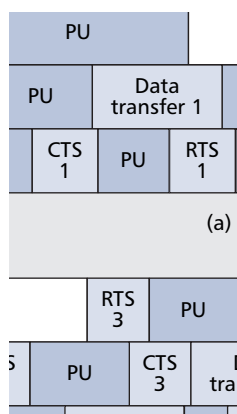


# QUALITY OF SERVICE ASSESSMENT OF OPPORTUNISTIC SPECTRUM ACCESS: A MEDIUM ACCESS CONTROL APPROACH

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Opportunistic Spectrum Access is a promising new spectrum management approach that will allow co-existence of both licensed and opportunistic users in each spectrum band, potentially decreasing the spectrum licensing costs for both classes of users.

## ABSTRACT

Opportunistic spectrum access (OSA) is a promising new spectrum management approach that will allow coexistence of both licensed and opportunistic users in each spectrum band, potentially decreasing the spectrum licensing costs for both classes of users. However, this has significant implications on the QoS experienced by the licensed and opportunistic spectrum users. In this article we investigate how tolerant to secondary user activity a licensed user should be so as to provide dependable communication with sufficient QoS to an opportunistic user. We also look at key multichannel MAC features for such OSA networks proposed in the literature, and discuss how the design of control channel management affects the QoS of opportunistic users as a function of the tolerance of licensed users. We quantify the trade-off between dependability of the OSA network and the dependability of licensed users. The main conclusion is that opportunistic users can indeed achieve good QoS, as long as the licensed users are not highly active. For example, in one of the scenarios we studied, opportunistic users can achieve a delay below 100 ms if licensed user activity stays below 30 percent.

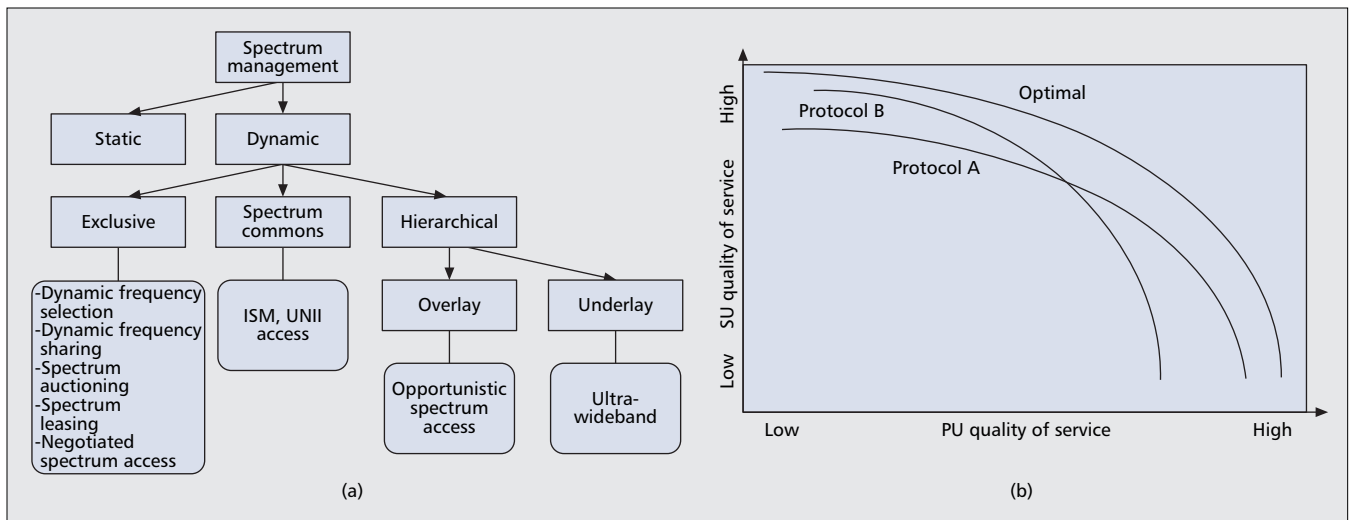
## INTRODUCTION

Static spectrum assignment, applied to radio frequencies for almost a century, results in a quasi-scarcity of spectrum. Finding a new unassigned frequency slot pushes system designers to explore higher and higher frequencies (e.g., 60 GHz). However, most of the already allocated frequencies are not used or are used sporadically. Therefore, it is logical to allow nonlicensed users to use these frequencies when they are free at a specific place and time. Theoretically, such an approach will increase overall frequency reuse without any licensing costs and boost the throughput for applications that opportunistically use the empty frequencies. This communication technique is called opportunistic spectrum access (OSA).

The concept of OSA, although very promising and attracting lots of attention, introduces new challenges to the notion of dependable quality of service (QoS)-driven communication. It raises questions about the amount of interference a licensed user is willing to tolerate. Many researchers follow a strict definition and assume a frequency band should only be used when there is no licensed user present. As a result, most research effort focuses on detecting the presence of a licensed user. In the example measurement we describe in the next section, 15.7 percent of measured frequency bins were free of licensed use over our whole measurement time, which means that OSA users could use this much spectrum. When incorporating the licensed user's duty cycle in the computation, we obtained an occupancy of only 6.8 percent, which means that theoretically an opportunistic user could use 93.2 percent of the spectrum. This, however, means that the opportunistic user shares the spectrum in the time domain with the licensed user. Clearly, in this case it is not possible to avoid all collisions between licensed and opportunistic transmissions, leading to a potential performance degradation for the licensed user.

In this article we look at the trade-off between QoS for the licensed user vs. that for the opportunistic user. There are many examples where it makes sense to decrease licensed user QoS when this reduction results in a much larger QoS improvement for the opportunistic user. Consider, for instance, a licensed user interested in broadcasting traffic information periodically. First, such broadcast is not that demanding in terms of data throughput, so an opportunistic user can take advantage of the idle periods between broadcasts. Second, for a car interested in the traffic information, missing a single broadcast is not that harmful, and a considerable amount of collisions could hence be tolerated. With OSA, both licensed and opportunistic users enjoy sufficient QoS, while the licensed user has reduced spectrum cost.

The goal of this article is to quantify the QoS for opportunistic users as a function of the



■ **Figure 1.** Modern spectrum management: a) classification with the application examples (see also [2, Fig. 1]); b) PU/SU QoS trade-off for different OSA MAC protocol designs.

licensed user activity level and collision tolerance. The opportunistic user's QoS is measured in terms of delay and throughput. To quantify this QoS, we need to make assumptions on the OSA medium access control (MAC) protocol design. Many different approaches are found in the literature, varying in terms of the number of radio front-ends used, the number of channels, the way the control information is exchanged, and the detection method for licensed users. Although we lack the space to give an exhaustive overview of all design options, we list the most important ones in the literature. We model some of those options in more detail to relate to the QoS parameters. We compare different approaches to distributing the opportunistic user's transmissions among many different channels using a multichannel MAC protocol.

The remainder of the article is organized as follows. First, we introduce the concept of dynamic spectrum sharing more systematically. Through measurements, we show that spectrum can be used more effectively if opportunistic users can time-share with licensed users. This possibility results in the fundamental question of the article: how much QoS degradation should a licensed user tolerate so that OSA becomes worthwhile for an OSA user? Quantifying this relation requires looking into details of the design of an OSA MAC protocol. In the following we discuss major OSA MAC design choices, and quantify their effects on the achieved QoS where possible. Finally, we list the main conclusions from this study in the final section.

## OPPORTUNISTIC SPECTRUM ACCESS: A BRIEF OVERVIEW

Before going into the details of OSA dependability challenges, let us look at OSA from a broader perspective. Static frequency planning leads to scarcity of the spectrum since it allocates spectrum based on worst case use, not actual use. Since the spectrum is getting full, new dynamic spectrum management techniques

have emerged [1, 2]. Promising dynamic spectrum management solutions are exclusive spectrum management (ESM), the spectrum commons (SC) sharing model, and hierarchical spectrum management (HSM). In Fig. 1a important spectrum management techniques and their hierarchy are introduced. The ESM model still gives exclusive channel use to each user or provider, but differs from a static assignment in the sense that the channels are allocated dynamically among possible licensees. In the SC model different users compete for the assigned frequencies on equal terms. The HSM model gives primary (licensed) users (PUs) more rights to use the spectrum than other secondary (nonlicensed) users (SUs). We can distinguish two HSM approaches. In *overlay* HSM, only one user/system can use a frequency band at a particular space and time, and the SU has to back off when a PU is present. However, when no PU is present, the SU can opportunistically use the frequency band; hence, this technique is also referred to as OSA. In *underlay* HSM, an SU can transmit in an already occupied band if this transmission does not increase the interference to the PU above a given threshold. A further classification of overlay HSM (not shown in Fig 1a) involves *symmetric coexistence* (when both SU and PU networks adapt) and *asymmetric coexistence* (when only the SU network adapts, obeying the PU requirements). In this article we consider the case where the PU does not adapt to the operation of SU.

Since the SU can only access the spectrum when it is free of PU activity, this approach inherently puts limitations on the level of QoS it can achieve. There is also some ambiguity about when a channel is considered to be free of PU activity. Some definitions state that a channel is occupied by a PU simply if the PU is present, irrespective of its duty cycle. Other definitions assume that the SU can also time-share the channel with a PU. In this article we use the second approach since clearly it can result in much higher spectrum availability for the SU, as motivated by the measurement discussed below.

Since the SU can only access the spectrum when it is free from PU activity, this approach inherently puts limitations on the level of QoS it can achieve. There is also some ambiguity about when a channel is considered to be free from PU activity.

Feature	Value
Mean channel utilization	6.8%
Total number of busy bins	1.7%
Total number of free bins	15.7%
Total number of bins with PU duty cycles	82.6%
Slot-to-slot difference in available bins	47%
Number of free bins within frequency pool (Max)	85%
Number of free bins within frequency pool (Min)	16.6%
Average ON time	4.3 s
Average OFF time	58.9 s

■ **Table 1.** Results of the PU channel observations.

### WHAT TO EXPECT FROM PU SPECTRUM USE

Although many researchers claim that the spectrum is used sparsely, it is in general very difficult to obtain good information about realistic spectrum use. To obtain an example of PU spectrum use, we measured the spectrum use in the frequency range  $F = [446.04; 467.82]$  MHz on 13 March 2007 at different times between 11 a.m. and 8 p.m. in the Electrical Engineering Department at the University of Twente in the Netherlands. Following the Dutch radio spectrum map, these bands are assigned to public mobile communication channels, with the exception of those channels that are assigned to the Dutch Ministry of Defense for aviation communication. We have extracted periods of PU signal activity (ON periods) and PU inactivity (OFF periods) for each frequency bin of 100 kHz, which made it possible to compute the PU activity metrics as listed in Table 1.

Only 1.7 percent of the frequency bins were busy the whole time, and could hence not be used by SUs at all. Also, 15.7 percent of all the observed frequency bins were free during the whole observation time. Therefore, the remaining 82.6 percent of all frequency bins showed ON and OFF patterns (with mean ON and OFF times of 4.3 s and 58.9 s, respectively). As a result, when an SU cannot time-share a frequency bin with a PU, it can only achieve a spectrum utilization of 15.7 percent. A striking fact is that the total channel utilization of the measured frequency range  $F$  was only 6.8 percent. So, when time-sharing is possible, the SU can achieve a utilization of 93.2 percent, which is a significant improvement compared to 15.7 percent.

Next we study the channel availability variations. For the chosen frequency range  $F$ , the average difference in available free frequencies between two consecutive time slots of 140 ms was 47 percent, which shows that the spectrum

available to the SU can vary significantly. The minimum difference was 16.6 percent, which means there was always a variation. The maximum difference was 85 percent.

### OSA QoS TRADE-OFFS

Translating the spectrum availability into an acceptable level of QoS for the SU is the key task of the OSA MAC protocol. A network is only dependable when the required level of QoS (i.e., delay or throughput) can be achieved consistently or with a high enough probability. Clearly there is a fundamental trade-off between the PU spectrum requirements and the dependability that can be achieved, since no protocol design can deliver an acceptable QoS when no resources are available. We depict this trade-off in Fig. 1b.

The goal of this article is to quantify OSA dependability in terms of classical QoS parameters like throughput and delay as a function of PU parameters such as load and tolerance to interference or collisions from SUs. Intuitively, the OSA QoS will be improved when the PU is more tolerant to interference or has a lower load. Quantifying this, however, requires making assumptions about the OSA MAC protocol, since the optimal MAC design will result in the best joint SU-PU performance, as shown conceptually in Fig. 1b. Another question that hence needs to be addressed is “How should the SU exploit the available spectrum to achieve a reliable communication?” As we are focusing on MAC design here, we answer this question by first listing all features that are important for OSA networks and showing how these have been addressed in the literature. Where possible, we quantitatively assess which solution is optimal and hence results in the best SU QoS for a given PU set of requirements.

### KEY FEATURES OF OSA MACS

Quantifying dependability for the scenario where SUs and PUs share a set of channels in time and frequency requires making assumptions about OSA network operation. We have listed many important OSA MAC proposals found in the literature and identified a set of key features required to enable OSA operation. Our focus is on decentralized MAC protocols only; that is, in which each OSA node locally decides when and how to access the channel. In addition, many centralized solutions have been proposed where a coordinator organizes the channel access. For instance, the current proposal for IEEE 802.22 wireless radio access network (WRAN) [3] is an example of such an OSA protocol. We are also aware of proprietary OSA MACs found in the OSA devices of Shared Spectrum Company, Philips, and Microsoft, but since their specifications are not public, we were not able to include them in the survey.

We briefly introduce the identified features, as listed in Table 2, for the protocols found in the literature. Before an SU network can start operating, it should decide on the set of channels to use. This bootstrapping is hence a first SU MAC feature that deserves attention. Next, after the set of possible channels is identified,

the network should decide on how to organize SU communication over those channels. The more channels of a given bandwidth are used, the more throughput the SU network can achieve. Also, since each channel can potentially be claimed by a PU, the probability that an SU loses all its channels decreases when using more channels. We hence assume a multichannel OSA MAC, and selecting a MAC type is considered the next important feature. Next, OSA operation requires information about the presence of PUs, and how this is implemented is a third important design choice. Depending on the multichannel MAC type and the organization of the scanning, more or fewer front-ends are required to work in parallel, which is a fourth design choice. Finally, a policy is required to establish the coexistence rules with the PU. The stricter the policy, the more difficult it becomes for the SU. Below, we discuss each feature in more detail and quantify the effect on QoS where possible.

### BOOTSTRAPPING

Bootstrapping is the process during which an SU node decides which PU channels are suited to opportunistic spectrum communication. In one scenario third parties provide information about such channels so that the SU node only has to consult such a third party when it wants to start or join a network. Other scenarios assume that each node finds those channels locally, which can involve a significant amount of spectrum scanning. Next to finding the channels, each node should distribute its set of channels to other users in the network. Interestingly, only a handful of proposed OSA MACs consider bootstrapping: C-MAC [6], AS-MAC [10], DOSS [11] (only for a control channel), and HD-MAC [15]. Usually MAC designers assume that each OSA node has a preprogrammed list of PU channels for use. In the rest of this article we assume that each node has decided the set of opportune channels, and that this set of channels is available to each node in the SU network. Hence, each SU node operates on the same set of channels. Motivated by the measurement example discussed earlier, we assume that a channel is opportune when a PU is not using it constantly (i.e., channels with no PU present and channels with some PU activity). In most cases this gives us a set with more than one channel. In the next section we discuss how to organize the SU communication across those channels.

### CONTROL CHANNEL DESIGN

After the bootstrapping procedure, the SU network has decided on a set of possible channels. Now, for each data packet transmission, the SU transmitter and receiver have to coordinate which channel and time slot they will use for that transmission. This coordination is typically implemented with a (common) control channel (CC). From a reliability viewpoint, this CC is a very crucial element of the MAC design, since no SU data communication is possible when it is obstructed.

Using the approach defined in [16, Sec. II] for general multichannel MACs, we can identify four types of CC implementation, as listed in Fig. 2.

Protocol name	Bootstrap	Type	Scan.	No. RFEs	Policies
BB-OSA [4]	No	DCC	No	1	—
ESCAPE [5]	No	DCC	Yes	1	P1, P2
C-MAC [6]	Yes	DCC	Yes	1	—
MMAC-CR [7]	No	DCC	Yes	1	P1
Choi <i>et al.</i> [8]	No	DCC	No	2	—
Shu <i>et al.</i> [9]	No	DCC	No	2	P1
AS-MAC [10]	Yes	DCC	Yes	1	—
DOSS [11]	Yes	DCC	Yes	3	—
HC-MAC [12]	No	DCC	Yes	1	—
Su <i>et al.</i> [13]	No	DCC	No	2	—
SRAC [14]	No	SPCC	No	1	P1
HD-MAC [15]	Yes	SPCC	Yes	1	P1

■ **Table 2.** Survey of representative OSA MACs.

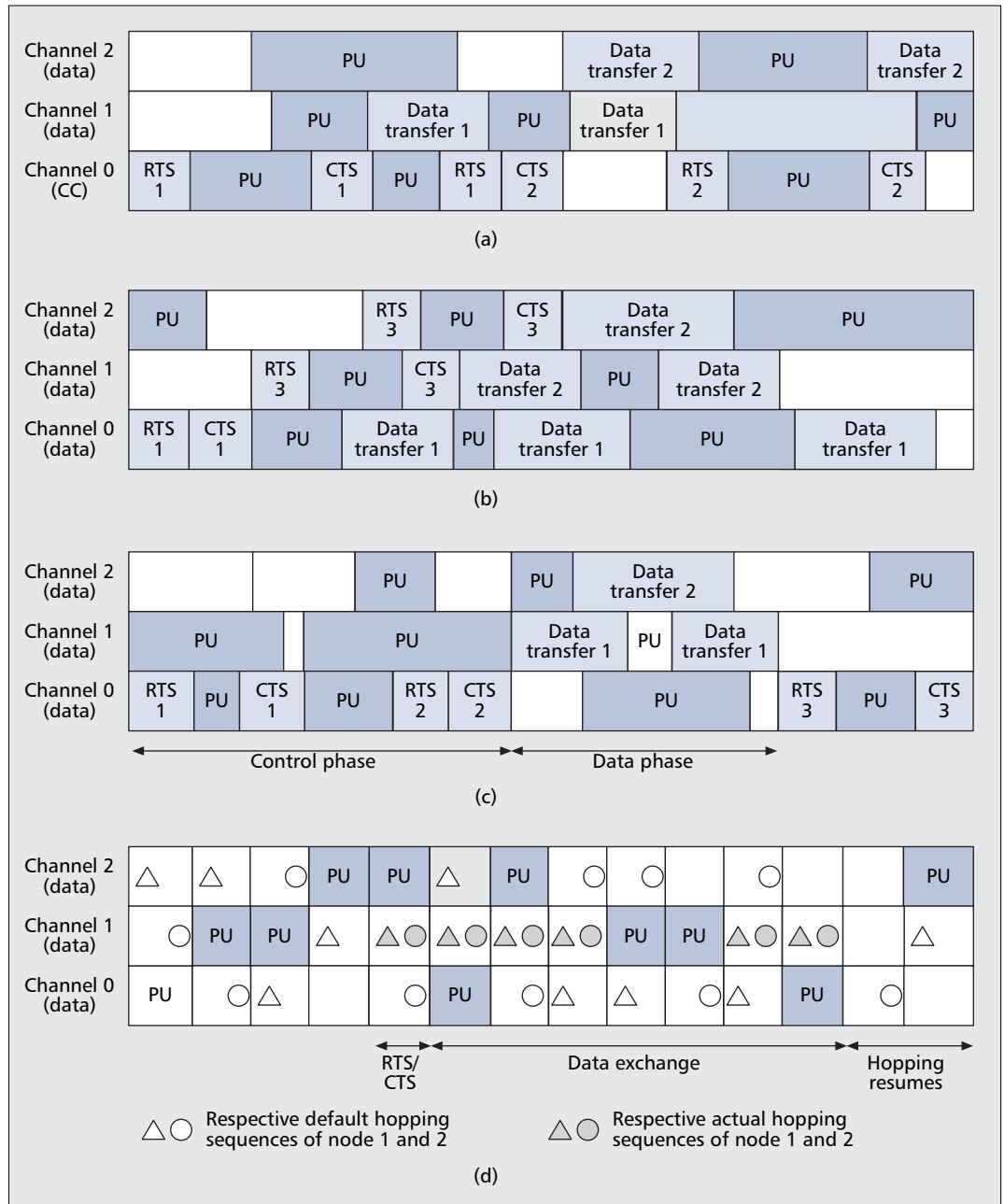
1. Dedicated (common) CC (DCC), where one SU channel is dedicated solely to the transport of control messages. All nodes should overhear the control data exchange, even during the data exchange. As a result, one radio front-end (RFE) needs to be dedicated to the exchange of control data. When only one RFE is used, transmission of control and data packets is time divided, but then the operation of the protocol gets more complex. The drawback of the DCC approach in the context of OSA is that when a PU is active on the CC, all communication is obstructed. It is hence often assumed that the CC should always be available or free from PU. We discuss this issue in more detail below.

2. Hopping CC (HCC), where all nodes hop between all channels following a predefined pattern. When both sender and receiver successfully exchange control messages on the current channel, they stop hopping and start transmitting data. After that, they come back to the original hopping pattern. HCC has the advantage that it uses all channels for transmission and control, whereas in DCC the CC can be used to transfer control packets only. Also, HCC does not require a single channel to be free from PU activity.

3. Split phase CC (SPCC), where time is divided into control and data phases. During the control phases, all nodes switch their RFEs to the dedicated CC and decide on the channels to use for the upcoming data transfers. After each control phase, a data phase allows for data transmissions on the agreed channels. The advantage is that the CC can be used during the data phases. Also, compared to DCC, no extra RFE for the CC is needed. On the other hand, SPCC needs stronger synchronization to identify control and data phases.

4. Multiple rendezvous CC (MRCC), where

For HCC and MRCC the exchange of control messages on PU channels is inevitable since the exchange of control data is spread among all channels in the SU network. This certainly affects network availability and communication reliability.



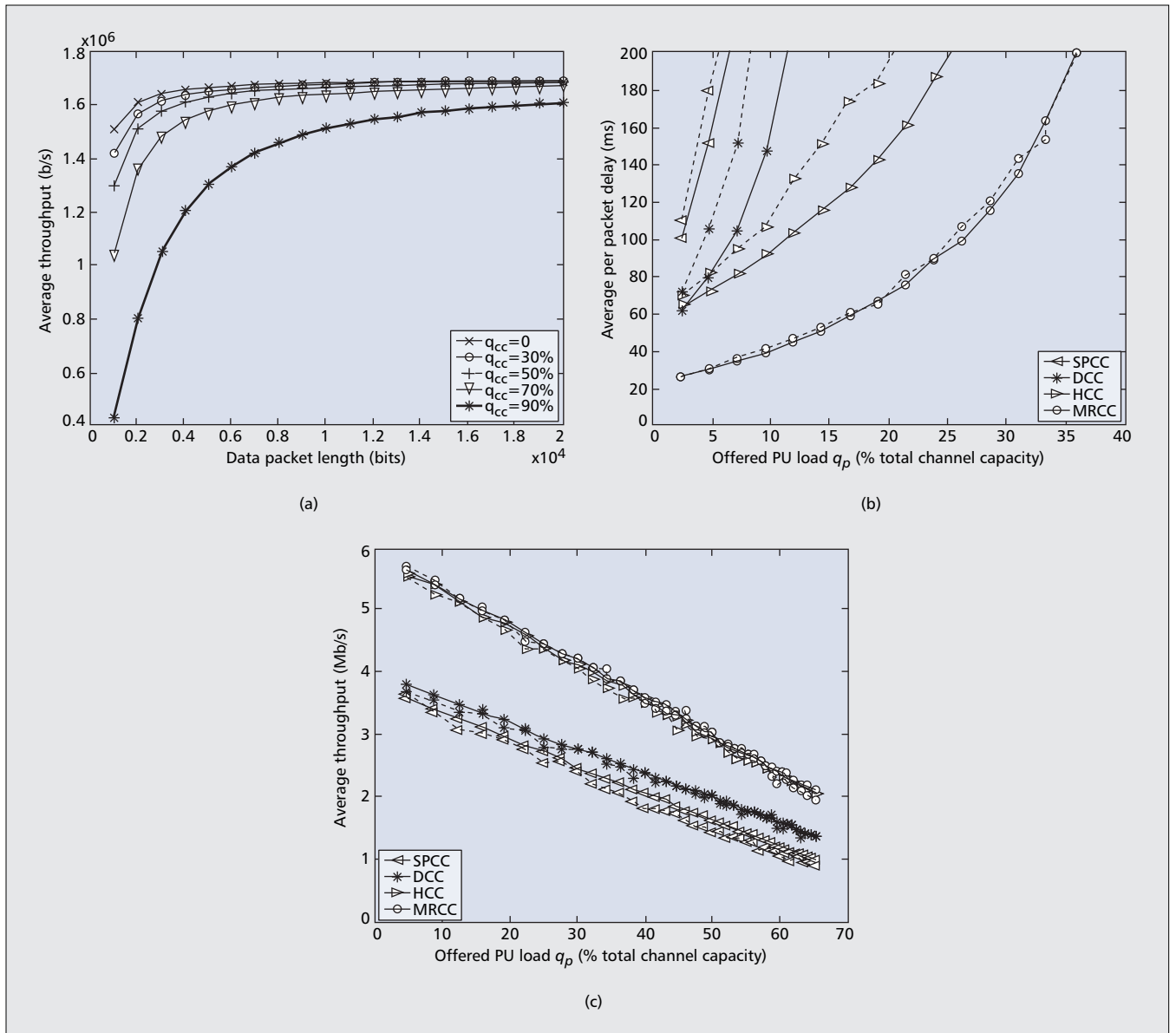
■ **Figure 2.** Illustration of the operation of different multichannel MAC types, with PU activity on each channel: a) DCC; b) HCC; c) SPCC; d) MRCC.

multiple nodes can exchange control information at the same time, using all available channels. Each node knows the hopping pattern of the others (such a hopping pattern is based on the seed of a pseudo-random generator), which makes control exchanges possible by following the intended receiver on its hopping sequence. MRCC maximally spreads both control and data exchanges across the channels in a very random way. As a result, MRCC seems to be the most robust to PU activities on any of the channels. We illustrate this quantitatively below. However, MRCC also requires more stringent synchronization between hopping users since users have to keep track of meeting times.

We further study the different MAC types. First, we assess the impact of PU activity on the

control messages exchange. Next, delay and throughput of the SU network are determined for each of the four MAC types.

**1. PU activity on the CC:** For HCC and MRCC, the exchange of control messages on PU channels is inevitable since the exchange of control data is spread among all channels in the SU network. This certainly affects network availability and communication reliability. However, for DCC and SPCC, the CC does not necessarily need to be implemented on a channel with PU activity. More specifically, a single DCC that does not suffer from PU activity can be built using a proprietary non-PU channel (e.g., ISM or UNII channels), or a wideband transmission technique such as code-division multiple access (CDMA) or ultra-wideband (UWB). The first



**Figure 3.** QoS assessment for 3 PU channels and 20 SU users: a) analytical throughput of an OSA network as a function of data packet length for different levels of PU activity  $q_{cc}$  on CC for DCC MAC; b) simulated impact of PU channel occupancy rates for four different classes of OSA MACs in terms of delay; c) throughput; dashed and solid lines represent different PU packet sizes (see text for more explanation).

approach is the most used in the literature [6, 15]. Spreading the CC across a wide bandwidth is very robust against PU activity, but limits the operating range of the network since UWB throughput decreases strongly with distance. When it is not possible to use a proprietary or wideband channel, the concept of a backup CC has been proposed [6]. Indeed, the probability that both CCs are occupied by a PU simultaneously is smaller. However, this solution is resource inefficient.

Since DCC is a very popular choice for OSA MAC protocols (Table 2), we quantify the impact of PU activity in the CC on the throughput that can be achieved in an SU network using DCC. This will allow us to assess how important it is for an SU network to get a proprietary channel for its operation. For this, we have extended the analytical model for multi-

channel MACs proposed in [16] with a more detailed physical layer model to capture the impact of PU and SU interference. Also we have implemented the PU presence and the PU scanning process (detailed later in this article). In Fig. 3a we plot the impact of PU presence in the 2 Mb/s dedicated control channel on the SU throughput as function of SU data packet size. In the simulation, PU presence was modeled as a Bernoulli process with average presence rate  $q_{cc}$ . This presence is detected with a probability of 0.99 and with a probability of 0.03 the SU falsely assumes the PU to be present on the channel and pauses control message exchanges. A total of three SU channels are considered, and one of those is the CC. The PU was assumed to be present in the CC only. The interesting conclusion is that the SU can control how dependent it is on the control

Because of their opportunistic nature, it is generally assumed that SU networks should be highly tolerant to delays. Indeed, it can happen that all channels are used by the PU, causing the communication to be suspended.

channel by tuning its data size. Indeed, for larger data packets, less control messages need to be exchanged, so the impact of the control channel is smaller. When the data size needs to be smaller, the impact of PU activity is larger, and in this case the concept of a backup CC could be helpful.

**2. PU activity vs. SU throughput and delay:** Because of their opportunistic nature, it is generally assumed that SU networks should be highly tolerant to delays. Indeed, it can happen that all channels are used by the PU, causing the communication to be suspended. Let us now quantify how large the SU delay becomes as a function of PU activity on the channels. This will give us important information on the type of applications that can be supported on OSA networks, or alternatively how the PU activity should be limited to be able to support a targeted SU application.

From Table 2, it is clear that the majority of OSA MAC proposals use DCC and only two use SPCC. Surprisingly, we were not able to identify HCC and MRCC proposals in the OSA literature. To be complete, however, we have considered these four MAC classes. We have implemented all the protocols in a coarse time-slotted simulator. It allows us to capture all the intrinsic features of the considered MACs, especially the way the control data exchange is organized. For a more detailed description of the simulator readers are referred to [16, Sec. V]. We have extended the simulator with PU activity patterns. In Fig. 3b we plot the simulated delay of the SU applications as a function of PU activity for each of the MACs. In the simulation the OSA network consists of 20 devices; every user was generating traffic following a Poisson distribution with average transmission rate of 150 kb/s (the total SU load is 50 percent of the total bandwidth). There are three channels. Every channel has a fixed bandwidth of 2 Mb/s. PU activity was modeled through a geometrically distributed on-off process. The average PU packet was 0.8 ms (solid line in Fig. 3b) or 8 ms (dashed line in Fig. 3b), while the average off time was varied from 0.8 ms to 160 ms, resulting in a range of average PU activity levels. We have assumed perfect detection of PU activity on each individual channel. The striking fact is that MRCC is the best MAC of all, whatever the PU activity level. Its immunity to temporal nonavailabilities of the channel and efficient use of the whole channel capacity presents this type of MAC as a candidate for real-life implementation. This is because MRCC randomizes both control and data exchange significantly. Another observation is that the delay of all MAC classes becomes higher with increasing PU packet size. Because of its randomizing properties, MRCC suffers less. As noted previously in our measurements, PU traffic can have ON times or packet durations on the order of seconds. For the given scenario, even when the PU activity reaches 30 percent, the delay experienced by the SU is still lower than 100 ms. This delay could even fit within the bounds for packet voice communication, where the round-trip delay for a voice conversation should not exceed 400 ms according to International

Telecommunication Union — Telecommunication Standardization Sector (ITU-T) Recommendation G.114.

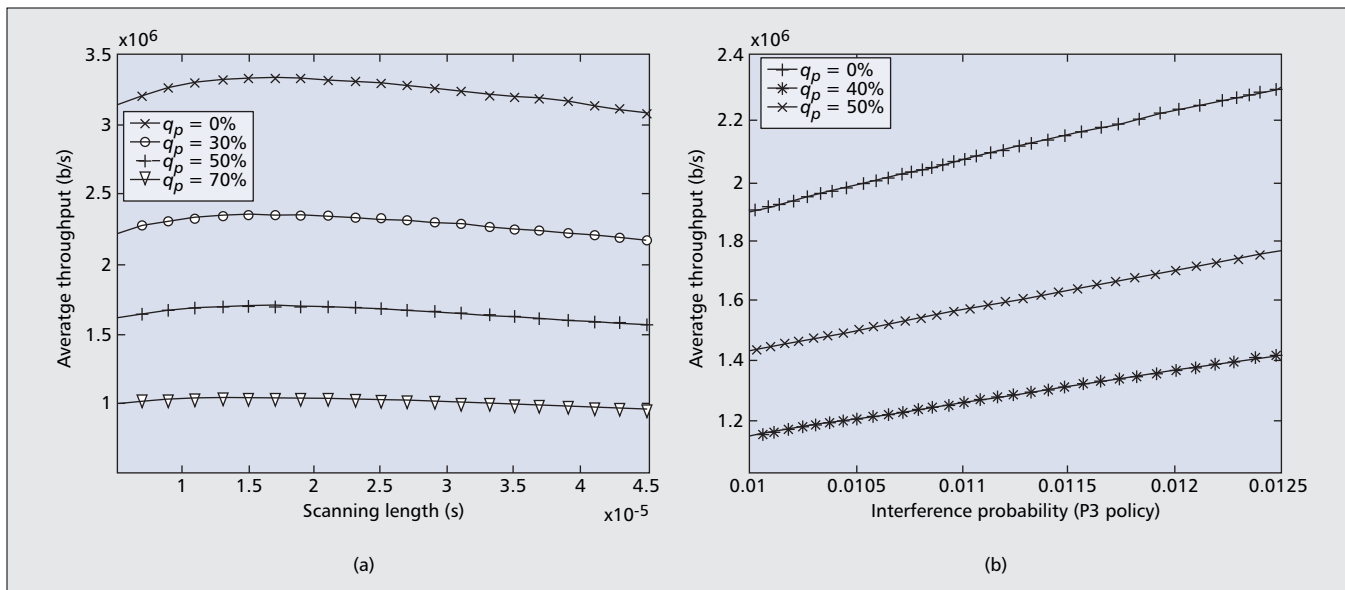
Next, in Fig. 3c we assess OSA network throughput as a function of PU activity for a similar scenario (the solid line is now 8 ms and dashed 80 ms PU packet size). As expected, the average SU throughput decreases linearly with PU activity. SPCC performs the worst in this case, since it wastes a lot of bandwidth on the data channels during the control phase. MRCC is still the best MAC design. The average throughput does not vary a lot with PU packet size.

## SCANNING PROCESS

Since an SU cannot use the channel when a PU is present, it should obtain information about PU activities on each channel. Typically, this is implemented using PU detectors [17]. Alternatively, PU activity information can be assumed to be broadcast by a central device. We can thus classify OSA MAC protocols into sensing and non-sensing OSAs. From Table 2 we can conclude that the majority of the considered protocols assume having the scanning under their control.

Unfortunately, scanning increases the overhead since nodes cannot transmit when they are scanning. Since it is often difficult to distinguish SU and PU signals, the whole SU network has to be quiet during sensing, which requires *quiet period management* [6]. Scanning, or quieting the network, can be done periodically or before each transmission attempt. The distance between two consecutive sensing intervals varies, and is often a function of the policy. The more tolerant the PU to interference, the less often sensing should be done. Noise, fading, multipath shadowing, and low PU signal levels make a reliable detection process difficult. Suboptimal detectors affect not only the PU QoS levels, but the SU QoS as well.

Scanning performance is measured in terms of the probability of detecting a PU when present, and the probability of falsely detecting a PU. In the former case, both SU and PU QoS is degraded, since an SU will transmit and collide with the PU, resulting in packet loss for both PU and SU. In the latter case SU QoS is degraded, since an SU will not transmit when the channel was actually free. It is well known that scanning performance improves with increasing scanning length [18], and in Fig. 4a we investigate the optimal sensing time in terms of SU QoS for a scenario with DCC MAC. Scanning is performed using energy detection before each transmission attempt, and Rayleigh fading is assumed. SU throughput indeed improves with increasing detection reliability. When detection performance is acceptable, the throughput starts to decrease since the scanning overhead dominates. This effect is less visible with high PU activity, since an OSA network will not have enough opportunities to communicate; therefore, it will not lose much of the already small PU channel capacity. The impact on PU QoS is discussed later since PU QoS can be considered to be a policy constraint.



**Figure 4.** QoS assessment for 3 PU channels and 20 SU users: a) OSA network analytical throughput as a function of scanning length for DCC MAC; b) analytical relation between level of interference to PU and SU network throughput for DCC MAC. Throughput and interference have been computed as a function of scanning length varying from 1 to 45 ms (resulting in decrease of probability of false alarm from 0.23 to 0.024 and increase in probability of detection from 0.82 to 0.92) and three different levels of PU activity  $q_p$  on all channels.

## RADIO FREQUENCY FRONT-ENDS

The exact multichannel MAC operation and scanning implementation degrees of freedom depend on the number of front-ends that are available in each SU node. Indeed, when multiple RFEs are available, it is possible to use multiple channels simultaneously for transmission. Alternatively, spare RFEs can be used for scanning only, decreasing the impact of scanning on the network throughput. When only one RFE is available, sensing and communication should be split in time. Of course, increasing the number of RFEs increases the reliability of the system and decreases delay, but simultaneously increases the total cost. Typically this number varies from 1 to 3 (Table 2). In this article, we assume two RFEs for the DCC and a single RFE for the other MAC types.

## INTERFERENCE MANAGEMENT POLICIES

Since it is impossible to detect PU presence with certainty, harmful interference to the PU cannot be avoided. The maximum level of interference is typically specified through interference policies (IPs), which define how SUs can behave in certain PU bands while maintaining the QoS requirements of the PU. The more relaxed the IPs, the better the SU can take advantage of spectrum opportunities. In other words, policies are rules that determine the trade-off between SU and PU QoS. Defining such IPs, however, is a very difficult task. In this article we want to see how much an SU could benefit from more relaxed PU policies.

From our literature search (Table 2), we can enlist three major policy classes for OSA networks:

**P1 Time-based:** These policies define time metrics that regulate SU transmissions. An example metric is the evacuation time that defines

how fast an SU should vacate a channel after a PU is detected.

**P2 Power-based:** These policies define the power limits each SU needs to take into account when using PU channels. Example metrics are maximum (peak) power, power mask, and average transmit power.

**P3 Collision-based:** These policies are defined at the MAC layer, usually assuming packet-based transmissions. They define collision probability limits, bounding the probabilities that an SU packet will harm a PU packet.

Depending on the PU system, one of these policies is most appropriate (e.g., policy P3 can only be applied to packet-based networks). Also, a given policy can often be described, or implemented, differently. The exact description often significantly impacts the usability and cost of the SU network. For example, policy P2 can also be defined as a maximum distance between PU and SU, which requires the OSA network to embed expensive localization capabilities. We note that the definition of policies for OSA networks is a very hard problem and an ongoing topic of research.

Next to the policy format, its level of PU protection can be too restraining. For a given policy (we use the P3 policy since we assume both SU and PU networks are packet-based), we investigate what QoS the SU can achieve (Fig. 4b). The probability of collision with a PU packet and the SU throughput have both been computed as a function of the scanning duration (and hence scanning quality). A stricter collision constraint is only achieved with improved detection performance, requiring the SU to scan over a very long time. When the PU constraint is relaxed, the SU can scan for a shorter time, resulting in throughput improvement of the SU.

The P3 policy, avoiding collisions with the PU, can be implemented using listen-before-

It can be concluded that although many individual contributions can be found, it is important to assess how these subtasks can be integrated together into a complete solution to be able to fully assess the expected QoS of OSA networks.

send scanning. Since the PU does not scan for SU presence, it is possible that the PU will start a new packet during SU transmission. This can only be avoided by assuming small SU packets, since it is not realistic to assume any synchronization between the PU and SU networks. However, assuming such synchronization is very convenient for analysis [15], and we have also assumed such synchronization in our models. The only OSA MAC that can actually assume such synchronization is AS-MAC [10], which was specifically designed for operation on GSM channels, where slot boundaries can be captured easily. In general, since it is very hard to preserve SU/PU synchronization, certain policies like P1 and P3 have to be defined very carefully.

## DISCUSSION AND CONCLUSION

In the previous section many features that are important for OSA MAC design are listed and discussed, first by means of reviewing the proposals found in the literature and also by quantitatively assessing the impact of some features on PU or SU QoS. A first conclusion is that most of the proposed solutions do not cover many of the crucial elements of a proper OSA MAC protocol design. Indeed, since the operating conditions of OSA networks are typically unknown during the design time phase, the bootstrapping procedure to set up the network before communication is very important. However, it is omitted in many of the protocol designs. In the case of OSA networking, this bootstrapping cannot be considered to be a one-time effort at the start of the communication network, so it is crucial to make it as efficient as possible and embed it in the MAC protocol design. Also, the required scanning for the presence of the PU is sometimes omitted in the protocol design or performance analysis. More important, the specification of policies to regulate the coexistence with PUs is often described very vaguely or even fully omitted. It can be concluded that although many individual contributions can be found, it is important to assess how these subtasks can be integrated together into a complete solution to be able to fully assess the expected QoS of OSA networks.

Often, the solutions proposed for the subtasks are suboptimal. In this article focus has been on the organization of the control channel since this is a very important aspect of multi-channel OSA networking. Although the solutions proposed in the literature always assume the availability of a fixed channel for control information exchange (for DCC this channel is only for control, in SFCC the channel is also used for data), we show that this is not necessarily optimal. Indeed, especially when there are a lot of possible channels to use, a fixed control channel easily becomes the bottleneck. Also, when no channel can be assumed to be free of PU activity, it is best to spread the control exchanges over different channels as much as possible. As a result, we show that the MRCC actually outperforms DCC, HCC, and SFCC over a broad range of PU traffic conditions.

Very often, researchers stick to a given design for OSA MAC since it is the most practical, and

it does not make sense to make the design more complicated in the absence of measurements or detailed performance analysis. In this article we have included the results of a simple measurement campaign since we want to emphasize that it is important to build conclusions using realistic assumptions. Those measurements have shown that it is not impossible to find a channel that is not used for a very long time, facilitating the use of a dedicated control channel. However, it was also shown that the instantaneous capacity varies a lot, advocating the use of a protocol that can easily take advantage of these variations.

Finally, we want to emphasize that no solutions found so far in the literature assess the QoS given to the secondary network in detail. This is, however, a very crucial area of study since the introduction of OSA networks only makes sense if a sufficient level of QoS can be expected. In this article we attempt to study the delay and throughput performance of a broad range of OSA designs as a function of PU activity. Also, we assess the fundamental trade-off between PU QoS and SU QoS. The more freedom is given to the SU to access the channel, the more capacity it can use and the better its performance. However, more freedom to the SU means less guarantees for the PU, and the success of OSA networking will depend on how well we can optimize this trade-off with a given policy.

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