reservation and release mechanisms. Furthermore, the channel reservation/release approach should ensure fairness among contending secondary devices.

In QPDP MAC, channel reservation and release are achieved mainly through the use of beacons. By default, all the MASs in DSSP of a superframe are available for contention-based access by all the devices in the DSA network. However, they can also be reserved for solitary 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 transmission during the reserved MASs is 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 process. Reservation is secured in a FCFS fashion, even when there is a conflict in the process during the same superframe.

8 Network and Spectrum Management

In this section, we discuss efficient network and spectrum management with the overlay Master-Slave approach introduced earlier. We focus on four key aspects: bootstrapping, spectrum sensing, channel switch, and channel sharing between neighboring (or coexisting) networks.

8.1 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. It directly impacts user-perceived QoS, especially in consumer-oriented home/office networks. Network entry and association is not straightforward in case of distributed DSA since no default channel is available.

In QPDP, this is accomplished as follows. When the master powers up, it automatically performs an initial channel scan from channel 21 to 51 (excluding 37). On each channel, the master senses for at least one superframe duration to look for QPDP beacons. After the initial scan, the master selects one of the clean (free/only SU-occupied) channels as the operating channel, and other clean channels as backup channels. The master then starts beaconing on the selected channel.

When a slave 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 choose to start another round of channel scan until it finds the master. After locating the master device, the slave device starts association with the master device by sending a special join request message in the SW of a superframe. On receiving the request message, the master device can start the authentication process. After authentication, the master device replies indicating whether the new device has been accepted or denied. A new device may be denied either due to authentication failure or traffic congestion. This provides a degree of network admission control. If the new device is accepted, a beacon slot will be allocated to the new device for its beaconing.

As part of the association process, the slave device also reports the channel scan results to the master, especially the channel status of the current operating channel and the backup channels. The master then resolves discrepancies in sensing information, if any; and both the master as well as the associated slave devices can select the best operating channel (in terms of channel quality), as well as, the list of best available backup channels.

8.2 Spectrum Sensing

Spectrum sensing consists of two major components: the PHY sensing algorithm and the MAC sensing schedule (or QP schedule). The selection of a spectrum-sensing algorithm is critical in ensuring reliable protection for incumbents. The algorithm depends on the type of incumbent signals to be detected. In UHF band, the typical incumbent signals are TV broadcasting and wireless microphones.

There are two basic types of sensing schemes, fine sensing and fast sensing (or simple energy detection). Fine sensing is mandatory (from FCC) and should be able to detect incumbent signal as low as -116 dBm. An example of fine sensing algorithm is the FFT-based algorithm proposed in [5], which is also used in our evaluation. Since fine sensing requires large QP duration, it cannot be scheduled frequently.

Energy detection (fast sensing) is optional, and can detect incumbents when incumbent signal is higher than -85 dBm, 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, a combined fine sensing and energy detection scheme performs much better in terms of service recovery.

As mentioned earlier, QP requires all traffic to be suspended, causing interruptions to QoS-sensitive applications. Therefore, in a multimedia CR system, long QPs should be avoided. For this, we propose scheduling of multiple short QPs throughout CDT. Assume that QPs are scheduled at a periodic interval (say QPI) with each sensing lasting for certain minimum duration (say QPD). Note that QPD value depends on the underlying sensing algorithm. Let T be the sensing time (which also depends on the sensing algorithm) needed to detect incumbent at IDT with required PD and PFA. Then, as long as $(QPD/QPI) \cdot CDT \geq T$, the regulatory requirement is met. QPDP schedules QPs once every M superframes by putting the QP right before the SW. To ensure that each device follows the same QP schedule, the master and other nodes advertise the QP schedule within their beacons. Further, nodes joining the network could obtain the QP schedule from the master as part of the association procedure.

In addition to regular QPs, on-demand QPs can always be scheduled whenever some abnormal behavior is observed. For example, if strong interference or sudden channel quality drop is observed, a device can request to schedule QP for the detection of incumbents or other interfering sources.

8.3 Channel Switching

If incumbent signal above the IDT threshold is confirmed on the operating channel, the secondary network must switch to another channel (within the CMT), in order to avoid interfering with the incumbent. Moreover, a network may also decide to move to another channel if a hidden neighbor network is found (network merge, to be discussed later, is another option).

The interruption overhead (and hence 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. Thus, BCs can play an important role in maintaining the desired QoS level during DSA operations. The master is responsible for designating backup channels, ordered by certain metric (e.g., channel utilization).

Once an incumbent is detected, the master should broadcast a channel-switch-command (CH-SWITCH) in its beacons in the next N superframes, indicating the time to move to the first pre-negotiated backup channel. It is also possible, however, that the incumbent signal power level is so high that no beacons can be received. Therefore, a timeout mechanism must be implemented at the nodes to deal with such a situation. For instance, once a slave device cannot receive the master's beacon for N consecutive superframes, it would automatically start a channel-switching procedure, in order to discover the master, starting with the BC.

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, transmission suspension (or QoS violations) due to channel switching process can be reduced.

8.4 Channel Sharing

Two secondary networks may be closely located, or come into range due to mobility of the constituent nodes. A device discovers an alien network by detecting alien beacons which may be received in periods other than BP. It is the responsibility of the master to decide whether to share channel with the alien network or to switch to another channel. The decision is based on available bandwidth.

If the two networks negotiate and decide to merge, the lower MAC then figures out how to share the channel. One approach is to share a channel as shown in case 1 of Fig. 3, i.e., each network alternates the use of channel for certain duration (static contiguous time block). Although this solution is straightforward, QoS provisioning will be a major issue, especially for delay-sensitive applications. For example, the packet delay variation will increase significantly since no transmission is allowed during the silent periods. QPDP addresses these issues by allowing two networks to merge into the same superframe, as shown in case 2 of Fig. 3. Superframe merge allows two neighboring networks to share channel MASs, thus improving channel efficiency and reducing delay variation. QPDP also merges QPs of the two networks, thus reducing sensing overhead.

Note that two neighboring networks can still choose to function independently. One network can decide to move to another channel or re-start without disrupting the operation of another network.

9 Performance Evaluation

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 rate, low delay, and small error rate in a typical indoor environment; (2) MAC robustness in response to incumbent disruptions.

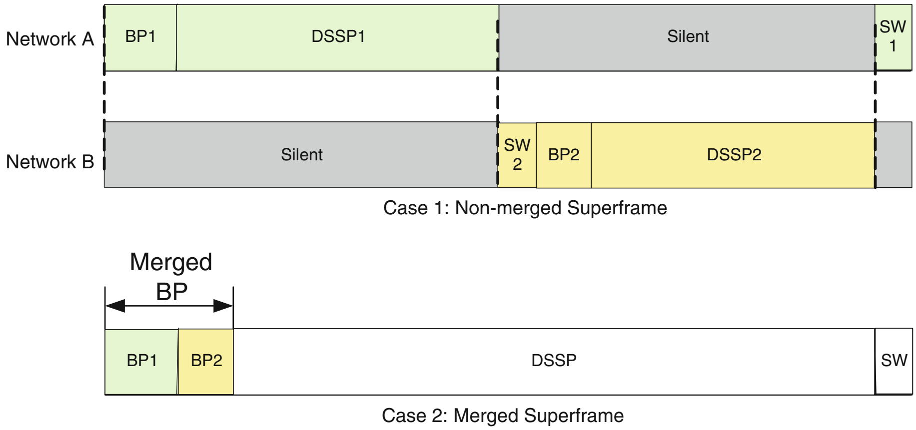


Fig. 3 Possible ways of channel sharing between neighboring secondary networks

We simulate QPDP in a home network setting using the OPNET Modeler [18]. We use HDTV streaming as the application for evaluation because it requires extremely high-level of QoS, making it close to the worst-case usage scenario for any consumer network QoS provisioning model. HDTV requires high data-rate (20 Mbps), small end-to-end delay (less than 100 ms), small jitter (less than 50 ms), and very low bit error rate (less than 5%).

9.1 Evaluation Setup

The setup consists of a single-house home network (range of up to 30–40 m). The channel is modeled with exponential Rayleigh multipath fading. The path loss factor is set to 3. We assume the transmission distance between the HDTV transmitter and the HDTV receiver is 30 m. As introduced in Sect. 4, the system operates in UHF band. Each channel is 6 MHz wide.

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 and therefore, the OFDM symbol duration is 21.25 μs. In other words, it allows the system to mitigate inter symbol interference (ISI) when delay spread is less than 100 ns, typical in home environments.

In the simulation scenarios, 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, discussed earlier in Sect. 8. HDTV streaming is started once the network is formed. The rest of simulation parameters can be found in Tables 1, 2, and 3.

Also, the list of sensing schemes (used to study the impact of sensing schedule) is presented in Table 4. Note that in each of the fine sensing schemes, the long-term average sensing overhead remains the same. Also, energy detection works only when incumbent signal strength is greater than -85 dBm.

9.2 Simulation Results

Figure 4 shows the throughput performance in presence of a low power incumbent. We observe that the sensing mechanism does detect the incumbent by aggregating multiple

Table 1 PHY parameters

Parameter	Value
Transmission power (dBm)	20
Noise power spectrum density (dBm)	−174
Noise figure (dB)	6
Implementation loss (dB)	6
Communication distance (m)	30
Path loss exponent	3
Multipath fading model	Exp. Rayleigh

Table 2 PHY-OFDM parameters

Parameter	Value
Signal bandwidth (MHz)	5.40
FFT size	128
Inter-carrier spacing (KHz)	50
No. of data subcarriers	4
Modulation for data payload	64-QAM, 5/6
Modulation for PLCP header, beacon, control frame	16-QAM, 1/2
RS outer coding t	5
Preamble	4 sym
PLCP (PHY+MAC) header	1 sym
Guard interval	$T_{FFT}/16$
Symbol duration (μs)	21.25

Table 3 MAC parameters

Parameter	Value
Superframe length (μs)	110,592
No. of MAS	256
MAS length (μs)	432
Max. BP length (MAS)	5
Min. sensing time per CDT (ms)	30
Beacon slot length (μs)	432
Channel switch command repetition count	3

sensing samples, and the devices switch to a BC. The incumbent signal power received (*iRxPr*) is found to be at -100.25 dbm. 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 5 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

Table 4 Sensing schemes used

Abbreviation	Comments
FS-1	Fine sensing scheme 1. 5 ms QP scheduled every 3 superframes
FS-2	Fine sensing scheme 2. 10 ms QP scheduled every 6 superframes
FS-3	Fine sensing scheme 3. 15 ms QP scheduled every 9 superframes
FS-4	Fine sensing scheme 4. 20 ms QP scheduled every 12 superframes
FS-5	Fine sensing scheme 5. 25 ms QP scheduled every 15 superframes
FS-6	Fine sensing scheme 6. 30 ms QP scheduled every 18 superframes
ED	Energy detection—if enabled, 1 MAS QP scheduled every superframe.

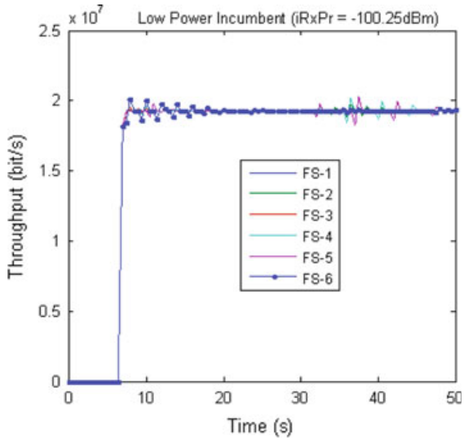


Fig. 4 Throughput in presence of low power incumbent

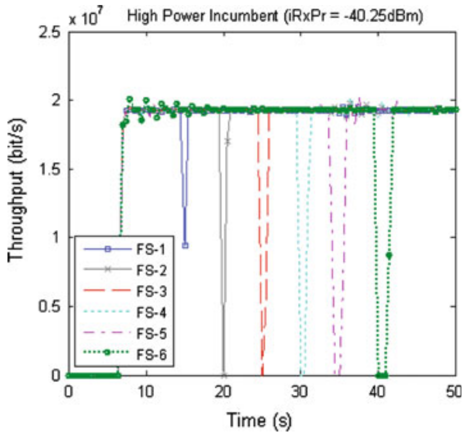


Fig. 5 Throughput when high power incumbent present

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.

The graph in Fig. 5 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 (5 ms every 3 superframes), the impact on application QoS is much less than the case

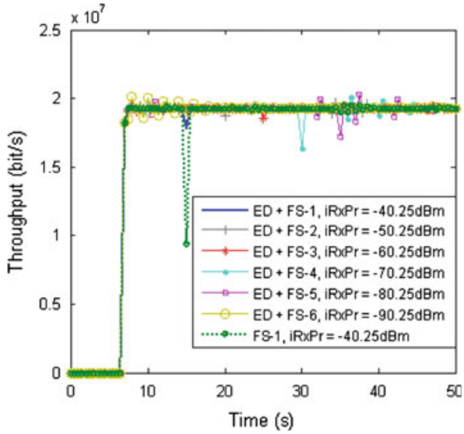


Fig. 6 Combined fast sensing (energy detection) and fine sensing

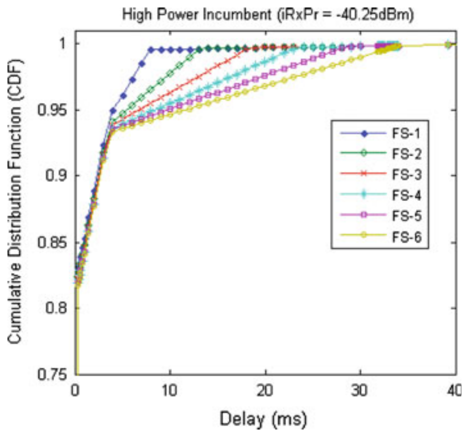


Fig. 7 QP schedule directly impacts delay performance

when sensing is less frequent (e.g., 30 ms every 18 superframes). For sensing scheme FS-6, service recovery could take up to 18 superframes, i.e., 2s. For sensing scheme FS-1, service recovery time (detection time plus channel switching time plus session resume time) is bounded by 3 superframes, about 0.33 s. Note that in both 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 without increasing the overall overhead. Also, we observe that channel imaging mechanism contributes significantly in minimizing the disruption on channel-switches.

Figure 6 shows the throughput performance when both energy detection (fast sensing) and fine sensing are incorporated. As received incumbent signal increases from −100.25 to −40.25 dBm, 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). Thus, incumbent detection time can be limited to one superframe when incumbent signal is strong enough to cause immediate service disruption to the secondary users.

Figure 7 shows the delay performance. As expected, the sensing schemes significantly affect the delay experienced. As shown, more than 5% packets experience significantly higher delay when the sensing QP duration is increased from 5 ms (every 3 superframes) to 30 ms

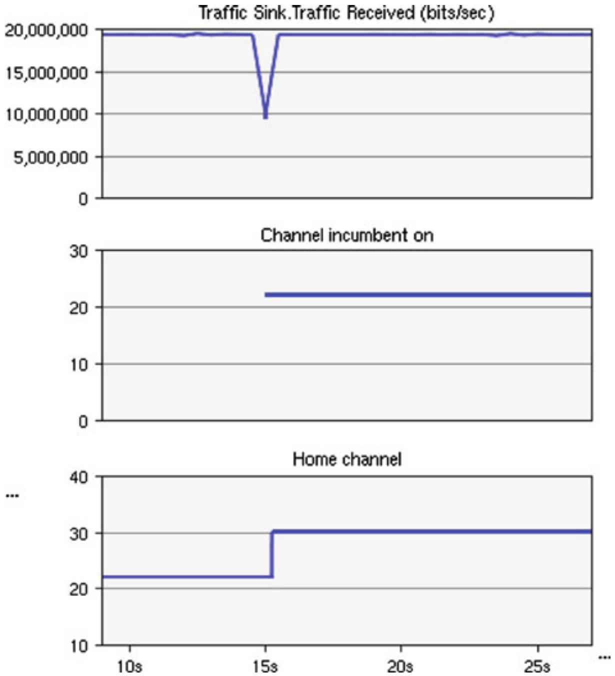


Fig. 8 Fast incumbent detection and avoidance (by channel-switches) by QPDP minimizes traffic loss and sustains QoS

(every 18 superframes). With low power incumbent, similar delay performance is observed. The primary reason for this is the suspension of transmission during QPs.

In all of the above scenarios, quick incumbent detection and fast channel switches (Fig. 8) play a significant role in sustaining the required application QoS levels (e.g., achieving nearly 20 Mbps bandwidth) with minimal disruptions. The top part of the figure shows the throughput variation with time. When the incumbent starts transmitting on the same channel (middle part of the figure), a quick channel-switch is initiated for recovery. Use of BCs and channel imaging contribute to fast recovery from disruption to HDTV traffic.

The narrow spectrum-width (approx. 6 MHz) of TV channels necessitates designing extremely efficient DSA protocols in order to sustain stringent multimedia QoS. The results highlight the efficiency of QPDP in delivering a high-quality HDTV stream consisting of small packets. The techniques of channel reservation and frame aggregation (see Fig. 9) play a key role in ensuring protocol efficiency. The spectrum efficiency, represented by goodput divided by signal bandwidth, can be as high as 3.7 bit/s/Hz.

10 Conclusion and Future Work

In this paper, we have provided a case study of DSA QoS provisioning through the proposed 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

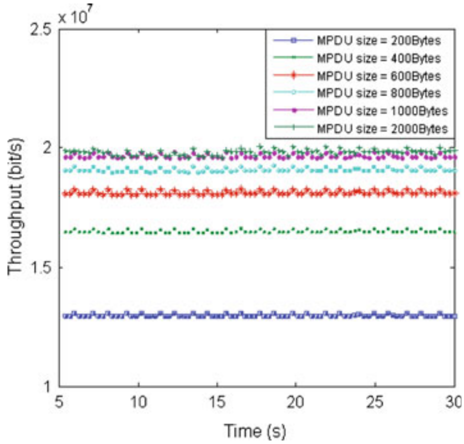


Fig. 9 Frame aggregation is crucial in achieving the high protocol efficiency

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 like sensing schedule in minimizing traffic disruption while ensuring effective incumbent protection. 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 TV bands.

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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