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Spectrum Efficient QoS Support for Secondary Users in Cognitive Radio Systems

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Abstract

The fundamental performance criterion for Dynamic Spectrum Access (DSA) approaches is the protection of the Primary User (PU). However, for DSA to become a reality, it is crucial to also ensure some Quality of Service (QoS) support for the Secondary User (SU) communication. In this paper, we propose sensing based opportunistic spectrum access approaches achieving both, protection of the PU, as well as QoS support for the secondary communication. Given the requirements of PU protection and secondary QoS support, we show that there is a tradeoff between the spectral overhead needed to achieve both requirements. PU protection is realized by a sensing process, for which the amount of spectral overhead drives the probability of false positives (the probability of declaring the PU to be present although it is not). This probability in turn influences the amount of spectral overhead required for secondary QoS support. We introduce performance metrics to quantify the spectral overhead and the spectral efficiency of DSA approaches. Furthermore, for a secondary QoS metric of uninterrupted data transmission, we show performance results for selected link maintenance approaches with respect to their spectral efficiency.

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Chapter 1

Introduction

Opportunistic spectrum sharing is a very promising *D*ynamic *S*pectrum *A*ccess (DSA) approach for more efficient spectrum usage. In opportunistic spectrum sharing so called *S*econdary *U*sers (SUs) utilize the parts of the spectrum temporarily not used by the license holders (the *P*rimary *U*sers (PUs)). These unused parts of the spectrum are detected by a sensing process. Spectral resources used by the SU have to be periodically re-sensed to assure that they are still not used by the PU.

The fundamental requirement of such a sensing based opportunistic spectrum usage is to protect the PU, i.e., ensure non-interference beyond some – very limited – scope. To quantify this scope, each PU has to specify a so called maximum interference time ($t_{\max}$), which specifies the maximum time a re-occurring PU can tolerate interference from an SU before the interference is considered to be harmful. Obviously, $t_{\max}$ heavily depends on the service provided by the PU. For usage of white spaces in the TV bands, e.g., it is set to 2 s.

The protection of the PU can be quantified by the probability of false negatives in the sensing process, i.e., the probability of not detecting the PU although it is present. A lot of effort [1–3] has been devoted to the sensing process, and it is nowadays pretty well understood that the quality of sensing as defined by the probability of false negatives and the probability of false positives (indication of the presence of the PU although it is absent) directly depends on the *diversity* of the sensing measurements. This diversity can be in time (time of sensing), frequency (amount of bandwidth used for sensing), and space (multiple, spatially diverse, sensors).

Unfortunately, there are rigorous limits on the above mentioned diversity approaches: The above mentioned $t_{\max}$ creates a limit on the upper bound for the sensing time. In reality, this time has to be strictly shorter than $t_{\max}$ because some additional time is needed to assure that all SUs are notified in case a PU appears and abandon the respective spectrum. The diversity in frequency is limited by the bandwidth of the PU. For spatial diversity, the limit is usually in the manageability of spatially diverse sensors. These limits create a real challenge for the sensing process.

As elaborated above, protection of the PU is pretty well understood and defined. In contrast, the QoS of a secondary communication has so far not attracted much attention in the research community (with a few exceptions).

In [4], the authors tradeoff the probability of false negatives and the probability of false positives to maximize the *joint* QoS. In our opinion – which is in agreement with current viewpoints within the FCC and IEEE – the quality of the PU operation is **not** to be jeopardized by secondary usage. This means a pretty strict limit on false negatives in the sensing process.

But we do also advocate the position, that the quality of the SU communication has to be assured if DSA approaches are to be broadly accepted. In fact, in our earlier research we have contributed to development of DSA mechanisms assuring uninterrupted data transmission for SUs despite of re-occurring PUs [5, 6].

In this paper we start with a fundamental observation, that both the

- quality of SU transmission in spite of reconfigurations due to re-occurring PUs as well as due to false positives, and
- the quality of the sensing process measured by the number of false positives under a strict limitation of the false negatives,

can be achieved by using a proper spectral overhead. Furthermore, we claim that the overhead needed for both the above mentioned goals can be – to some extent – traded against each other.

To analyze the design space opened by this tradeoff we discuss the spectral overhead of both the sensing process and the SU's quality assuring process and introduce proper metrics for their quantification. In addition, for selected system models and quality assuring processes, we present the minimization of the joint spectral overhead.

In [7, 8], the authors show a tradeoff for the secondary throughput between the sensing time and the probability of false positives. Similarly, in [9], we propose an approach to optimize the overhead used for a secondary communication link. However, to our knowledge, the work presented in this paper is the first to investigate the joint optimization of the spectral overhead caused by spectrum sensing and secondary QoS support.

The reminder of the paper is structured as follows. In Section 2 we give a general overview on spectrum sensing concepts and in Section 3 on link management and secondary QoS support approaches. Section 4 introduces spectral availability as a performance metric to quantify efficient spectrum usage. In Section 5 we explain the secondary QoS approaches to support uninterrupted data transmission investigated in the paper and show performance results in Section 6. We conclude in Section 7.

Chapter 2

Spectrum Sensing

Spectrum sensing is the process of deciding – based on measurements – whether or not a PU is present in its spectrum band. The measurement techniques used range from simple power measurements to matched filter or cyclo-stationary feature detection [3]. Conceptually, there are two different sensing processes a SU system has to perform: *initial* sensing and *periodic* sensing.

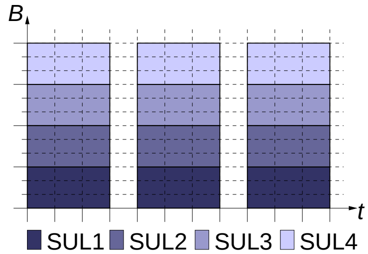
Initial sensing is done before setting up a communication link. The SUs have to determine which spectral ranges are available for secondary communication. The initial sensing process, thus, often covers a wide spectrum range trying to determine the spectrum most suitable for the communication link. Initial sensing also has to be performed in order to find new spectral resources to reconfigure the link in case a PU appeared on some of the spectral resources (see Section 3.3). The initial sensing process is usually not time critical.

Periodic sensing has to be done periodically after the setup of a communication link. The SUs have to verify that the used resources are still available and that no PU has appeared and reclaimed its spectrum. In contrast to the initial sensing process, only the used spectral resources are sensed in the periodic sensing process. Periodic sensing is time critical since a frequency band reclaimed by a PU has to be vacated within the maximum interference time (t_{max}), which puts a strict upper limit on the sensing time.

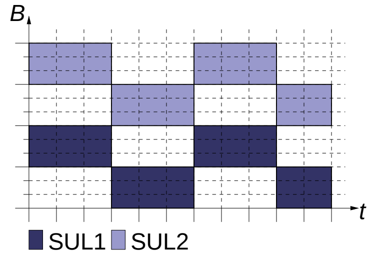
2.1 Performance Metrics

The fundamental performance criterion of spectrum sensing is reliability. One measure for reliability is the probability of false negatives (P_{fn}), i.e., the probability of not detecting a PU although it is present. Since non-interference is a very important objective of a *C*ognitive *R*adio (CR) system, minimizing the false negatives is the top priority of spectrum sensing. The other side to reliability is the probability of detecting a PU although it is not present (false positives) (P_{fp}). There is usually a tradeoff between the probability of false positives and false negatives. Assuming a very low target probability of false negatives, a performance metric for spectrum sensing remains the probability of false positives.

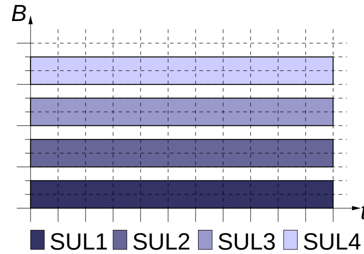
A fundamental problem of spectrum sensing can be stated as follows: It is impossible to reliably detect the PU in a certain spectrum range, while at the same time performing data transmission in that range. It is, thus, crucial to ensure that the spectrum range to be sensed



(a) Interrupted sending



(b) *D*ynamic *F*requency *H*opping



(c) Partial sensing

Figure 2.1: Different sensing approaches: The colored areas represent spectrum used for different communications links (SULs), the white areas spectrum available for sensing.

is not used for data transmission by the SU system at the same time.

Given the constraint that no data transmission can take place during the sensing process, another performance metric for spectrum sensing is spectral overhead, defined as the product of the spectrum bands used for sensing and the time in which these bands are sensed and, thus, completely blocked for other usage.

2.2 Diversity Approaches

There are several approaches to improve the quality of the spectrum sensing process. The general idea of all of them is a *diversity* approach to reduce the noise of the measurements. The three diversity dimensions for quality improvement (reduction of false positives) are time, frequency, and space.

Diversity in time is achieved by performing sensing over a certain time span. However, as already elaborated, sensing time is strictly bounded by the maximum interference time ($t_{\max}$). Furthermore, time samples should be spaced by a lag comparable to the time-variance of the fading and interference processes in the environment, in order to have independent sensing samples. Another possibility of improving the quality of sensing is diversity in the frequency domain [3]. In this case, again, to have independent samples, care about the proper correlation properties should be taken. Using more bandwidth for sensing usually improves the accuracy of the sensing process.

Taking multiple concurrent sensing measurements in spatially diverse locations can further improve the quality of sensing. The approach is commonly referred to as *distributed* sensing (as opposed to local sensing performed in one location). Studies on local sensing have shown, that a PU cannot be detected reliably by just one sensing device [1, 2]. In *distributed* sensing, the sensing entities exchange their local sensing results and then combine the sensing results to make a decision on the presence of the PU.

Whereas all three approaches introduced above contribute to the quality of the sensing process, they also have an impact on the spectral overhead of the sensing process. Using time and frequency diversity increases the bandwidth-time product required for sensing. Using spatial diversity requires spectral resources to exchange the sensing data and also delays the decision process on the presence of the PU. Obviously, the overhead for distributed sensing depends on the number of participating sensors.

2.3 Sensing Approaches

There are basically three different approaches how to organize the periodic sensing process. Interrupted sending (Figure 2.1(a)) is the approach mostly followed in the research community so far. In this approach, secondary data transmission has to be periodically interrupted to perform sensing. If the sensing process detects a PU in the used resources, the communication is continued in another, unused spectrum range.

The second approach, *D*ynamic *F*requency *H*opping (DFH) (Figure 2.1(b)), is an approach introduced in [6] in order to avoid the periodic interruptions of the secondary data transmission. The basic idea is to perform data transmission on one frequency while sensing on another frequency. Once the first frequency has to be sensed, the other frequency is used for data transmission. If the sensing process detects a PU, instead of jumping back to the previously used frequency, another (free one) has to be used. One drawback of DFH is that a more complex radio front end – usually in form of two radios – is needed, since data transmission and sensing has to be performed in parallel.

The last approach is partial sensing (Figure 2.1(c)). Similarly to the DFH approach, it supports continuous data transmission. The idea is that not the whole spectrum of the PU is used for the secondary data transmission, but that some part is always left idle to perform periodic sensing. If a PU is detected, data transmission on the affected spectrum range has to be discontinued and other resources have to be used instead.

The approaches described above can be applied as local or distributed sensing process.

Assuming that for interrupted sending and DFH the whole bandwidth of the PU band is used for sensing, the probability of false positives for these approaches can be adjusted by varying the sensing time (given the upper bound of $t_{\max}$). For partial sensing in contrast, usually the total allowed time ($t_{\max}$) is used for sensing, such that the probability of false positives can be traded against the bandwidth used for the sensing process.

Chapter 3

Link Management

*S*econdary *U*sers create communication links to perform data transmission. We refer to these links as *S*econdary *U*ser *L*inks (SULs). SULs are built using idle spectral resources from the PUs. They have to be set up and maintained, which are the two major components of link management.

3.1 Link Definition

There are two possibilities how to define SULs: contiguous SULs and non-contiguous SULs (see Figure 3.1).

A contiguous SUL consists of a contiguous amount of spectrum. It can span a whole frequency band of a PU, multiple frequency bands, or only parts of a frequency band. Figure 3.1 shows three examples for contiguous SULs: one which only occupies parts of a PU frequency band (SUL 1), one which occupies a whole frequency band (SUL 2), and one, which occupies more than one PU frequency band (SUL 3). One example where the use of contiguous SULs is envisioned is within the IEEE 802.22 standardization [10].

Non-contiguous SULs consist of multiple, non-adjacent spectrum bands. One approach, introduced in [5, 11], is to divide the PU bands into small sub-channels. The idea is to scatter the sub-channels of an SUL over multiple PU frequency bands, such that (i) a reappearing PU is less affected (only one or two sub-channels are used), and (ii) only a very small number

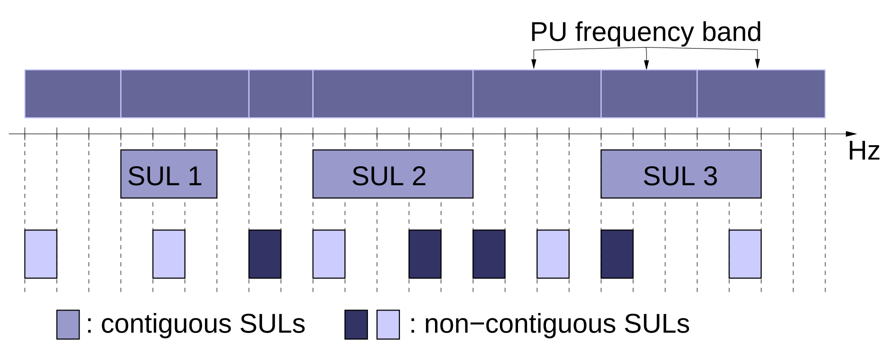


Figure 3.1: *S*econdary *U*ser *L*inks (SULs)

of sub-channels has to be exchanged in the SUL if a PU appears. Note that using this approach partial sensing can be naturally supported. In Figure 3.1 two non-contiguous SULs are shown.

3.2 Link Setup

As mentioned previously, before setting up an SUL, initial sensing has to be performed to determine spectral resources available for secondary communication. Based on these sensing results the SUL can be built in a centralized or distributed manner. In the centralized approach the central controller has to gather the sensing results of the communication peers, decide on which resources to use for the SUL, and distribute the decision back to the communication peers. In the distributed approach the communication peers jointly decide on which resources to use for the SUL.

Setup of an SUL only happens once at the beginning of the communication. Although the initial sensing and initial negotiation of parameters requires spectral overhead, the impact on the overall system performance is small assuming a long lifetime of the SUL. We will, thus, not investigate the influence of link setup in this paper.

3.3 Link Maintenance

During the lifetime of the SUL, it has to be periodically maintained and reconfigured, if necessary. Generally speaking, link maintenance is the process of surveying the spectral resources used for the SUL and adjusting them in case a PU appeared. Furthermore, maintaining the QoS of the link is also part of the link maintenance process. In this paper, we focus on assuring uninterrupted data transmission as a SU QoS metric. As with link setup, link maintenance can be realized in a centrally controlled or a distributed manner.

Link maintenance can be logically divided into three steps: periodic sensing to check whether a PU appeared, link reconfiguration in case the PU appeared, and QoS maintenance to assure uninterrupted data transmission.

Periodic sensing can be realized by the three different approaches introduced in Section 2.3. Link reconfiguration consists of *initial* spectrum sensing to find new spectral resources (as opposed to periodic sensing for revalidation of the used spectral resources) and the actual reconfiguration of the resources, which includes negotiating / deciding which new sub-channels to use for the SUL.

The spectral overhead required by the sensing processes has already been discussed in Section 2. The spectral overhead required by link reconfiguration mainly depends on the number of SUs participating in the SUL. The more SUs participate in the SUL, the more control traffic is required for the negotiation of the new resources and the longer is the duration of the reconfiguration process.

QoS maintenance to assure uninterrupted data transmission can be achieved in two ways: Either to not interrupt data transmission at all or, alternatively, to develop mechanisms to compensate for the interruptions.

For the first approach, the complete link maintenance process has to be executed in parallel to data transmission. Performing sensing in parallel to data transmission can be achieved by the partial sensing and DFH approaches introduced in Section 2.3. In order to be able to quickly reconfigure the link, some backup spectrum has to be reserved for the SUL, which is instantly available if a PU appears. We refer to this approach as *resource reservation* approach. Obviously, the amount of resources that are reserved for an SUL has an influence on the spectral overhead. An example for resource reservation is given in Section 5.1.

In the second QoS maintenance approach, interruptions in data tranmission are tolerated as long as they are compensated for. One way to achieve this is to add redundancy to the SUL such that even if *some* part of the SUL has to be interrupted, there is still enough spectrum available for the SUL to maintain the required QoS. We refer to this approach as *redundancy* approach. The amount of redundancy added to the SUL has a direct influence on the spectral overhead. An example for a redundancy approach can be found in Section 5.2.

Chapter 4

Spectral Availability

In the previous sections we have introduced the spectral overhead involved in both the sensing process and the link maintenance process needed for secondary link reconfiguration and QoS assurance. In order to make an orderly performance comparison of different opportunistic spectrum usage approaches transparent, we will now introduce some measures for efficiency of spectrum usage. For simplicity we consider in the following a spatial area small enough as to assure the *unified* availability or non-availability of spectrum for opportunistic re-usage. For such an "elementary area" we define spectral availability in terms of frequency and time availability. To quantify spectral availability, we conceptually slot the time axis into pieces of length $t_{\max}$ and define spectral availability at a basis of $t_{\max}$. We will differentiate between three notions of spectral availability.

4.1 Theoretical Spectral Availability

With the theoretical spectral availability ($C_{\max}$) we specify the spectrum which is not used by the PU within $t_{\max}$ and the elementary spatial unit under consideration. The theoretical spectral availability is the "ground truth" or the "Gods view" and reflects the real spectrum usage of the PU. It can be seen as a benchmark to compare the performance of different DSA approaches. Up to now, there are only very limited (public) research efforts for analyzing the theoretical spectral availability. Part of the reason is that in-network data is needed, which network providers often are not willing to share. However, in a cooperation with a big U.S. network provider we were able to publish one of the first investigations in this direction [12, 13]. Another example is the evaluation of the TV station database for the U.S. [3] as required by the IEEE 802.22 standard.

4.2 Sensed Spectral Availability

The sensed spectral availability (C_{sens}) is the spectrum sensed to be idle, i.e., not used by a PU and is, thus, an estimate of the theoretical availability achieved using a given sensing approach. How close this estimate comes to the theoretical availability depends on the quality of the sensing process.

Let us remind of our assumption that sensing has to assure non-interference with the PU beyond the permitted limits: no interference is allowed if the primary is in continuous operation, and interference has to be limited to t_{max} in case of the PU re-appearing from an idle state. The required non-interference with PUs implies that the sensing process has to provide some very limited probability of false negatives. Thus, the sensed spectral availability only depends on the probability of false positives. It specifies how much of the idle spectrum can be discovered without declaring used spectrum as idle.

There are many analytical works on the quality of sensing algorithms (e.g. [1–3]) and there is a huge set of spectrum measurements to show the underutilization of spectrum (e.g. [14–17]) by doing wide-band spectrum measurement. However, there is very limited work on validating the analytical or measurement results against the *real* spectrum usage (theoretical availability). There are some campaigns trying to analyze the usage of the cellular bands [15, 18], but they do not compare their results with the real usage. For the TV white spaces an actual comparison of theoretical and sensed availability is presented in [19].

4.3 Effective Spectral Availability

In Section 2 we have explicitly indicated that each sensing approach requires some spectral overhead: keeping some spectrum resources unused in order to make sensing possible. In fact this pertains not only to the spectrum which is to be kept unused in order not to disturb the sensing, but it also pertains to the frequency band needed for signaling: bringing together the sensed data in order to jointly evaluate them (in case of distributed sensing). The definition of the sensed spectral availability ignores this need.

Additionally, as indicated in Section 3, also the link maintenance process requires some spectral overhead: backup spectrum / redundancy to maintain uninterrupted data transmission and additional spectrum for signaling (to negotiate the reconfiguration of the SUL).

Therefore, we introduce the additional concept of effective spectral availability (C_{eff}) being the part of the spectrum which actually can be used for secondary data transmission according to the spectrum sensing results achieved on the basis of reserved spectral overhead.

Whereas there is already a lot of work on distributed sensing algorithms or merging strategies for sensing results [1, 2, 20–24], the work on quantifying the communication overhead and required time for distributed sensing or link maintenance is very limited.

Chapter 5

Link Maintenance Approaches

The underlying system model we assume for the investigations presented in this paper is based on *O*rthogonal *F*requency *D*ivision *M*ultiplexing (OFDM), which means that spectrum sensing can be done *in parallel* for the whole operation range of the secondary network. Thus, during the *periodic* sensing on the used resources also the rest of the spectrum can be sensed, proactively identifying free resources usable if the PU appears on a used resource (*initial* sensing).

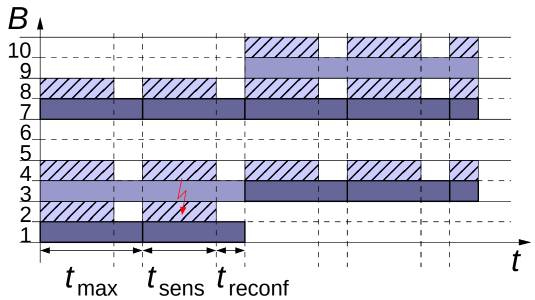
The QoS metric considered is support of uninterrupted data transmission. We, thus, do not consider the interrupted sending approach anymore, since this approach – by design – requires interruptions of the data transmission to perform sensing.

For our investigation, we consider DFH and a CORVUS [5] based system model supporting partial sensing. Both system models are designed to support uninterrupted data transmission, since sensing is performed in parallel to data transmission. We, thus, have to develop link maintenance mechanisms that also do not interrupt data transmission or, alternatively, develop mechanisms to compensate for the interruptions. In this paper, we investigate two such approaches: a *resource reservation* and a *redundancy* approach.

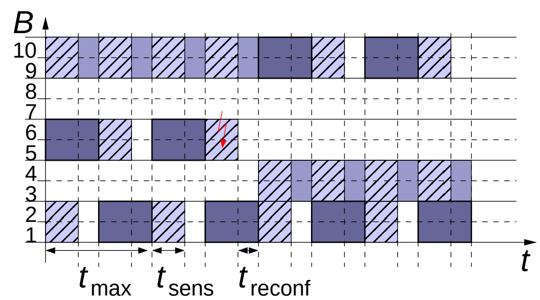
Figure 5.1 shows both approaches, using DFH and partial sensing. For the examples we assume five different PU bands each consisting of two sub-channels and an SUL also consisting of $N_{\text{sul}} = 2$ sub-channels. The dark areas correspond to data transmission periods, whereas the light, shaded areas indicate spectrum sensing periods. For the resource reservation approach, the light unshaded areas mark reserved resources. DFH is designed to work with contiguous SULs spanning a whole PU frequency band, whereas the partial sensing approach naturally supports non-contiguous SULs.

5.1 Resource Reservation Approach

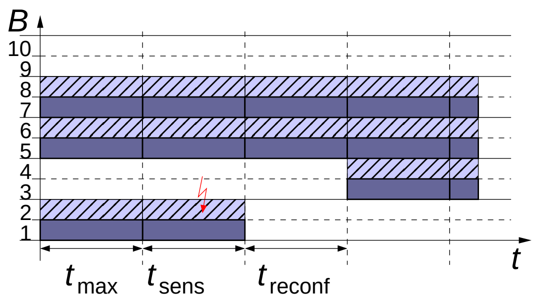
The idea of the *resource reservation* approach is to never interrupt data transmission. Consequently, spectrum sensing and link reconfiguration have to be performed in parallel to data transmission. Furthermore, it has to be assured that, each time a PU appears, some backup spectrum is *instantaneously* available. Thus, in addition to the normal resources used for the SUL, additional backup resources need to be maintained. In Figures 5.1(a) & 5.1(b) the light unshaded areas mark the backup sub-channels. As the regular sub-channels of the SUL, the



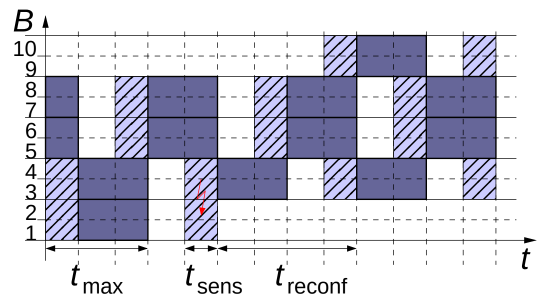
(a) Partial sensing & resource reservation



(b) DFH & resource reservation



(c) Partial sensing & redundancy



(d) DFH & redundancy

Figure 5.1: Link maintenance approaches

backup sub-channels have to be regularly sensed to ensure that no PU appeared. They, thus, can be immediately used if a sub-channel of the SUL needs to be exchanged.

Figure 5.1(a) shows the partial sensing approach using the resource reservation link maintenance approach. In the example we use one sub-channel of the PU band for sensing, and one for data transmission. Note, that sensing cannot be performed over the whole data transmission period, since also the resource reconfiguration (having a duration of t_{reconf}) needs to be performed in parallel to data transmission. The sensing time, thus, has to be limited to $t_{\text{sens}} = t_{\text{max}} - t_{\text{reconf}}$.

In Figure 5.1(a), initially, sub-channels 1 and 7 are used for the SUL and sub-channel 3 is maintained as a backup sub-channel[1]. During the second sensing period, the PU covering the first two sub-channels appears and consequently sub-channel 1 has to be vacated. During the resource reconfiguration period (t_{reconf}) a replacement for sub-channel 1 has to be selected from the backup sub-channels and in addition a new backup sub-channel has to be selected (sub-channel 9 in our example). At the end of t_{max} also the reconfiguration (t_{reconf}) is finished so that data transmission can be continued on sub-channels 3 and 7 without interrupting the data transmission.

In Figure 5.1(b) we show the same process for DFH. Note that, since in DFH sub-channels of an SUL are not spread over multiple PUs, also the backup sub-channels have to be multiples of the number of sub-channels required for the SUL. Also, since resource

[1]Although we are only showing one backup sub-channel in our example, there will generally be more than one, so that a selection process has to take place if the SUL needs to be reconfigured.

reconfiguration (t_{reconf}) needs to be done in parallel to data transmission, sensing cannot be done at the end of $t_{\max}$ but has to be shifted by t_{reconf}. This effectively means, that the data transmission period has to be shortened to $t_{\max} - t_{\text{sens}} - t_{\text{reconf}}$.

5.2 Redundancy Approach

The *redundancy* approach – in contrast to the resource reservation approach – does not try to avoid interruption of data transmission, but instead to compensate for QoS loss due to interruptions. Consequently, link reconfiguration does not have to be done in parallel to data tranmission anymore, but can be done sequentially with data transmission.

In the redundancy approach rate-less erasure codes are used to add additional redundant sub-channels to the SUL. The basic idea is to add X redundant sub-channels to the N_{sul} sub-channels of the SUL. The receiver can decode the message, if *any* N_{sul} out of the $N_{\text{sul}}+X$ sub-channels are received. For details please refer to [9]. Using this approach the SUL can tolerate the concurrent appearance of PUs on up to X sub-channels and still achieve the requirement of uninterrupted data transmission.

In Figure 5.1(c) we show partial sensing using the redundancy approach. In the example we use $X = 1$ redundant sub-channels resulting in a total number of 3 sub-channels used for the SUL (sub-channels 1, 5, and 7). In the second sensing period the PU covering sub-channels 1 and 2 appears, such that sub-channel 1 has to be excluded from the SUL. However, the QoS requirement is nevertheless satisfied since there are still two sub-channels available for the SUL. During the next data transmission period, resource reconfiguration has to be performed, which means to add new redundant sub-channels to the SUL. For this approach, the only constraint on resource reconfiguration is $t_{\text{reconf}} \leq t_{\max}$.

Figure 5.1(d) shows DFH using the redundancy approach. For DFH (as already explained for the resource reservation) redundancy has to be added in multiples of N_{sul}. As shown in Figure 5.1(d), for DFH, resource reconfiguration can have a duration of up to $t_{\text{reconf}} = 2 \cdot (t_{\max} - t_{\text{sens}})$, since DFH alternates between the usage of two different “resource blocks”.

Chapter 6

Performance Tradeoffs

In this section we present a performance analysis for the four different link maintenance approaches introduced in the previous section. We compare the different approaches based on their effective spectral availability (C_{eff}), given the constraints of non-interference to the PU and maintenance of uninterrupted data transmission.

In this paper we only consider the spectral overhead of the local sensing process and do not evaluate the influence of distributed sensing. Furthermore, we do not consider the influence of spectral resources needed to exchange control information. The investigation of distributed sensing approaches and the overhead due to control traffic is subject to future work.

Using the link maintenance approaches introduced in Section 5 and the spectral efficiency definition of Section 4 we investigate the performance of the different approaches with respect to the achieved effective availability. We first calculate the effective availability only considering the overhead of spectrum sensing and link reconfiguration (C_{rec}) and based on C_{rec} the overall spectral efficiency (C_{eff}) also considering the overhead to support uninterrupted data transmission.

6.1 System Model

For the performance analysis we consider a scenario with N_{pu} PUs each covering a bandwidth of B hertz divided into N_{sub} sub-channels of bandwidth B_{sub}. The maximum interference time of all PUs is $t_{\max}$. The probability that a PU is active within $t_{\max}$ is set to P_{pu}. With P_{fn} and P_{fp} we denote the probability of false negatives and false positives, respectively, and with $P_{\text{d}} = 1 - P_{\text{fn}}$ the probability of detecting the PU.

Assuming a slotted system (with a slot length of $t_{\max}$) we define the total spectral availability per slot as

$$C_{\text{tot}} = N_{\text{pu}} \cdot B \cdot t_{\max} \ . \tag{6.1}$$

The theoretical spectral availability for the SU system is

$$C_{\max} = (1 - P_{\text{pu}}) \cdot C_{\text{tot}} \ . \tag{6.2}$$

In the following, we will use $C_{\max}$ as a reference and define all other availabilities as a fraction of $C_{\max}$.

The sensed availability is determined by the probability of false positives, i.e., the theoretical availability less the reduction in spectral availability due to false positives:

$$C_{\text{sens}} = C_{\max} - P_{\text{fp}} \cdot (1 - P_{\text{pu}}) \cdot N_{\text{pu}} \cdot B \cdot t_{\max} \ , \tag{6.3}$$

or defined as a fraction of $C_{\max}$:

$$C_{\text{sens}} = 1 - P_{\text{fp}} \ . \tag{6.4}$$

As introduced in Section 2, the probability of false positives (P_{fp}) depends on the amount of spectrum (time-bandwidth product) used for sensing. This can be quantified by the number of sensing samples (N). In the time domain, N depends on the sensing time t_{sens} and the sampling frequency f_{s}. The requirement of having i.i.d. sensing samples puts an upper limit on f_{s}. In our study, we assume to always use the maximum sampling frequency f_{s} to still get i.i.d. samples. Furthermore, we assume that the SUs use OFDM based sensors, such that N_{sens} power samples are recorded in parallel with N_{sens} being the number of sub-channels used for sensing. In order to get i.i.d. samples in the frequency domain, the bandwidth of a sub-channel cannot be smaller than the coherence bandwidth. We choose the width of a sub-channel to be exactly the coherence bandwidth. Given the mentioned constraints, N computes to

$$N = N_{\text{sens}} \cdot t_{\text{sens}} \cdot f_{\text{s}} \ . \tag{6.5}$$

For the calculation of P_{fp} we use the formula introduced in [7], which defines P_{fp} as a function of the number of power samples (N) used:

$$P_{\text{fp}}(N) = Q\left(\sqrt{2\gamma+1}\, Q^{-1}(P_{\text{d}}) + \sqrt{N}\,\gamma\right) \ , \tag{6.6}$$

with $Q(x)$ being the Q-function and γ the received *S*ignal-to-*N*oise *R*atio (SNR). For details please refer to [7].

An SUL consists of N_{sul} sub-channels and the time needed for reconfiguration of the link is specified by t_{reconf}. If not otherwise stated we use the following values for our analysis: $N_{\text{pu}} = 100$, $N_{\text{sub}} = 50$, $N_{\text{sul}} = 10$, $P_{\text{pu}} = 0.2$, $P_{\text{d}} = 0.99$, $f_{\text{s}} = 500\,\text{kHz}$, $t_{\max} = 0.5\,\text{s}$, and $t_{\text{reconf}} = 0.1\,\text{s}$.

6.2 Partial Sensing

Looking at Figures 5.1(a) & 5.1(c), the overhead for partial sensing only depends on the number of sub-channels used for sensing (N_{sens}). Note that although the sensing time in the resource reservation approach (Figure 5.1(a)) is only $t_{\text{sens}} = t_{\max} - t_{\text{reconf}}$, the remaining time cannot be used for data transmission, since it is assumed that the sensing sub-channels are always reserved and cannot be used for data transmission. Thus, for the reservation as well as for the redundancy approach, C_{rec} computes to

$$C_{\text{rec}} = C_{\text{sens}}\left(1 - \frac{N_{\text{sens}}}{N_{\text{sub}}}\right) \ . \tag{6.7}$$

The only difference between the two approaches is in the calculation of the number of sensing samples N and thus P_{fp}. In the reconfiguration approach the sensing time in Equation (6.5) has to replaced by $t_{\text{sens}} = t_{\max} - t_{\text{reconf}}$, whereas in the redundancy approach the whole slot can be used for sensing $t_{\text{sens}} = t_{\max}$.

In order to calculate the overhead needed to assure uninterrupted data transmission, we need to calculate the number of sub-channels to reserve for the SUL (for the reservation approach) or the number of redundant sub-channels to add to the SUL (for the redundancy approach). These additional sub-channels are needed, if the SUL needs to be reconfigured. The probability that the link needs to be reconfigured (P_{rec}) depends on the appearance probability of the PU (P_{pu}) and the probability of false positives (P_{fp}) and computes to

$$P_{\text{rec}} = P_{\text{pu}} \cdot P_{\text{d}} + (1 - P_{\text{pu}}) \cdot P_{\text{fp}} \ . \tag{6.8}$$

Using P_{rec} we can calculate the probability that there are not enough sub-channels available for the SUL, such that data transmission needs to be interrupted (P_{int}). Assuming that we reserve X additional sub-channels for the reservation approach (or add X redundant sub-channels in case of the redundancy approach), the probability that data transmission has to be interrupted since there are not enough sub-channels available computes to [9]

$$P_{\text{int}} = \sum_{i=1}^{N_{\text{sul}}} \binom{N_{\text{sul}} + X}{X + i} {P_{\text{rec}}}^{X+i} (1 - P_{\text{rec}})^{N_{\text{sul}} - i} \ . \tag{6.9}$$

Setting the target probability of interruption to $P_{\text{int}} = 0.01$ we can numerically find the optimal number of reserved / redundant sub-channels X_{opt} satisfying this criteria. Using X_{opt} sub-channels for the two maintenance approaches, C_{eff} computes to

$$C_{\text{eff}} = C_{\text{rec}} \left(1 - \frac{X_{\text{opt}}}{N_{\text{sul}} + X_{\text{opt}}}\right) \ . \tag{6.10}$$

6.3 *D*ynamic *F*requency *H*opping

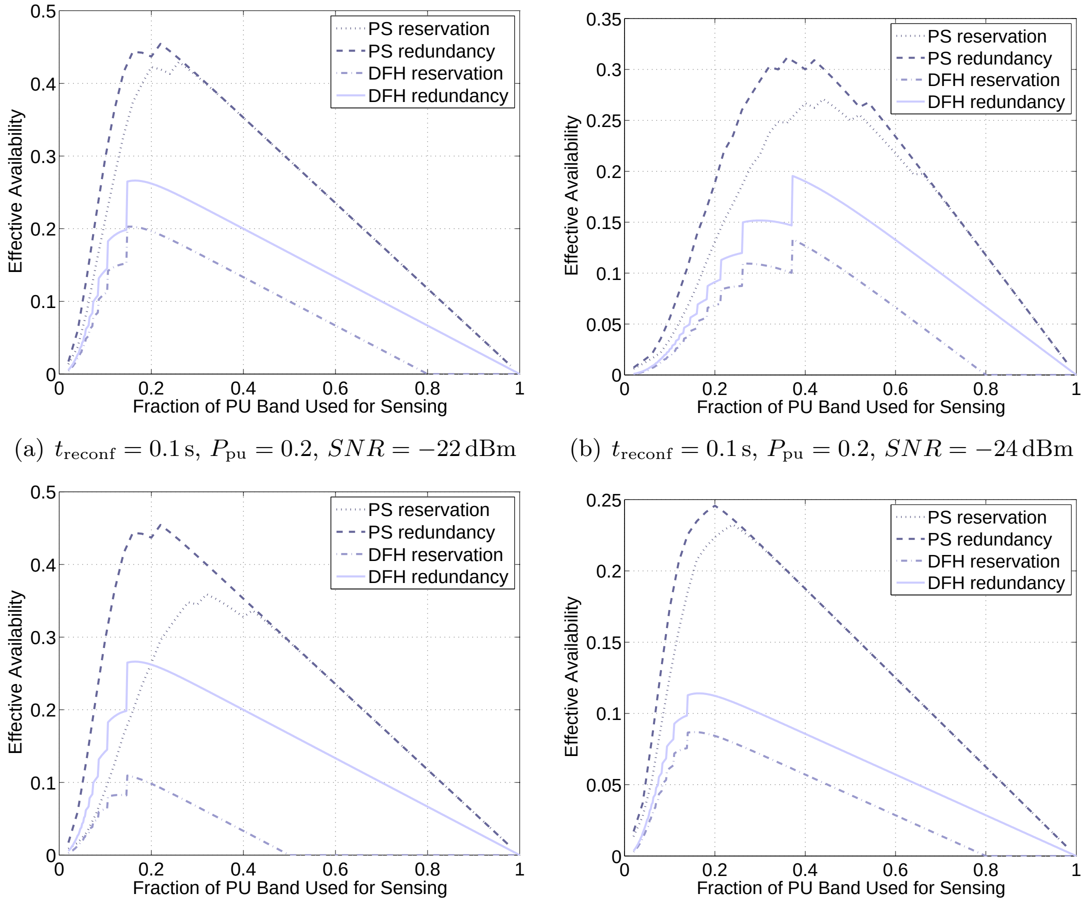
For DFH, always the whole PU band is used for sensing, so in order to calculate P_{fp} we need to replace $N_{\text{sens}} = N_{\text{sub}}$ in Equation (6.5). The overhead due to sensing and link maintenance depends on the chosen approach (resource reservation or redundancy). As can be seen in Figure 5.1(d), for the redundancy approach C_{rec} only depends on the sensing time and computes to

$$C_{\text{rec}} = C_{\text{sens}} \left(1 - \frac{t_{\text{sens}}}{t_{\max}}\right) \ . \tag{6.11}$$

For the resource reservation approach, in order to reconfigure the link without interruption of data tranmission, t_{sens} has to be shifted by t_{reconf} as can be seen in Figure 5.1(b). Consequently, C_{rec} computes to

$$C_{\text{rec}} = C_{\text{sens}} \left(1 - \frac{t_{\text{sens}} + t_{\text{reconf}}}{t_{\max}}\right) \ . \tag{6.12}$$

To calculate the spectral efficiency we need the probability that the link needs to be reconfigured (Equation (6.8)). For DFH the whole SUL is placed within one PU band, so that we always need to reserve / add multiples of N_{sul} sub-channels. Assuming that we add



(a) $t_{\text{reconf}} = 0.1\,\text{s},\ P_{\text{pu}} = 0.2,\ SNR = -22\,\text{dBm}$

(b) $t_{\text{reconf}} = 0.1\,\text{s},\ P_{\text{pu}} = 0.2,\ SNR = -24\,\text{dBm}$

(c) $t_{\text{reconf}} = 0.25\,\text{s},\ P_{\text{pu}} = 0.2,\ SNR = -22\,\text{dBm}$

(d) $t_{\text{reconf}} = 0.1\,\text{s},\ P_{\text{pu}} = 0.5,\ SNR = -22\,\text{dBm}$

Figure 6.1: Spectral efficiency (C_{eff}) for the four different link maintenance approaches

$X \cdot N_{\text{sul}}$ sub-channels, the probability of interruption of the data transmission (P_{int}) computes to

$$P_{\text{int}} = {P_{\text{rec}}}^{(1+X)} \ . \tag{6.13}$$

Choosing a target probability of interruption of $P_{\text{int}} = 0.01$, we can calculate the optimal number of reserved /redundant sub-channels to $X_{\text{opt}} \cdot N_{\text{sul}}$ and with this the effective availability to

$$C_{\text{eff}} = C_{\text{rec}} \left(1 - \frac{X_{\text{opt}} N_{\text{sul}}}{N_{\text{sul}}(1 + X_{\text{opt}})}\right) \ . \tag{6.14}$$

6.4 Performance Results

In Figure 6.1 we present the performance results of the four investigated link maintenance approaches for different sets of parameters. For all approaches there exists an optimal amount of spectrum to use for sensing which maximizes the effective availability. This is due to the adverse effects of the amount of spectrum used for sensing and the amount of spectrum which is required for link maintenance and is falsely declared as occupied (reduction in spectral availability due to false positives).

Looking, e.g., at the partial sensing redundancy approach in Figure 6.1(a), the maximum availability is reached if 22% of the sub-channels are used for sensing. Using less sub-channels for sensing increases the probability of false positives which reduces the spectrum available for secondary communication. Furthermore, an increase of false positives results in a higher probability of link reconfiguration and thus requires more sub-channels to be reserved in order to ensure uninterrupted data transmission. On the other hand, increasing the amount of spectrum used for sensing further reduces the effect of false positives but also results in more spectrum blocked for sensing and, thus, not usable for data transmission. Using less spectrum for sensing than the optimum, false positives are the dominating effect on the effective availability whereas using more than the optimum the spectrum blocked for sensing is the dominating effect on the availability.

Comparing the different approaches, we can see that the partial sensing approach always outperforms the DFH approach. In fact, it roughly only requires half the spectral overhead for most parameter combinations shown. This is mainly due to the fact that the granularity of the amount of reserved spectrum / spectrum used as redundancy is much finer. In the DFH approach only multiples of the whole SUL can be used whereas in the partial sensing approach the granularity is on sub-channel basis.

It can also be seen that the redundancy approach always outperforms the resource reservation approach. Note, that the amount of redundancy needed is equal to the amount of resources that need to be reserved. Thus, for partial sensing, the difference between the two approaches stems from the difference in time available for sensing. Since the sensing time has to be shortened in the reservation approach, its performance is worse. For the DFH approach, the difference is because, for the reservation approach, in addition to sensing also resource reconfiguration has to be performed in parallel to data transmission further reducing the effective availability.

Note, however, that if the performance of multiple SULs is considered, the reservation approach has the advantage of a potential multiplexing gain. Instead of having each SUL maintaining its own set of backup spectrum, multiple SULs could cooperatively maintain a common backup spectrum resulting in an increase of the overall spectral efficiency. This is especially attractive for the DFH approach, which depends on a cooperative frequency selection in order to operate in a spectrum efficient way [6, 25]. We plan to investigate the joint spectral efficiency of multiple SULs in future work.

Comparing Figure 6.1(a) with Figure 6.1(b) shows the effect of the SNR on the spectral efficiency and optimal amount of sensing spectrum. A lower SNR results in a more difficult detection of the PU, i.e., more sensing spectrum is required to achieve the maximum availability. Consequently, also the overall efficiency is degraded. The comparison of Figure 6.1(a) and Figure 6.1(d) shows the effect of an increased PU activity: The SUL has to be reconfigured more often resulting in more resources needed to support uninterrupted data transmission, resulting in a decreased spectral efficiency.

Finally, comparing Figure 6.1(a) and Figure 6.1(c) shows the effect of t_{reconf}. Whereas the redundancy approaches are not influenced by t_{reconf} (as long as it is below the bounds specified in Section 5), the effective availability is greatly impacted in the reservation approach.

Note, that in non of the figures shown, the effective availability exceeds 50%. Part of

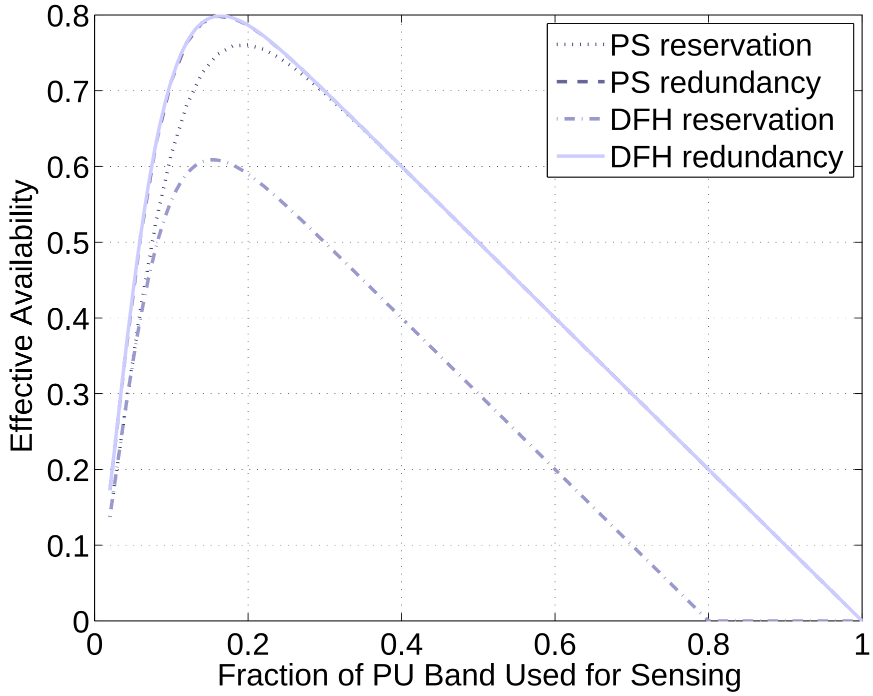


Figure 6.2: Effective Availability (C_{rec}) only considering sensing and link maintenance overhead. Note that the DFH redundancy curve disguises the partial sensing redundancy curve.

the reason is that we show results for very low SNR values. However, in Figure 6.2 we show the effective availability only considering spectral overhead due to sensing and link reconfiguration using the same parameter set as Figure 6.1(a). Comparing both figures, we can see that for the DFH approaches a considerable amount of spectrum is required to assure uninterrupted data transmission. Looking, e.g., at the DFH redundancy approach, more than 50% of the spectrum is required (using the optimal sensing time) to ensure uninterrupted data transmission, whereas only 20% are required for sensing. For the partial sensing approaches in contrast spectral overhead for sensing and QoS assurance are within the same range.

Chapter 7

Conclusions

In this paper we investigate two approaches to support uninterrupted data transmission for secondary communication given the constraint of assuring the protection of the PU: a resource reservation and a redundancy approach. We investigate both approaches using *D*ynamic *F*requency *H*opping (DFH) and partial sensing and compare the performance with respect to their spectral efficiency. The key finding of this paper are:

- There is a tradeoff between the spectral overhead required for spectrum sensing and the spectral overhead due to false positives, resulting in an optimal amount of spectrum to use for sensing in order to maximize the spectral efficiency.
- The partial sensing approach clearly outperforms DFH, since the optimal amount of resources used to ensure uninterrupted data transmission can be selected on finer granularity.
- Not considering a potential multiplexing gain by multiple *S*econdary *U*ser *L*inks (SULs) jointly maintaining backup spectrum, the redundancy approach outperforms the resource reservation approach.

Whereas we only considered selected influences on the spectral availability, our results indicate that there are various factors influencing the spectral efficiency. We hope that our work motivates and fosters further research in this area.

In the future, we plan to extend our work by investigating the effects of distributed sensing and the influence of and requirements on control communication. Furthermore, we plan to investigate the joint performance of multiple SULs.

Appendix A

Acronyms

CORVUS *CO*gnitive *R*adio for usage of *V*irtual *U*nlicensed *S*pectrum

CR *C*ognitive *R*adio

DFH *D*ynamic *F*requency *H*opping

DSA *D*ynamic *S*pectrum *A*ccess

IEEE *I*nstitute of *E*lectrical and *E*lectronics *E*ngineers (www.ieee.org)

OFDM *O*rthogonal *F*requency *D*ivision *M*ultiplexing

PU *P*rimary *U*ser

QoS *Q*uality *o*f *S*ervice

SNR *S*ignal-to-*N*oise *R*atio

SU *S*econdary *U*ser

SUL *S*econdary *U*ser *L*ink

t_{max} maximum interference time

t_{sens} local sensing time

t_{reconf} reconfiguration time

B bandwidth of one PU

B_{sub} bandwidth of a single sub-carrier

C_{tot} total capacity

C_{max} theoretical spectral availability capacity

C_{sens} sensed spectral availability

C_{eff} effective spectral availability

C_{rec} effective spectral availability considering sensing and link maintenance overhead

P_{pu} probability of PU appearance

P_{fp} probability of false positives

P_{fn} probability of false negatives

P_{d} probability of detection

P_{rec} probability of link reconfiguration

P_{int} probability that link has to be interrupted

f_{s} sampling frequency

N number of samples

N_{sub} number of sub-carriers

N_{sens} number of sub-carriers used for sensing

N_{pu} number of primary user

N_{sul} number sub-carrier per SUL

X number redundant sub-carrier per SUL

X_{opt} optimal number redundant sub-carrier per SUL

References

[1] T. Weiss, J. Hillenbrand, and F. Jondral, "A diversity approach for the detection of idle spectral resources in spectrum pooling systems," in *Proceedings of the 48th International Science Colloquium*, Ilmenau, Germany, September 2003.

[2] A. Sahai, R. Tandra, S. M. Mishra, and N. Hoven, "Fundamental design tradeoffs in cognitive radio systems," in *TAPAS '06: Proceedings of the first international workshop on Technology and policy for accessing spectrum*. New York, NY, USA: ACM Press, 2006, p. 2.

[3] R. Tandra, S. M. Mishra, and A. Sahai, "What is a spectrum hole and what does it take to recognize one?" *Proc. IEEE*, vol. 97, no. 5, pp. 824–848, May 2009.

[4] X. Gelabert, I. F. Akyildiz, O. Sallent, and R. Agustí, "Operating point selection for primary and secondary users in cognitive radio networks," *Compututer Networks*, vol. 53, no. 8, pp. 1158–1170, 2009.

[5] R. W. Broderson, A. Wolisz, D. Cabric, S. M. Mishra, and D. Willkomm, "CORVUS: A cognitive radio approach for usage of virtual unlicensed spectrum," White Paper, 2004.

[6] W. Hu, D. Willkomm, L. Chu, M. Abusubaih, J. Gross, G. Vlantis, M. Gerla, and A. Wolisz, "Dynamic frequency hopping communities for efficient IEEE 802.22 operation," *IEEE Commun. Mag.*, vol. 45, no. 5, pp. 80–87, May 2007.

[7] Y.-C. Liang, Y. Zeng, E. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326–1337, 2008.

[8] E. C. Y. Peh, Y. C. Liang, Y. L. Guan, and Y. Zeng, "Optimization of cooperative sensing in cognitive radio networks: A sensing-throughput tradeoff view," *IEEE Trans. Veh. Technol.*, vol. PP, pp. 1–1, 2009, accepted for future publication Vehicular Technology.

[9] D. Willkomm, J. Gross, and A. Wolisz, "Reliable link maintenance in cognitive radio systems," in *Proceedings of the 1st IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore (MD), Nov. 2005, pp. 371–378.

[10] "IEEE 802.22 working group." [Online]. Available: http://www.ieee802.org/22

[11] D. Cabric, S. M. Mishra, D. Willkomm, R. W. Broderson, and A. Wolisz, "A cognitive radio approach for usage of virtual unlicensed spectrum," in *14th IST Mobile Wireless Communications Summit 2005*, Dresden, Germany, June 2005.

[12] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, "Primary users in cellular networks: A large-scale measurement study," in *Proceedings of the 3rd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2008 (DySPAN 2008)*, Chicago, IL, Oct. 2008.

[13] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, "Primary user behavior in cellular networks and implications for dynamic spectrum access," *IEEE Commun. Mag.*, vol. 47, no. 3, pp. 88–95, Mar. 2009.

[14] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C. S. Hood, "Chicago spectrum occupancy measurements & analysis and a long-term studies proposal," in *TAPAS '06:*

Proceedings of the first international workshop on Technology and policy for accessing spectrum. New York, NY, USA: ACM Press, 2006, p. 1.

[15] O. Holland, P. Cordier, M. Muck, L. Mazet, C. Klock, and T. Renk, "Spectrum power measurements in 2G and 3G cellular phone bands during the 2006 football world cup in germany," in *Proceedings of the 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2007 (DySPAN 2007)*, Apr. 2007, pp. 575–578.

[16] J. T. MacDonald, "A survey of spectrum occupancy in chicago," Illinois Institute of Technology, Tech. Rep., 2007.

[17] Shared Spectrum Company, "Recent spectrum measurements." [Online]. Available: http://www.sharedspectrum.com/measurements/recent.html

[18] T. Kamakaris, M. M. Buddhikot, and R. Iyer, "A case for coordinated dynamic spectrum access in cellular networks," in *Proceedings of the 1st IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore (MD), Nov. 2005, pp. 289–298.

[19] M. Mishra and A. Sahai, "How much white space is there?" EECS Department, University of California, Berkeley, Tech. Rep. UCB/EECS-2009-3, Jan. 2009. [Online]. Available: http://www.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-3.html

[20] E. Peh and Y.-C. Liang, "Optimization for cooperative sensing in cognitive radio networks," in *Proceedings of the IEEE Wireless Communications and Networking Conference, 2007 (WCNC 2007)*, Mar. 2007, pp. 27–32.

[21] P. Qihang, Z. Kun, W. Jun, and L. Shaoqian, "A distributed spectrum sensing scheme based on credibility and evidence theory in cognitive radio context," in *Proceedings of the 17th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2006 (PRIMRC '06)*, Sep. 2006, pp. 1–5.

[22] C. Sun, W. Zhang, and K. B. Letaief, "Cooperative spectrum sensing for cognitive radios under bandwidth constraints," in *Proceedings of the IEEE Wireless Communications and Networking Conference, 2007 (WCNC 2007)*, Mar. 2007, pp. 1–5.

[23] N. Ahmed, D. Hadaller, and S. Keshav, "GUESS: gossiping updates for efficient spectrum sensing," in *MobiShare '06: Proceedings of the 1st international workshop on Decentralized resource sharing in mobile computing and networking.* New York, NY, USA: ACM Press, 2006, pp. 12–17.

[24] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *Proceedings of the 1st IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) 2005*, Baltimore (MD), Nov. 2005, pp. 131 – 136.

[25] D. Willkomm, M. Bohge, D. Hollós, J. Gross, and A. Wolisz, "Double hopping: A new approach for dynamic frequency hopping in cognitive radio networks," in *Proceedings of the 19th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2008 (PIMRC 2008)*, Sep. 2008.