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# COgnitive Ultra-Wide BAckhaul Transmission system – COUWBAT Technical Report

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## Abbreviations

- AMC** Adaptive Modulation and Coding
- ARQ** Automatic Repeat reQuest
- BP** Beacon Period
- BPSK** Binary Phase Shift Keying
- CB** Connectivity Brokerage
- CBP** Coexistence Beacon Protocol
- CDF** Cumulative Distribution Function
- COUWBAT** COgnitive Ultra-WideBand Transceiver
- CoV** Coefficient of Variation
- CQI** Channel Quality Indicator
- CR** Cognitive Radio
- CR-BS** Cognitive Radio – Base Station
- CRC** Cyclic Redundancy Check
- CRN** Cognitive Radio Network
- CSMA** Carrier Sense Multiple Access
- CSW** Contention Signaling Window
- CR-STA** Cognitive Radio – Client Station
- DA** Destination Address
- DAMA** Demand-Assigned Multiple Access
- DFS** Dynamic Frequency Selection
- DL** DownLink
- DS** Downlink Subframe
- DSA** Dynamic Spectrum Access

**DTP** Data Transfer Period

**EIRP** Equivalent Isotropically Radiated Power

**ETSI** European Telecommunications Standards Institute

**EUT** End-User Terminal

**FCC** U.S. Federal Communications Commission

**FCS** Frame Control Sequence

**FDMA** Frequency Division Multiple Access

**FSM** Finite-State Machine

**FTP** File Transfer Protocol

**GSM** Global System for Mobile Communications

**HFT** High Frequency Technique

**HTTP** Hyper Text Transfer Protocol

**IP** Internet Protocol

**ISI** Inter Symbol Interference

**ISM** Industrial Scientific and Medical

**LTF** Long Training Field

**MAC** Media Access Control layer

**MIMO** Multiple Input Multiple Output

**MPDU** MAC Protocol Data Unit

**NC-OFDM** Non-Continuous OFDM

**ND** Neighbor Discovery

**OFDM** Orthogonal Frequency Division Multiplexing

**OSA** Opportunistic Spectrum Access

**PAPR** Peak-to-Average Power Ratio

**PHY** PHYsical layer

**PLCP** Physical Layer Convergence Procedure

**PSS** Primary Synchronization Sequence

- PU** Primary User
- QAM** Quadrature Amplitude Modulation
- QPSK** Quadrature Phase Shift Keying
- QP** Quiet Period
- QoS** Quality Of Service
- RB** Resource Block
- RR** Radio Resources
- RRC** Radio Resource Control
- RSW** Reservation-based Signaling Window
- SA** Source Address
- SB** Spectrum Broker
- SCH** Superframe Control Header
- SCW** Self-Coexistence Window
- SDB** Spectrum DataBase
- SIG** Signal Field
- SR** Selective Repeat
- STF** Short Training Field
- SU** Secondary User
- TPC** Transmit Power Control
- TU** Technische Universität
- TVWS** TV White Spaces
- UCS** Urgent Coexistence Situation
- UL** UpLink
- US** United States
- UWB** Ultra-WideBand



# Chapter 1.

## Introduction

Future mobile wireless networks are faced with an increasing demand for higher data rates. Some studies e.g., [1], predict that the mobile traffic will increase more than 1000 times over the next decade. Furthermore, with the expected proliferation of machine-to-machine communication the number of wireless devices will increase to 7 Trillion by next year 2017 [2].

Due to the high costs of frequency spectrum these systems need to be extremely efficient in terms of the spectrum usage, i.e., bit/s/Hz. One promising approach to provide the expected high data rates is the use of small wireless cells which enable wireless data offloads from the wide-area networks (e.g., cellular networks). Small cells create new wireless capacity at locations where many users are and allow the spatial reuse of the available spectrum.

A major challenge for the deployment of small cells is the required backhauling network. A wired backhaul is not always possible or sometimes too expensive. There are various solutions for a wireless backhauling like mmWave (60 GHz) or directional antennas in licensed spectrum. In this report we are targeting a wireless backbone solution for wireless small cells based on a wideband overlay Cognitive Radio (CR) system.

An overlay Cognitive Radio system exploits the circumstance that despite a static spectrum allocation, where governmental agencies assign wireless spectrum to license holders on a long-term basis for large geographical regions, a large number of frequency bands have considerable, temporary, dormant time intervals, leading to underutilization of a significant amount of spectrum. Cognitive Radio was proposed by Mitola [3] to solve these spectrum inefficiency problems by allowing secondary spectrum usage based on Opportunistic Spectrum Access (OSA). OSA is the key technology which allows to share the wireless channel with licensed users in an opportunistic manner.

The requirements regarding the capacity of the envisioned wireless backhaul for small cells are high, i.e., peak data rates of several Gbit/s are expected. Thus, a narrowband CR will unlikely meet these requirements and we therefore target on a wideband CR system using several hundreds of MHz of spectrum (e.g., 512 MHz). However, the challenge in such a wideband overlay CR system is the efficient use of the available spectrum snippets scattered over a large part of the radio spectrum. Here Non-Continuous OFDM (NC-OFDM) seems to be a promising approach allowing to efficiently shape the spectrum by disabling a fraction of subcarriers and thus avoiding interference with Primary Users (PUs) on these parts of the spectrum. Unfortunately, a NC-OFDM receiver requires exact information about the used subcarriers in order to synchronize and to decode the packet transmission. Hence, a reliable signaling is required.

## 1.1. Objective and Contributions

This report is about the design of a wireless backhaul for wireless small cells based on a wideband overlay Cognitive Radio technology. Our focus is on the development of a Media Access Control layer (MAC) which adequately deals with the challenges in the envisioned wideband overlay CR network such reliable protection of licensed (primary) users as well as to ensure a certain level of quality-of-service of the secondary system when the primary occurs. Our project partner AED is responsible for the development of the NC-OFDM [4] physical layer (PHY) and the design of a wideband transceiver hardware supporting a very large bandwidth of up to 512 MHz.

The following research related questions are addressed in this paper:

**Environment** The envisioned wideband overlay CR system which has to deal with time, space and frequency dependent spectrum availability in a spectrally heterogeneous environment.

**Design challenges** The main challenges when designing a CR-MAC protocol is efficient utilization of secondary spectrum, reliable protection of Primary Users (PU) from secondary user's interference by means of fast spectrum reconfiguration, as well as avoiding harmful interference between secondary users.

**Control channel** A reliable control signaling is required to provide the receiver with initial rendezvous information and the actual spectrum allocation to be used the data channel.

**Cross layering** To enhance the systems performance a tight inter-layer coupling, i.e. MAC and PHY, has be considered.

## Acknowledgment

This work has been supported by the COUWBAT project of the German Federal Ministry of Education and Research (BMBF 16KIS0029).

## Chapter 2.

# Cognitive Radio Primer

In this section, we provide a brief introduction to Cognitive Radio (CR). The most important terms and definitions used throughout this report are introduced.

### 2.1. Introduction

Future wireless communication systems need to be extremely efficient in terms of spectrum usage in order to provide the required capacity within the limits of the available spectrum. A promising solution to achieve this goal is Cognitive Radio (CR). It is based on the observation that spectrum assigned to license holders, called Primary Users (PU), remains frequently unutilized in some geographical areas even over long time periods. The CR approach allows Secondary Users (SU) to utilize parts of the licensed spectrum temporarily not claimed by the proper PUs based on Opportunistic Spectrum Access (OSA).

Various measurement campaigns have shown that today's radio spectrum is heavily under-utilized (ref. Appendix A), which stays in contrast as all frequencies are assigned to licensed users by the regulatory domains like FCC in US or ETSI in Europe. Cognitive Radio exploits this by opportunistically utilizing unused licensed spectrum bands. To be able to do this, each CR user in the CR network must fulfill the basic functionality of a CR device which is illustrated in Fig. 2.1 [5]:

- **Sense** – Determine which portions of the spectrum are available. If no sensing device is available a database or similar needs to be in communication reach to gather spectrum usage information. In most systems a hybrid approach is favored.
- **Understand** – Analyze the sensed spectrum and select the best suitable portion of spectrum according to the requirements.
- **Decide** – Coordinate access to this spectrum portion with other secondary users.
- **Adapt** – Access the selected spectrum, but vacate it, as soon the licensed user is detected.

In May 2003 also the FCC [7] recognized CR as a way to improve the spectrum efficiency. According to FCC four possible scenarios for CR can be identified [8]:

- **Licensed Networks:** A licensee employs cognitive radio technologies internally within its own network to increase efficiency of use of the radio resource.
- **Secondary Market:** A licensee and third party sign an agreement allowing secondary spectrum uses for cognitive radio devices.

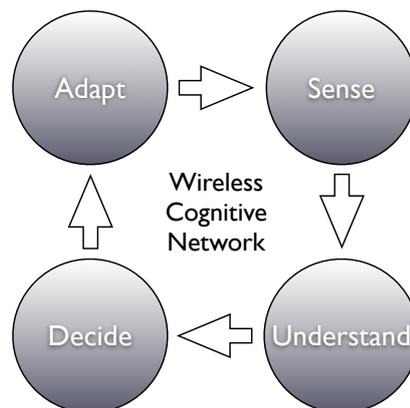


Figure 2.1.: Cognitive cycle in wireless networks (modified from [6])

- **Coordination of Licensed Operation:** Multiple licensed services can operate in the same frequency bands by coordinating their use to avoid mutual interference.
- **Non-voluntary third party access:** Unlicensed cognitive devices operate at times and locations where licensed spectrum is not in use.

## 2.2. Opportunistic Spectrum Access

To alleviate the spectrum scarcity problem, Dynamic Spectrum Access (DSA) is a key technology. Three different spectrum access models are discussed in the literature [9]. The two most common DSA models are depicted in Fig. 2.2:

- **Overlay cognitive radio:** SU devices transmit simultaneously with primary (licensed) systems by adopting techniques to compensate the interference generated towards the primary user by supporting their communications by e.g., channel coding.
- **Interweave cognitive radio:** SU devices monitor the spectrum and use them as long as no primary user is detected. This case can be assumed as a special case of the overlay cognitive radio approach.
- **Underlay cognitive radio:** SU devices can transmit simultaneously with primary systems, but adopt very low power levels or other techniques over a very wide frequency band to guarantee that interference remains acceptable or below PU noise level.

## 2.3. Available Spectrum for Secondary Usage

To explore the available parts of the spectrum for secondary usage two approaches, sensing and database based, are used today. The sensing approach is mainly used in CR Ad-Hoc networks, since it requires no infrastructure (e.g. no connection to the Internet). Nevertheless, the hidden terminal problem due to insufficient sensing sensitivity of the CR devices is still an unsolved problem [10]. Different classes of PUs require different sensing sensitivity, as well as sample rates [11]. Field trials

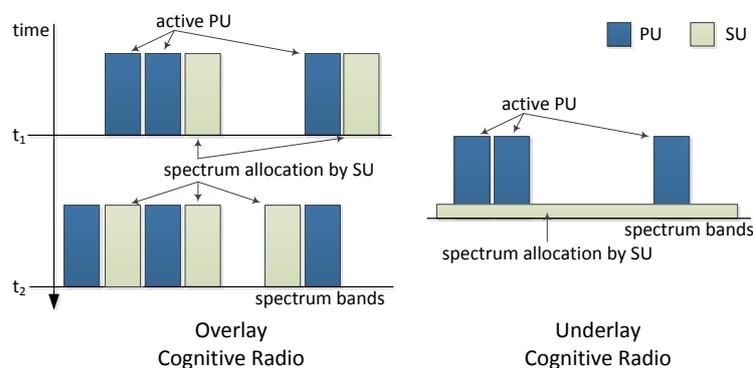


Figure 2.2.: Overview of the most common overlay and underlay DSA models. In the overlay or interweave DSA model, a SU can transmit only on a spectrum band where the PU is not active. In the underlay DSA model, a SU can transmit on a spectrum band no matter the PU is active or not, but at a low power on each band to limit interference. [9]

have shown that to protect a DVB-T and a wireless microphone PU, both operating in TV white spaces, different sensing sensitivities are required: -120 dBm vs. -126 dBm [12]. Unfortunately, such a high sensing sensitivity is very hard to achieve with today's hardware. Therefore, in e.g., the 802.22 standard, spectrum access is mainly based on a lookup into a spectrum database to ensure reliable protection of licensed users by any means.

## 2.4. Challenges

The main challenges in designing a CR are according to [13]:

- CR provides (and relies on) the capability of achieving awareness of the external environment.
- A CRN can only be efficient, if a crosslayer approach is used. The spectrum awareness can not be ensured, when sensing results are not immediately processed and analyzed, a spectrum allocation decision taken and the radio frontend adapts. It must be part of the design, that algorithms and protocols operate at all layers of the protocol stack.
- A certain Quality Of Service (QoS) must be ensured.
- Ensure an accurate detection of weak signals of licensed users over a wide spectrum range. If this can not be achieved a database approach is necessary.

## 2.5. Summary

According to the classifications presented in this chapter our envisioned system belongs to the category four proposed by the FCC, i.e., non-voluntary third party access. Regarding the spectrum access it belongs to the class of interweave cognitive radio systems. Moreover, the available secondary spectrum is estimated based on the geographical position of the SU node (e.g. GPS) and the information

from a spectrum database which is according to the FCC rules for secondary access in TV White Spaces.

# Chapter 3.

## COUWBAT Architecture

In this chapter the envisioned architecture for a wireless small-cell backhauling based on overlay CR, called COGNITIVE Ultra-WideBand Transceiver (COUWBAT), is presented. Moreover, major design principles are described.

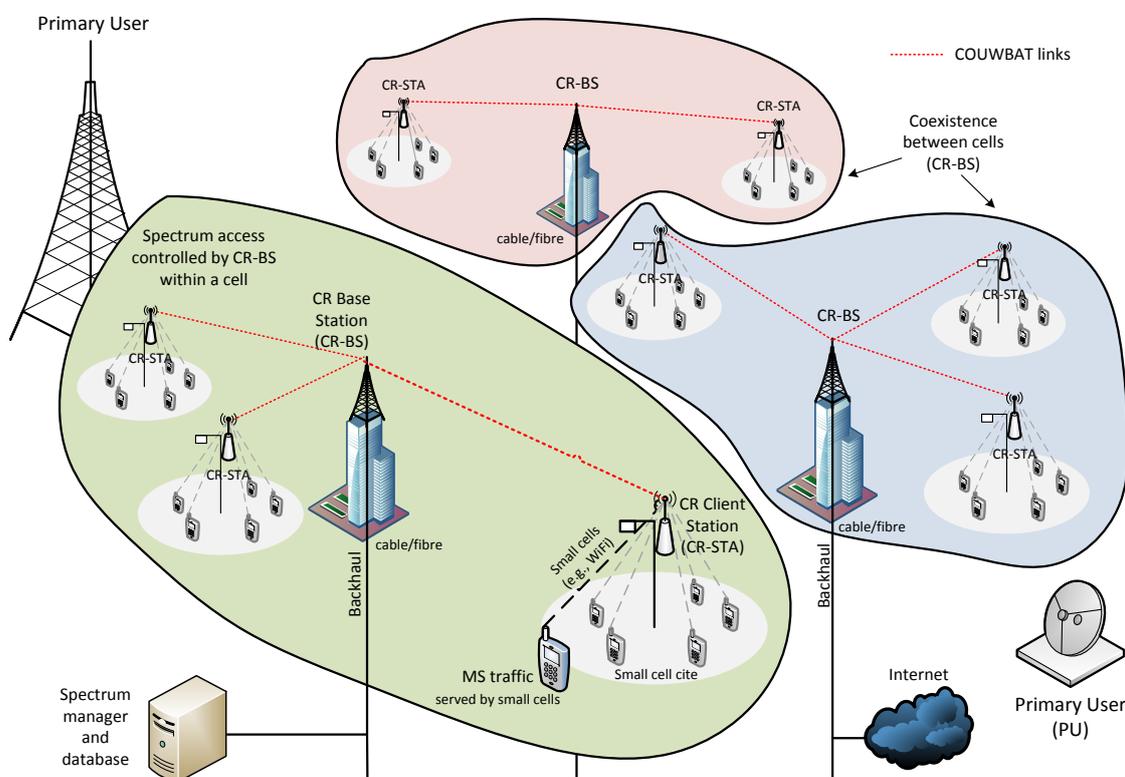


Figure 3.1.: Proposed wireless backbone architecture.

### 3.1. Network Architecture

A promising approach to provide the targeted high data rates, of more than 1 Gbit/s, is the use of small network cells (e.g., WiFi), which enables wireless data offloads from cellular networks (e.g. 3G/4G). Small cells create new wireless capacity at locations where many users are and allow the spatial reuse

of the available spectrum. In this report we target a wireless backbone for wireless small cells based on a wideband overlay cognitive radio system.

Our envisioned system has a two-tier architecture, as shown in Fig. 3.1. The access to the End-User Terminals (EUT) is provided by small cells using a wireless technology like IEEE 802.11 (WiFi). Therefore the Cognitive Radio – Client Station (CR-STA) is equipped with two different radio interfaces. The first one provides a wireless connection to the EUT whereas the second air interface provides the wireless backhaul link to the Cognitive Radio – Base Station (CR-BS) node. The communication in the wireless backhaul is restricted to one hop. A single CR-BS and their associated CR-STAs form a single cell with a targeted cell radius of about 300 m. We consider a static scenario which means CR-STA and CR-BS are not mobile. Only CR-STA can change their location when they are not in operation (nomadic behavior). Besides the air interface each CR-BS is equipped with a backbone interface (e.g., optical fiber, Ethernet or IEEE 802.11ad in 60 GHz) which is used to connect the network to the Internet, as well to access the CR Spectrum DataBase (SDB). Hence, we have a star topology with a single master node, the CR-BS, and multiple associated slave nodes, the CR-STAs.

We assume the following number of participating nodes in our network. There are 5-10 EUTs connected at every CR-STA. A single CR-BS provides the backhaul for 8-15 CR-STAs. Moreover, we expect the CR-BS cells to be overlapping to provide uninterrupted coverage.

## 3.2. Requirements

The envisioned system has peculiarities which need to be considered in the design.

### Properties of the data channel

The physical layer of the data channel is a wideband NC-OFDM system using an RF frequency below 1.5 GHz and a very large bandwidth of 512 MHz. Because the coherence bandwidth is much smaller than the total bandwidth the small-scale fading is frequency selective. Moreover, due to the used RF frequency and the very large bandwidth also the large-scale pathloss is frequency-dependent (see Sec. 8.2). COUWBAT takes this into account by assigning different Modulation and Coding Schemes (MCS) to different blocks of adjacent subcarriers.

### Supporting the data channel

The physical layer used in the data channel, i.e. the CR-STAs-to-CR-BS communication, is NC-OFDM (refer to Sec. 9). NC-OFDM allows the use of a fragmented and scattered radio spectrum. In Sec. 6.5 we show that in the envisioned CR network a blind synchronization scheme, where the NC-OFDM receiver has to guess (e.g. based on spectrum sensing) the set of subcarriers being used by the transmitter, is unreliable. Hence, we need a separate control channel to be able to signal the set of subcarriers used for by the data channel to receiver side.

### Control channel principles

Due to high cost a dedicated globally available licensed control channel is not feasible. Hence, conceivable solutions are inband deployments, IR-UWB or the use of 802.11ah in ISM bands.

**Co-existence of overlapping CR-BS cells**

In order to avoid intra-network interference, mechanisms for co-existence of adjacent CR-BS cells must be provided.

**Self-organizing network infrastructure**

The envisioned system should be fully self-organizing. There is no need for manual configuration, setup and maintenance.



## Chapter 4.

# Control Plane

This section is split into two parts. First, we describe the logical control plane of the envisioned COUWBAT architecture. Second, we show and discuss alternatives of implementing a control channel for signaling.

### 4.1. Overview

Fig. 4.1 illustrates the COUWBAT control plane from the logical point of view. In particular, the control plane covers aspects like discovery of network topology and spectrum assignment to network cells (CR-BSs) as well as control operations within each cell like management operations and radio resource control which assigns spectrum within a cell to the CR-STAs being served.

In COUWBAT we follow a *hierarchical spectrum assignment* approach [14]. First, based on the geographical location of the CR-BS nodes and optionally their associated CR-STAs the COUWBAT Spectrum Broker (SB) queries the CR Spectrum DataBase (SDB) to obtain the information about the available spectrum for secondary usage for each cell. Second, the SB calculates and assigns the actual spectrum to be used by each cell (*first tier*). Because adjacent cells are in interference range an orthogonalization in time or frequency is required in order to avoid interference. In the envisioned system we assign different parts of the spectrum to co-located cells. This requires information on the network topology which is obtained by the Neighbor Discovery (ND) component. Based on the spectrum assigned each CR-BS is able to schedule the Radio Resources (RR) within the cell independently which is performed by the Radio Resource Control (RRC) (*second tier*). In particular the RRC has to assign the proper number of RR for each CR-STA being served for both downlink and uplink.

Finally, each CR-BS needs to provide *management functions* within the cell, i.e. beaconing and association of new CR-STA.

### 4.2. Detailed Description

This section gives a detailed description of the control plane.

#### 4.2.1. Discovery of Network Topology

The Spectrum Broker (SB) (see Sec. 4.2.2) requires information on network topology in order to calculate the spectrum allocation for each CR-BS cell. This information is provided by this component which uses over-the-air beaconing (Sec. 4.2.3) to obtain a neighbor graph, i.e. CR-BSs are nodes and

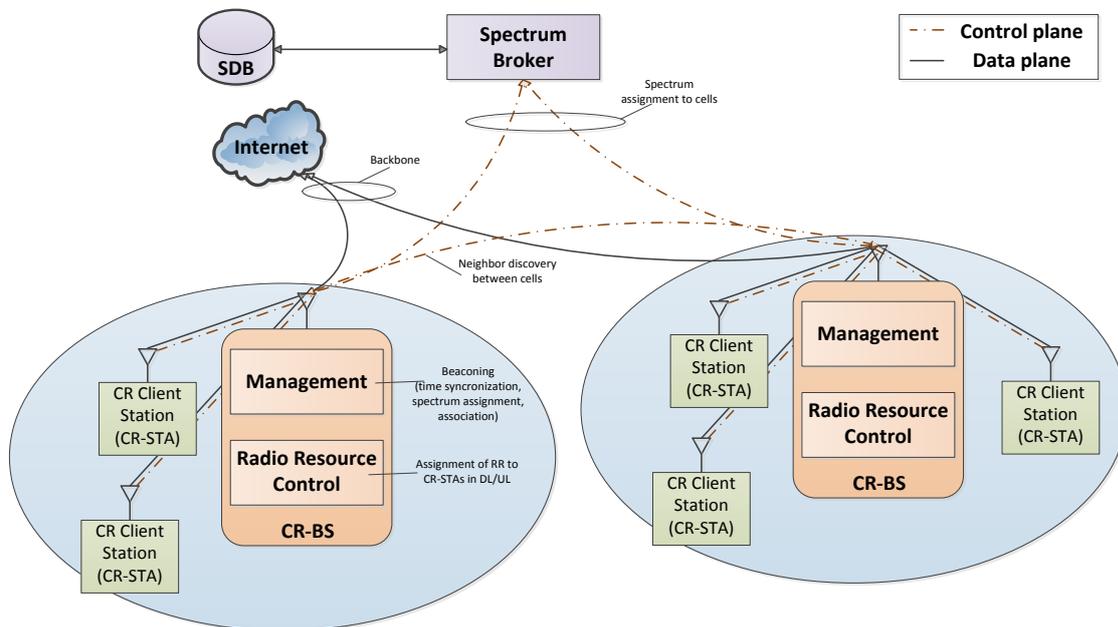


Figure 4.1.: Logical view on control and data plane of two cells.

there is an edge between two CR-BS nodes if these two nodes are in communication range (are able to receive the beacon).

The information about the network topology is updated each time a new CR-BS node joins or an existing CR-BS leaves the network. In the envisioned system this is sufficient since the CR-BS nodes are static and not mobile.

#### 4.2.2. Spectrum Broker

The Spectrum Broker (SB) fulfills two tasks. First, it makes sure that the allocated spectrum for secondary usage is not used by any co-located PUs. Therefore, it uses the geographical location of the CR-BS nodes, and optionally their associated CR-STAs under control, to query the CR Spectrum DataBase (SDB) to obtain the information about the available spectrum for secondary usage for each cell. Second, it performs interference management by assigning different parts of the spectrum to adjacent CR-BS cells. A concrete spectrum assignment algorithm can be either centralized or distributed. Moreover, the spectrum share assigned to each cell may also depend on the network load, i.e. less spectrum is assigned to cells serving only a few CR-STAs. For such a scheme to work the RRC needs to inform the SB about the number of active CR-STAs.

For our envisioned system we proposed a distributed algorithm which is explained in detail in Chap. 7.

### 4.2.3. Management Operations

#### Beaconing

The beaconing performs two tasks, namely, to support the network topology discovery process for CR-BSs (Sec. 4.2.1) and the network discovery for CR-STAs (Sec. 4.2.3). In particular the beacon frame contains time and address information but also spectrum allocation information which is currently used within the cell which is required by CR-STA to support the CR physical layer decoding.

#### Joining & Leaving of CR-BSs

If a new CR-BS is deployed and started the following bootstrapping process is performed. First, it starts the neighbor discovery process in order to detect co-located CR-BS cells (Sec. 4.2.1). This topology information is required by the spectrum broker (Sec. 4.2.2). On shutdown a CR-BS informs the spectrum broker about its leaving.

#### Association & Dissociation of CR-STA

Next, we describe the process of association and dissociation of CR-STAs. A new CR-STA starts the association process by passively scanning the channel for beacon frames. In case it detects at least one CR-BS in its neighborhood, it sends an association request frame to the CR-BS with the best wireless link quality (e.g. highest SINR). The CR-BS replies with an association reply (accept or reject). Moreover, the CR-BS registers the new CR-STA in the radio resource control component (Sec. 4.2.4) so that radio resources are scheduled for this CR-STA in DL/UL.

### 4.2.4. Radio Resource Control (RRC)

Based on the spectrum assignment by the SB the objective of the Radio Resource Control (RRC) is to allocate the Radio Resources (RR) to CR-STAs within the cell. In particular the CR-BS needs to i) decide on a proper ratio between downlink and uplink, i.e. DL/UL ratio, and ii) to assign subslots to CR-STAs in both the downlink and uplink. The DL/UL ratio can be either fixed (e.g. 80:20 traffic ratio) or dynamic. Also the assignment of DL/UL subslots to CR-STAs can be either static (e.g. the same number of RRs is assigned to each CR-STA) or dynamic. For dynamic approaches different solutions are conceivable. First, an explicit bandwidth requesting, in which a CR-STA can send request messages to the CR-BS, and the CR-BS can grant or reject the request according to the available radio resources. Second, an implicit method, where the CR-BS assigns the RRs based on the utilization of the previously assigned RRs in previous superframes. Third, a hybrid approach where a specific part of the RRs is assigned statically and the rest dynamically to the CR-STAs.

In COUWBAT the DL/UL ratio is fixed but configurable. The assignment of subslots within DL/UL slots is dynamic using an implicit method.

## 4.3. Control Channel Implementation

There are multiple options for the implementation of the control channel. In this section we present and discuss the possible alternatives.

### 4.3.1. Overview & Classification

A control channel can either use the licensed or the unlicensed spectrum [15]. The use of licensed spectrum has the advantage of having a dedicated and therefore interference-free and contention-free channel where it is easier to achieve a reliable low-latency communication. The major drawback is the scarcity and high cost of licensed spectrum.

Another possible classification is given by Lo [16] which is shown in Fig. 4.2 and described below.

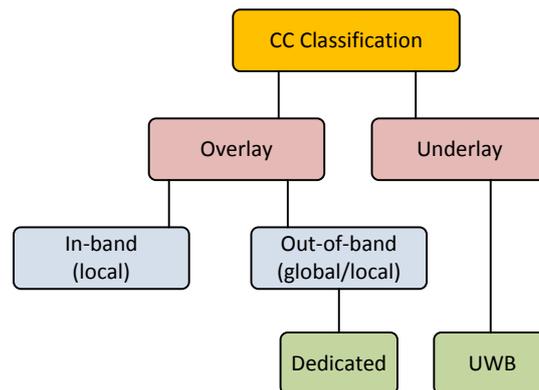


Figure 4.2.: Classification of control channel design (source: [16])

#### Underlay Control Channel

Considering the underlay approach first, Ultra-WideBand (UWB) technology allows transmission below the noise floor of other wireless transmission techniques and can therefore be used in parallel without interfering with PUs and therefore without requiring additional dedicated spectrum resources.

#### Overlay Control Channel

When considering an overlay control channel two different main approaches exist. First, an out-of-band solution. Here the control channel and corresponding data channel are orthogonalized in the frequency domain, i.e. they are using different parts of the radio spectrum. The advantage is that there is no interference and no competition for radio resources between both channels. The drawback is inefficiency, i.e. any unused radio resources in the control channel cannot be used for data communication. Second, an in-band solution. In this case control and the corresponding data channel share the same resources. Here, the former stated drawback of inefficiency is solved, but control and data channel compete for the same resources. Therefore, it is important to figure out the optimal split between both channels.

### 4.3.2. Discussion Towards our Implementation

In the following we discuss the advantages and disadvantages of using a particular class of control channel in the envisioned system. First, we discuss the requirements for the control channel when

used together with the envisioned overlay CR data channel. Second, we investigate whether specific radio technologies are able to meet the requirements.

### **COUWBAT Control Channel Requirements**

A Control Channel (CC) should have a similar or greater communication range than the corresponding data channel which is in our case around 100-300 m. Moreover, a moderate data rate in the control channel is desirable since it determines the total number of addressable resources in the data channel and hence impacts its efficiency. A high data rate in the CC increases the throughput in the data channel directly. For the envisioned system a data rate of around  $100 \text{ kbit/s}$  is sufficient (refer to Chap. 8.1). Moreover, a control channel must be reliable (i.e. low packet error rate) and low-latency in order to guarantee a fast spectrum reallocation due to PU activity. For the latter we assumed a maximum latency of 10 ms which ensures a co-existence with even low-latency PU applications (e.g. VoIP over LTE).

### **Discussion of Potential Solutions**

According to Lo et al. [16] general control channel design challenges are 1.) CC saturation, 2.) robustness to PU activity, 3.) CCC coverage and 4.) CC security. First, CC saturation means, when the collision rate in the CC is too high due to a large network load, e.g., caused by a large number of users, the CCs performance is suffering. This problem is known to any in- or out-of-band solution. Second, robustness to PU activity tackles the issue of how to maintain control communications when PUs appear in the allocated CCC. This is mainly an issue for in-band CCC solutions. The third point, CCC coverage addresses the issue of how to broadcast control information to all participating nodes in transmission range. This is particularly a problem when communication ranges are large and spectrum heterogeneity among the nodes exist. The main issue is to find a frequency band which is available for all nodes or if not, how to set up interconnected local CC to broadcast CCC information. The last point, CC security deals with the concern of attacks against the CCC. If the CCC is blocked by jamming or other threats no communication at all is possible. Especially out-of-band and fixed frequency in-band CCC have to deal with this issue.

When considering an underlay control channel a specific technology such as the Impulse-Radio-UWB (IR-UWB) technology might be an option. It provides a sufficient high bitrate. Unfortunately, most practical studies present results for very short communication ranges (10 m) and there is a lack of practical studies showing the performance of IR-UWB in real-world testbeds over longer distances. Therefore, we conducted experiments using a commercial off-the-shelf IR-UWB transceiver to evaluate IR-UWB in a realistic outdoor scenario. The experiment results are explained in detail in Sec. 8.1.3. In summary, our results show that IR-UWB can be used as control channel only under certain conditions.

When considering an out-of-band overlay control channel the use of the unlicensed Industrial, Scientific and Medical (ISM) radio bands is an option. The requirements for both the data rate as well as communication range are met. Unfortunately, because the ISM bands (especially the 2.4 GHz band) are already used extensively it is hard to achieve the reliability and low-latency requirements for the control channel.

An in-band overlay solution is able to meet all the requirements as long as the used (licensed) spectrum is never or at least rarely used by any PU. Moreover, there is a tradeoff in the data rate of

the control channel and the data channel. This is because both channels use the same radio resources and therefore need to be orthogonalized in time domain. We analyzed this tradeoff in great detail in Sec. 8.1.4.

In summary, we have decided for an in-band overlay control channel with flexible frequency allocation.

## Chapter 5.

# MAC Layer

In this chapter we present the Media Access Control layer (MAC) layer of COUWBAT and its mechanisms. We start with the description of the medium access within a cell and show how co-existence between co-located cells is realized. Moreover, we show how link reconfiguration due to (dis-)appearance of PUs is realized.

### 5.1. Design Challenges

The main challenges in designing a spectrum-aware MAC layer protocol can be summarized as follows:

- Protection of PUs must be ensured by any means, i.e. on appearance of a new PU the corresponding spectrum must be vacated as fast as possible.
- Self-coexistence with other COUWBAT cells, i.e. orthogonalization in time, frequency or space must be organized.
- Co-existence with other secondary users, i.e. non-COUWBAT nodes need to be considered.
- Spectrally efficient operation, i.e. no wastage due to unused spectrum as well as adaptive modulation and coding per radio resource block should be included.

### 5.2. Single Cell Scenario

To simplify the explanation, we start with the single cell scenario given in Fig. 5.1. Here  $M$  CR-STAs are connected to a single CR-BS which are in direct communication range. Every CR-STA provides the wireless access functionality for the Enduser Terminals (EUT). For our considerations only the communication between the CR-BS and the associated CR-STAs is of interest (see the red dotted links in Fig. 5.1).

As discussed in the former Chap. 4.3 we selected an in-band control channel, hence, the wireless links between CR-BS and CR-STAs provide both, the data channel, as well as the non-dedicated in-band control channel. To coordinate the medium access between control and data channel, the channel access is organized by superframes. Control and data phase are separated in time as depicted in Fig. 5.2. Moreover, the data phase is divided into downlink and uplink phase.

#### 5.2.1. Control Phase

The control phase is divided into two parts, a so-called narrowband and a wideband phase. The purpose of the narrowband phase is to disseminate information about the spectrum allocation used in

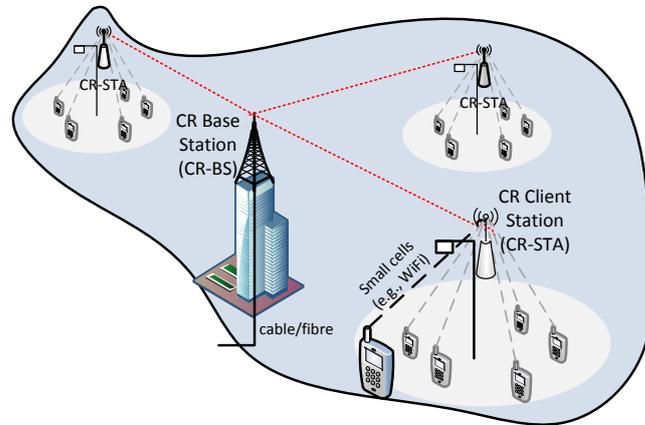


Figure 5.1.: Single cell scenario – single CR-BS with multiple associated CR-STAs.

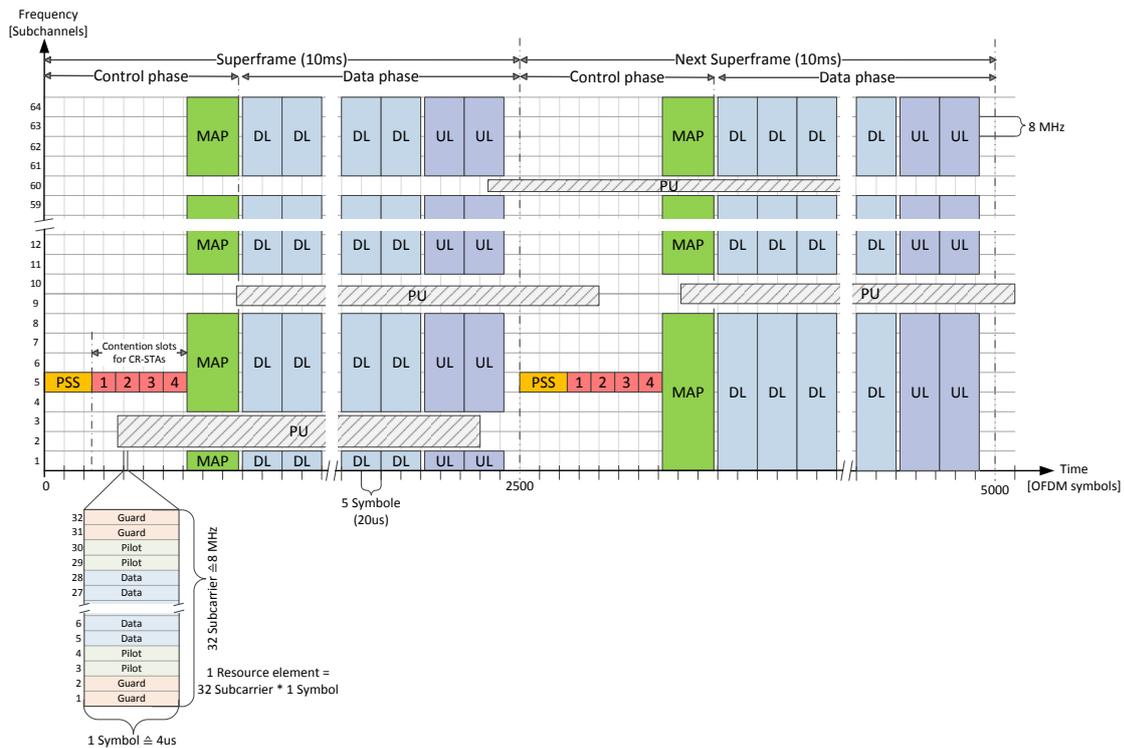


Figure 5.2.: COUWBAT framing in time and frequency for one CR-BS (A), two CR-STAs and three PUs blocking parts of the spectrum.

the wideband-phase, speed up the rendezvous process of CR-BS and CR-STAs because of the decreased number of possible channels and to support the network discovery process. In contrast to the

wideband-phase the spectrum used in the narrowband phase (called home channel) is selected once when a CR-BS is joining the network and in general does not change very frequently. Moreover, the candidate set of potential home channels used in the narrowband is known a priori and can therefore efficiently scanned by any new CR-BS or CR-STA. In Fig. 5.3  $CC_N$  such an exemplary control channel allocated by  $CR-BS_N$  is depicted. Note, that each node is listening on its home channel for control traffic while it is not transmitting.

The total number of candidate home channels must be large enough to make sure that even in a high density deployment scenario with lots of overlapping cells and high utilization of the spectrum by PUs there is at least one free home channel per CR-BS which can be used. Note, that because of the NC-OFDM physical layer we have a very flexible channelization allowing to flexible set not only the number of home channels but also their bandwidth. In Sec. 8.1.2 we show that there is an optimal configuration for each scenario.

Note, that the MAP (DL/UL) which contains scheduling information in the data phase is transmitted in the wideband phase due to efficiency considerations. The drawback is the necessity of a guard time of two OFDM symbols because the PHY needs a short reconfiguration time if the subchannels in the wideband-phase have changed.

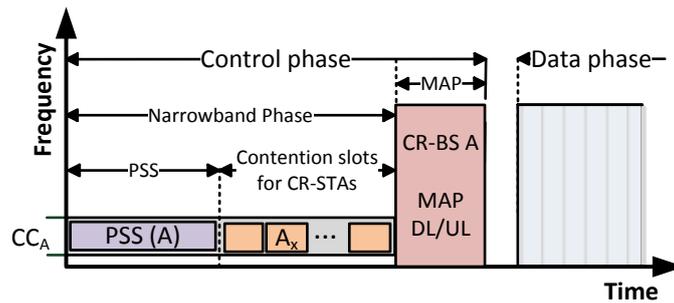


Figure 5.3.: **Control phase** in detail for a single cell. PSS and contention phase are bounded to the CR-BS home channel. The MAP is transmitted on (fragmented) wideband spectrum according to the cells spectrum allocation.

Finally, the description of three parts of the control phase is given.

### Primary Synchronization Sequence (PSS)

The Primary Synchronization Sequence (PSS) is a beacon packet that contains a source address and spectrum allocation information used in the wideband phase. Moreover, it is used for time synchronization between CR-STAs and the CR-BS. The PSS is only transmitted by the CR-BSs. Furthermore, the PSS is used in the discovery of the network topology, i.e. to find out which CR-BSs are in communication range.

### **Contention Phase**

The purpose of the contention phase is to provide a way for new CR-STAs to associate with a given CR-BS. In particular, the contention phase is divided into time slots which are accessed by CR-STAs in a random way (ALOHA) to send their association requests frame to a certain CR-BS.

### **MAP**

The MAP contains the scheduling information used within a cell for both DL and UL. It is transmitted by CR-BSs after the narrowband phase of the control phase. Logically it is part of the control channel.

### **5.2.2. Data Phase**

The spectrum used in the data phase is not limited to individual subchannels. All spectrum assigned by the spectrum broker can be utilized. Even fragmented and scattered spectrum can be used due to the flexibility of NC-OFDM. The data phase itself is divided into two parts, a DL and a UL subframe.

#### **DownLink (DL) Subframe**

In the DL subframe the CR-BS sends frames to selected CR-STAs. Therefore, it is divided into DL slots one for each scheduled CR-STA.

#### **UpLink (UL) Subframe**

Every CR-STA gets a slot for its UL transmissions, even the CR-STA has nothing to transmit. Again, the information which slot is reserved for each CR-BS is included in the MAP. Note, both DL as well as UL slots always use the full available spectrum, i.e. slots are packed from left to right.

In summary, the control and data channels are interleaved in time, which means the control channel is only used during the control phase, whereas the data channel is only used during the data phase.

## **5.3. Co-existence between Cells**

In a multi cells scenario we have to find mechanisms ensuring the co-existence between co-located CR-BSs and hence to manage inter-cell interference. In the envisioned architecture this task is accomplished by the spectrum broker by assigning different parts of the secondary spectrum to adjacent CR-BS cells. Nevertheless, cells will orthogonalized by using FDMA between them, while within the cells TDMA is used. See further Fig. 5.4.

### **5.3.1. Spectrum Sharing between CR-BSs**

To avoid interference between neighboring or co-located CR-BS cells we orthogonalize in the frequency domain (FDMA). In particular, the following heuristic is used to decide whether two CR-BS nodes are in interference range and hence must use different parts of the spectrum. We assume that the interference range is twice the wireless communication range. Hence, we make sure that any subcarrier is used at most once in the two-hop neighborhood. A detailed description of the fully distributed algorithm for computing the spectrum sharing is given in Appendix 7.

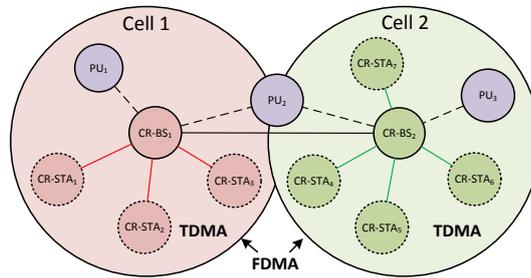


Figure 5.4.: Multiple Access - FDMA is used to orthogonalize adjacent CR-BSs, while TDMA is used within a CR-BS cell.

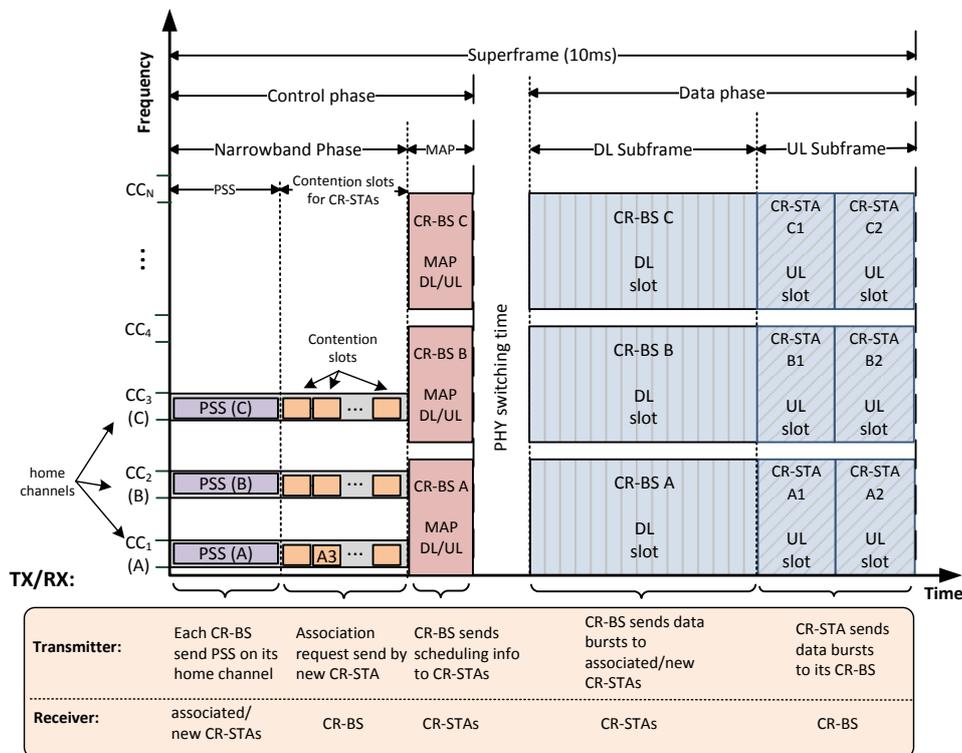


Figure 5.5.: Overall COUWBAT framing in time and frequency exemplarily for three CR-BSs (A,B,C) and two CR-STAs per CR-BS.

### 5.3.2. Exchanging Control Messages between CR-BSs

A new CR-BS starts the network joining with a bootstrapping phase by scanning all potential home channels for PSS beacons. This information about CR-BSs in communication range is sent to the spectrum broker using the wired interface. Since in the envisioned system the spectrum broker is

distributed the control messages are exchanged between neighboring CR-BSs.

## 5.4. Protection of Primary Users

Primary Users (PU) must be protected by any means. Because sensing based approaches in general are not reliable, a database approach is chosen. The spectrum database is able to retrieve the available secondary spectrum for any given geographical location. In the envisioned system the spectrum broker queries the database using the geographical locations of the CR-BSs under control.

Moreover, also the CR-STAs does not interfere with any PU. If no connection is setup between CR-BS and CR-STA, the CR-STA nodes continuously listening for PSS frames which contain the up-to-date spectrum allocation information before they access any spectrum.

## 5.5. Link Reconfiguration

Link reconfiguration is a common problem in CRN. Subcarriers on which a PU was detected have to be immediately excluded from SU usage. This results in a temporary reduction of the link capacity and requires link reconfiguration, i.e., adding new available subcarriers, which might take some time.

We tackle this problem with a combination of using a wideband transmission system of about 512 MHz and a random subchannelization scheme at the physical layer. The former demands that every link uses all assigned subcarriers for data transmission, thus, when a PU appears only a small relative fraction of link subcarriers will be affected, resulting in only minor reduction of link capacity. The latter has the effect that logical subchannels are randomly mapped to physical subchannels with the goal to scatter the continuous spectrum blocked by a PU over all links, i.e. the capacity of all links is reduced minimally (PU averaging). Thus, the random subchannelization scheme increases the robustness against interference from emerging PUs. This is because the adjacent physical subcarriers being blocked by a PU are no longer adjacent in the random permutation (Fig. 5.6).

The permutation scheme assures that even if PUs fluctuate every node gets some part of the spectrum. The chance that a node gets no spectrum, i.e., its spectrum is completely shaded by a PU, is very small and can be decreased by using more subchannels. We have a fair resource sharing among neighboring CR-BSs in networks with spatially heterogeneously distributed PUs. As previously mentioned the scheme is robust against interference from emerging PUs.

An illustrative example showing the proposed random subchannellization scheme is given in Fig. 5.7. We can see the following steps are: 1) getting the physical subcarriers, 2) grouping adjacent physical subcarriers into physical subchannels, 3) Outer random permutation of physical subchannels to logical subchannels, 4) Inner random permutation of physical subcarriers within every logical subchannel, 5) Assigning logical subchannels to CR-BSs, 6) Estimating set of physical subcarriers being blocked by PUs, 7) Excluding blocked subcarriers from assigned spectrum.

## 5.6. Generic Framing

Fig. 5.8 shows the format of the generic MAC frame used in COUWBAT. The individual components are described below.

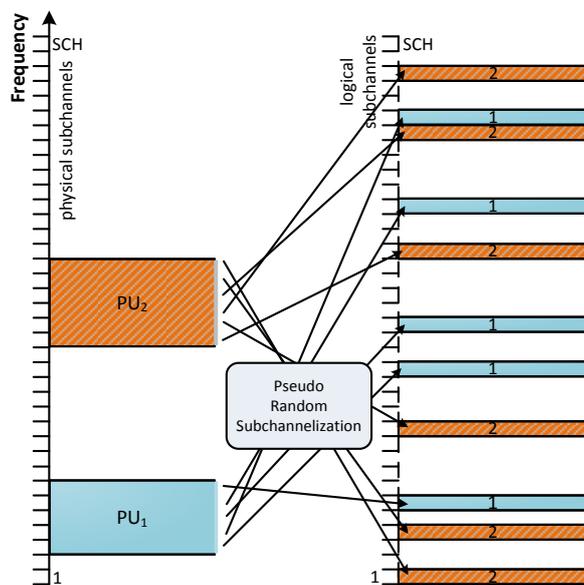


Figure 5.6.: To limit the influence of individual PUs on each CR-BS a distributed subchannelization scheme is proposed. Here logical subchannels are randomly mapped to physical subchannels.

## Frame Control

Each frame starts with a one-byte Frame Control (FC) subfield, shown in Fig. 5.8, which consists of two fields, namely Type and Subtype.

### Type

Type is a 2 bit field indicating the type of the frame. At the moment we distinguish between 1.) control (00) and 2.) data (01) frames.

### Subtype

Subtype is a 6 bit field indicating the frame subtype. At the moment we distinguish between four different control frame subtypes:

1. Primary Synchronization Sequence (PSS) beacon (000000)
2. CR-STA association request (000001)
3. CR-STA disassociation request (000010)
4. DL/UL MAP (000011)

and two different data frames:

1. DL Frame (000000)
2. UL Frame (000001)

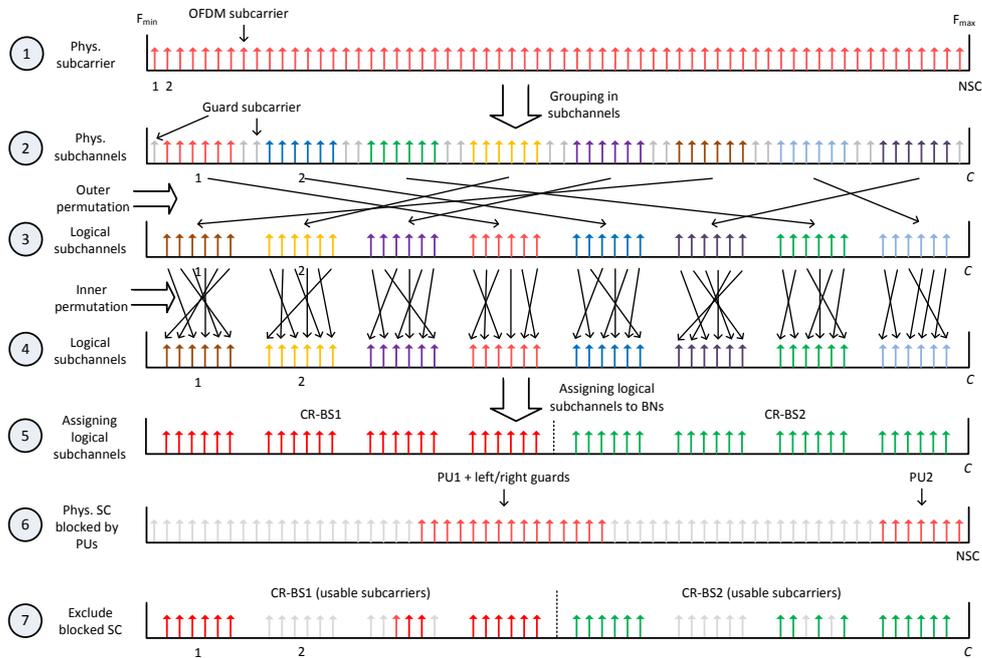


Figure 5.7.: Illustrative example – this example shows how spectrum is assigned to different CR-BS nodes, to prevent link fluctuations and QoS drop when PUs are changing.

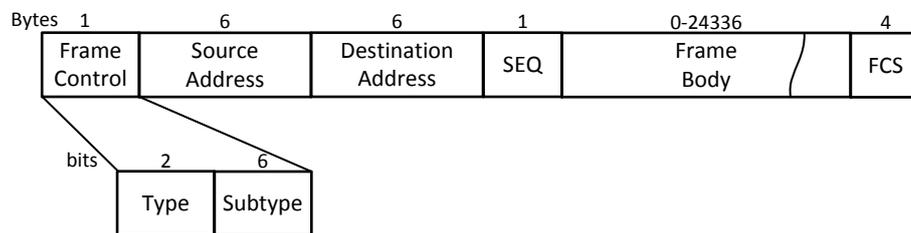


Figure 5.8.: Generic MAC Frame

## Address Fields

The MAC frame contains two address fields, the Source Address (SA) and the Destination Address (DA). Both addresses have a length of 6 Bytes and are IEEE vendor specific MAC addresses.

## Sequence number field

The Sequence number field (SEQ) is used to detect duplicate frame transmissions. It has a length of 1 Byte.

## Frame Body

The Frame Body, also known as data field, moves the payload from higher layers between the nodes. The length of such a frame varies dependent on the frame type between 0 and 2048 Bytes.

## Frame Control Sequence

As in Ethernet or 802.11, each COUWBAT frame closes with a Frame Control Sequence (FCS) which is used to detect corrupted frames. The FCS is a Cyclic Redundancy Check (CRC) with a length of 4 Bytes.

## 5.7. Encapsulation of Higher-Layer Protocols

From the network point of view we provide a layer-2 bridging, therefore it is transparent for IP communication as shown in Fig. 5.9. High-layer e.g., Ethernet packets are wrapped and transported completely without packet reassembling.

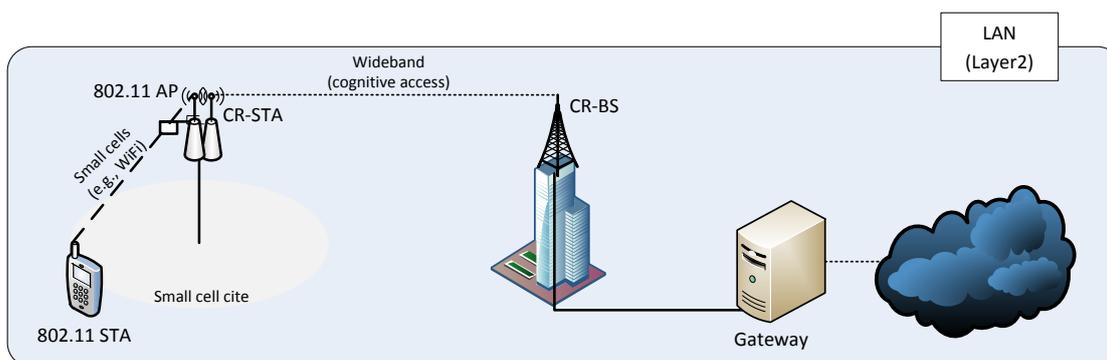


Figure 5.9.: Proposed layer-2 backhauling.

## 5.8. MAC Framing in Detail

In this section we give a detailed description on the frame formats used in COUWBAT.

### 5.8.1. Control Phase

In the envisioned architecture the control channel is implemented in-band. The basic idea is to divide the overall total bandwidth (here 512 MHz) into multiple narrowband channels (e.g. 5 MHz). From this set of channels, the so-called candidate set, each CR-BS has to select one channel to which we refer as home channel. Our assumption is that as long as the number of candidate channels is large enough it is very unlikely that all control channels are being blocked by PUs or other CR-BSs at the same time at a given location. Note, that in contrast to other approaches every cell can decide on its own control channel using purely local information and there is no need for a globally available control channel. Specifically, we have decided to define 64 a-priori known narrowband subchannels uniformly distributed over the whole 512 MHz band each with 6 MHz of bandwidth<sup>1</sup>.

The control phase is divided into a PSS beaconing phase and a contention phase. The former is used for the transmission of beacon frames by every CR-BS on their selected control channel (i.e., home channel). It marks the beginning of the superframe and allows the CR-STAs to synchronize in time and frequency. The contention phase is divided into four contention slots which are used for initial ranging, i.e. association of a new CR-STA. Slotted-ALOHA is used as random medium access scheme in the contention phase.

All frames in the control phase including the MAP are transmitted with the base rate using QPSK.

#### Primary Synchronization Sequence (PSS)

The PSS is sent by every CR-BS as a broadcast beacon on its own home channel. The main tasks of the PSS is to mark the begin of a superframe, provide beaconing of cell information and distribute spectrum allocation information among CR-STAs, i.e. the set of subchannels to be used in the data phase. The knowledge about the spectrum being used during the wideband NC-OFDM transmission is an important step to support the synchronization in NC-OFDM (see Sec. 9.1.1).

To keep the control channel overhead low, adjacent subcarriers are grouped into subchannels. The allocated set of subchannels is signaled in the PSS frame via a bitmask using the PSS resource allocation map field. The reserved 8 Bytes allow us to address up to 64 subchannels. If more than 64 subchannels are used, the PSS maintain field further gives the number of PSS fragments. This field also contains the length of the MAP in OFDM symbols.

The PSS beaconing is also used for network topology generation, i.e. information about which CR-BS nodes are in communication range. This is important information which is used by the spectrum broker (ref. to Sec. 7).

#### Contention Phase

When a CR-STA is switched on it starts passively scanning for CR-BSs in its vicinity. Specifically, all potentially available control (home) channels need to be scanned for PSS frames. After this scan, the CR-STA has to decide to which CR-BS it wants to associate. Here different strategies are feasible. As an example, the CR-STA associates with the CR-BS from which it received the PSS with the highest signal strength or SNR value. Therefore, the CR-STA sends an Association Request frame to the selected CR-BS in the contention period of the control phase using random access by means of slotted-ALOHA [17]. In our system the contention phase consists of  $S = 4$  slots, which is sufficient for the expected number of concurrent joining CR-STAs (see further Sec.8.5).

<sup>1</sup>This can be easily adapt to e.g., different TVWS channels widths.

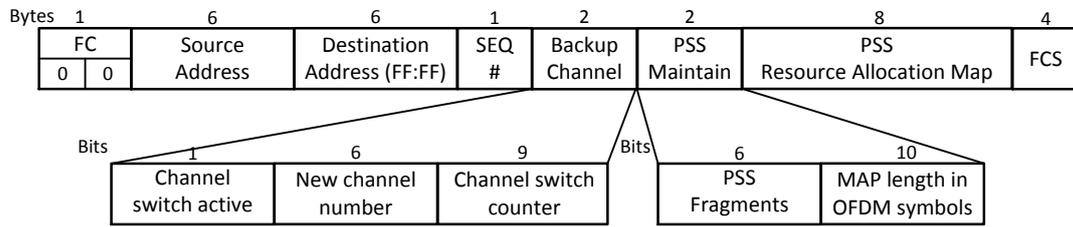


Figure 5.10.: PSS frame format (30 Bytes - 10 OFDM symbols)

To avoid congestion after home channel switches, where all CR-STA has to re-associate with the CR-BS, a backoff scheme known from 802.3 (truncated binary exponential backoff) is also implemented.



Figure 5.11.: Association request frame format (18 Bytes - 6 OFDM symbols)

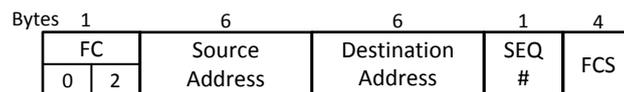


Figure 5.12.: Disassociation request frame format (18 Bytes - 6 OFDM symbols)

**DL/UL MAP**

The DL/UL MAP describes the radio resource usage within a cell. Specifically, it contains scheduling information, i.e. DL and UL slots reserved for a particular CR-STA. An entry in the MAP contains information about the relative position of a specific DL/UL slot in the data phase, i.e. the start and the length of a burst in number of OFDM symbols. Moreover, the information about the Adaptive Modulation and Coding (AMC) used in each subchannel is included in each MAP entry. The ratio between DL/UL is fixed to 80/20.

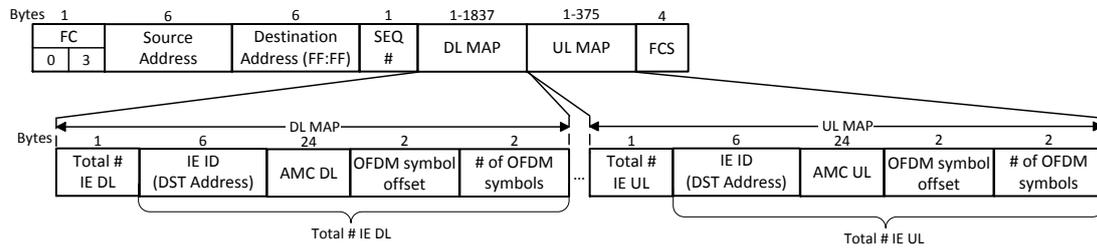


Figure 5.13.: MAP frame format (20-2230 Bytes - minimum 7-744 OFDM symbols (allocating only one subchannel))

### 5.8.2. Data Phase

The data phase is designed to provide the required high peak data rate of the envisioned wireless backhaul. To fulfill this goal, wideband NC-OFDM is used as physical layer to aggregate a large number of scattered spectrum snippets. This allows us to efficiently allocate the total available spectrum, even if Primary Users (PU) are blocking parts of the spectrum.

#### Burst Orientation

As mentioned in Sec. 4.2.4 the task of the radio resource control is to allocate the radio resources to CR-STAs within the cell. In particular, we have to decide on which time/frequency resource is assigned to which STA for both DL and UL which is as 2D packing problem.

Having the flexibility provided by a 2D packing we can address the specific needs of each associated CR-STA. Examples are power consumption, where from the scheduler perspective, it would be convenient to shape the data addressed to such CR-STAs in vertical bursts in order to maximize their sleeping times. Another example is the objective to reduce the packet error rate. Studies have shown that in distributed permutation schemes, due to frequency diversity reasons, packet error rate can be decreased by shaping bursts in a vertical way. Moreover, there are also examples where a horizontal shaping of bursts is preferable, e.g. opportunistic scheduling where multi-user diversity is exploited.

For the envisioned system we believe that a vertical burst shaping is more promising, i.e. achieving robustness due to frequency diversity as well being less sensible to the appearance of PUs due to the use of the total available spectrum within a cell.

#### MPDU Delimiter

Because Ethernet frames have no length field by definition, transmitted frames need an extra delimiter. The length field contains the length of the MPDU (one Ethernet frame) in bytes, followed by the CRC field. For uniqueness the MPDU has a fixed bit pattern of the value 0x43 (0100 0011) in the last field.

#### Downlink Slot

Data transmission is send in bursts from CR-BS to CR-STAs. Note, that the resource scheduling is done independent by each CR-BS for its cell. The CR-BS sends the scheduling information to

Table 5.1.: MPDU delimiter fields (4 Bytes)

Field	Size (bits)	Description
Reserved	4	
MPDU length	12	Length of the MPDU in octets
CRC	8	8-bit CRC of the preceding 16-bits.
Delimiter Signature	8	Pattern that may be used to detect an MPDU delimiter when scanning for a delimiter. The unique pattern is set to the value 0x43.

their associated CR-STAs using the DL/UL MAP. The frame format of the DL data burst is given in Fig. 5.14.

Every DL burst starts with a length field showing the number of MAC Protocol Data Units MPDU included. As we do Layer 2 backhauling up to 16 Ethernet frames are send per DL burst. Every Ethernet frame within the DL burst is separated by a MPDU.

**Uplink Slot**

The UL slots are accessed by the CR-STA regarding the relative location given in the UL MAP. It consists of an ACK field, Channel Quality Indicator (CQI) information and a UL burst field as depicted in Fig. 5.15. Even if a CR-STA has no uplink traffic an UL burst is reserved to gather CQI information (per subchannel one 8 bit CQI value). The number and length of UL frames depends on the number of associated CR-STAs per CR-BS. Initially all UL slots have the same length, e.g., the UL subframe length is divided by the number of CR-STAs. It is intended in later versions that if a CR-STA has no buffered data to send and hence cannot fill his slot with data, the length of the slot will be shortened in the next superframe. The other CR-STAs get larger UL slots and can send more UL data.

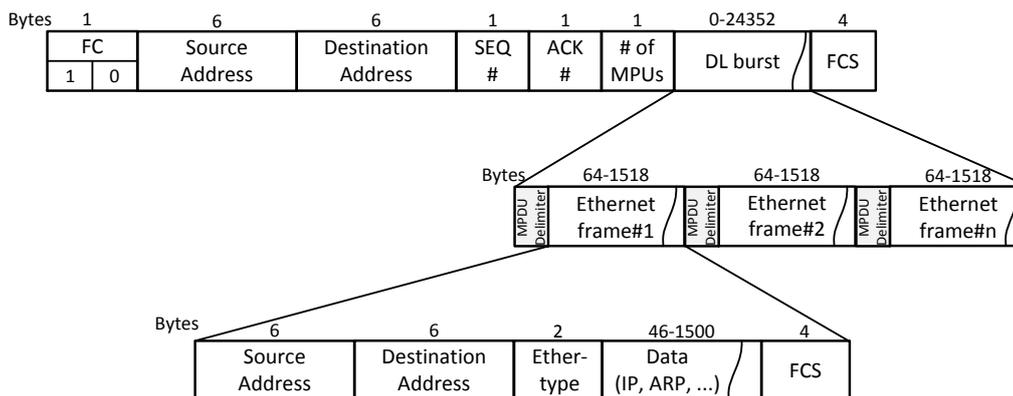


Figure 5.14.: DL frame format (20-24371 Bytes)

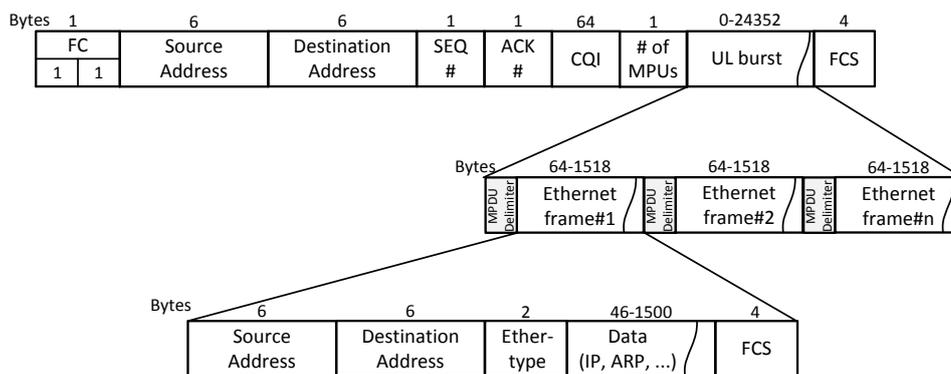


Figure 5.15.: UL frame format (84-24436 Bytes)

## 5.9. Inter-Layer Interactions

In this chapter the interactions, as depicted in Fig. 5.16 between network, MAC and PHY layer are explained. This includes a detailed description of the MACs Finite-State Machine (FSM). Afterwards an explanation of the intended MAC-PHY interface is given.

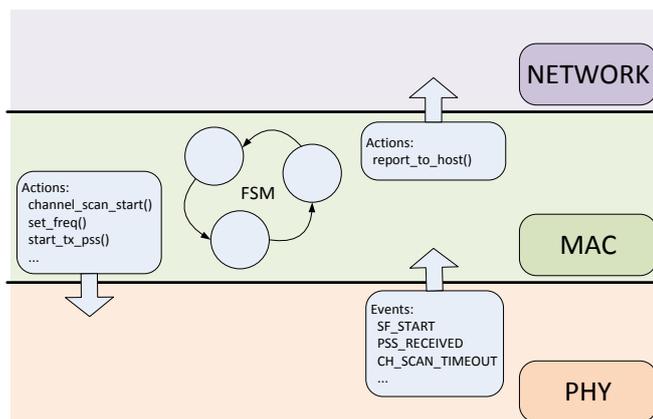


Figure 5.16.: Overview of interactions between network, MAC and PHY layer.

### 5.9.1. MAC Finite-State Machine

In this section the MAC operations in the CR-BS and CR-STA are described as Finite-State Machine (FSM). A FSM is a model of a computational system, which consists of a i) set of states, ii) transitions between states which in turn is triggered by iii) events, conditions and actions. Formally it can be written as

$$\text{State} \times \text{Event} \times \text{Condition} \rightarrow \text{State} \times \text{Action}.$$

The MAC program is completely defined by the FSM.

#### Events

The triggering of an events can be expressed similar to an interrupt. The corresponding hardware (PHY) notifies the MAC about a change by reporting an event. Known events in our system are:

- **SF\_START** Superframe starting trigger. This information is important for timing and synchronization.
- **RX\_ASSOC** When triggered, the reception of a ASSOC frame is indicated.
- **RX\_MAP** When triggered, the reception of a MAP frame is indicated.
- **RX\_FAILURE** This is an emergency event to vacate the current home channel and jump back in the scanning procedure.

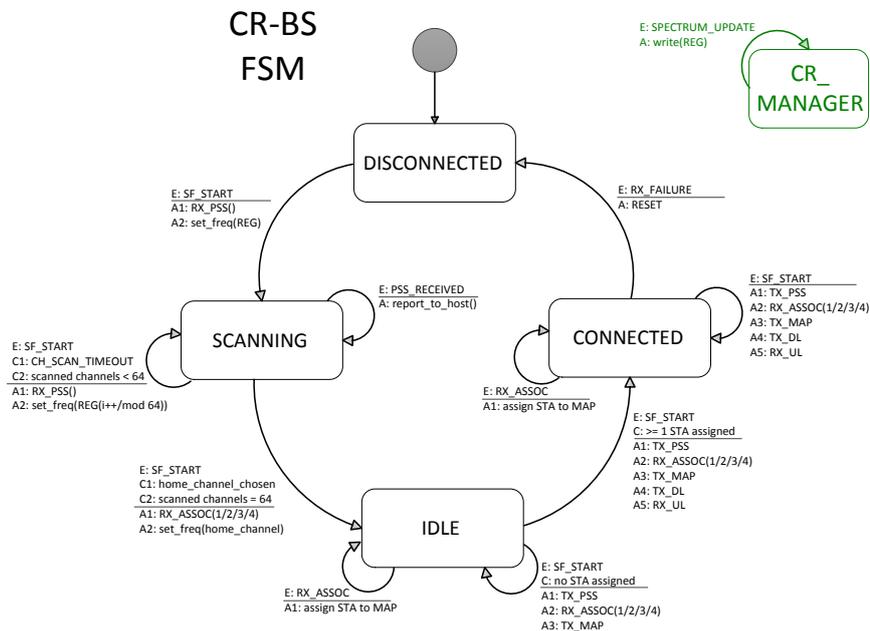


Figure 5.17.: FSM of CR-BS MAC. The transition parameters are marked as follows: Events (E), Conditions (C) and Actions (A).

## Conditions

If an event is reported the transition can immediately take place or an additional condition can be evaluated. In the following the a list of the conditions used in our system are given:

- `equal (VAR)` This condition can be used with different parameters. Here a register is evaluated before the state transition take place.

## Actions

Actions are elementary operations executed during a transition to a new state. Our system has defined the following actions in order to define the state machine:

- `channel_scan_start ()` When executed, a timer of 20 ms is started to scan for existing PSS of other CR-BS.
- `set_freq ()` This action defines used spectrum and is set by the REG1 – narrowband or REG2 – wideband.
- `report_to_host ()` When executed, the transmission/ reception status is directly reported to upper layers.
- `RX_*` Schedule a PSS frame for transmission in the next (n+1) superframe.
- `TX_*` Schedule a DL/UL MAP and data frame for transmission in the next (n+1) superframe.

MAC and PHY communicate via asynchronous messaging. The PHY maintains the global clock and informs the MAC via events about operational changes. The MAC schedules always the n+1 frame due to timing issues.

In Fig. 5.17 the FSM of the CR-BS MAC is shown. As described in the former sections the CR-BS starts with the scanning procedure. When a home channel is chosen it toggles between narrow- and wideband phase in its superframe. The REGX is filled from outside by the CR manager.

The MAC FSM of the CR-STA is similar and depicted in Fig. 5.18.

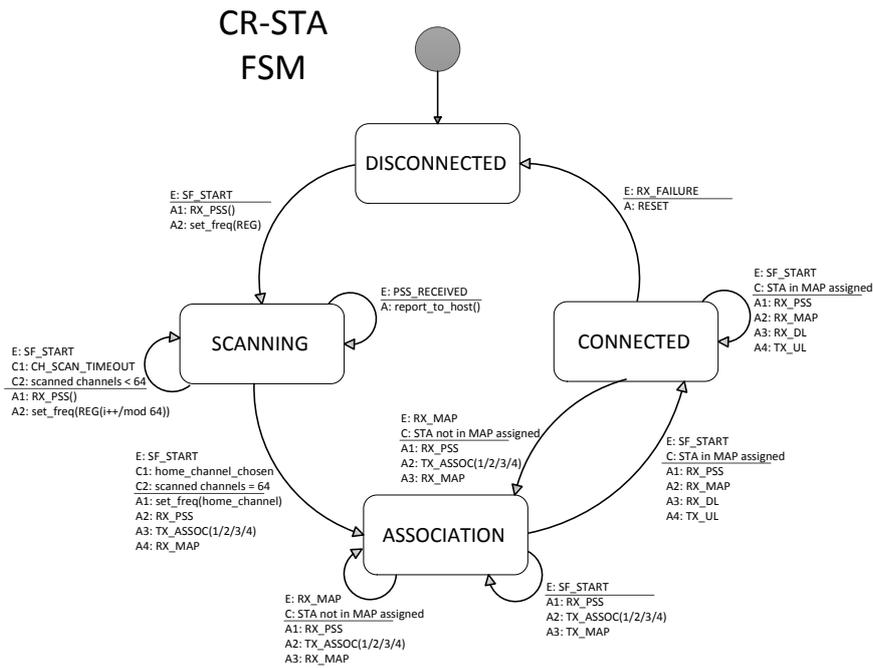


Figure 5.18.: FSM of CR-STA MAC

### 5.9.2. PHY/ MAC Asynchronous Exchange of Packets

At the time of this report, it is intended to implement the COUWBAT MAC processor using NS3. Interaction is done by asynchronous messaging between MAC and PHY layer. Due to time constraints the MAC has to schedule always the next (n+1) superframe. The PHY has a GPS or similar clock and is therefore the timekeeper. Every start of a superframe is triggered by an event towards the MAC.

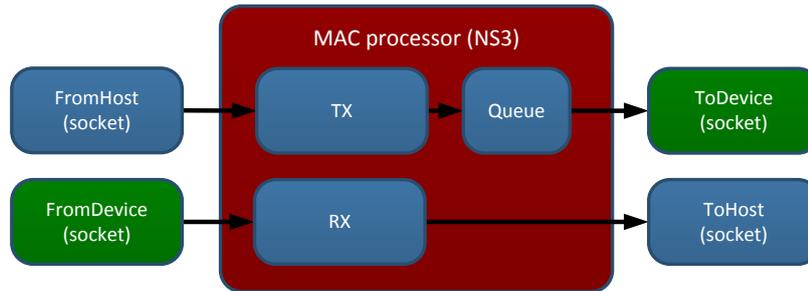


Figure 5.19.: Interaction between MAC and PHY via NS3

As shown in Fig. 5.19 an NETLINK socket is used to communicate between MAC and PHY. The frame format is shown in Fig. 5.20. The MAC processor creates and processes complete MAC frames, consisting of meta information and the MAC PDU, which further contains the MAC header and if available the payload.

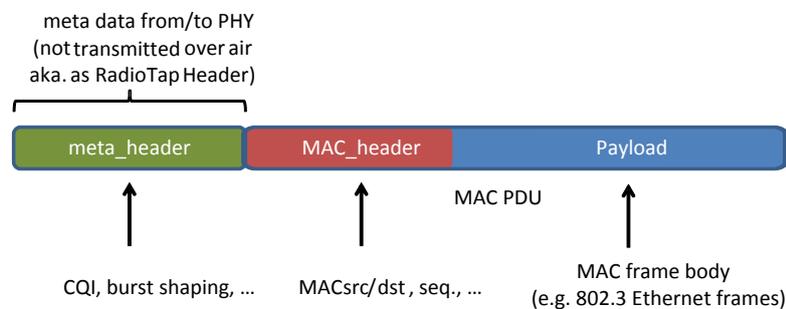


Figure 5.20.: Frame structure between PHY and MAC layer.

COUWBAT frames are defined as shown in the following Listings 5.1 and 5.2. The first part *meta\_header* is comparable with the radiotap header known from the de-facto standard for 802.11 frame injection and reception. The kernel module supports receiving the *meta\_header* before the actual frame to be transmitted. A "zero packet" is a command trigger to exchange state inform between MAC and PHY, but without exchanging data packets.

The *enum* in Listing 5.1 shows the reception status which a *meta\_header* can indicate. These states are described in the former FSMs.

The number of subchannels is a variable number of grouped subcarriers which can still be adapted when the evaluation is completed.

The *meta\_header* is defined in the *struct* with the same name. Elucidating information is given in the comments in the listing.

Listing 5.1: meta\_header frame format

```
enum {
    CW_CMD_WIFI_EXTRA_UNSPEC          = 0x00, /* Reception status */
    CW_CMD_WIFI_EXTRA_ZERO_SF_START = 0x01, /* reserved, do not edit */
    CW_CMD_WIFI_EXTRA_ZERO_RX       = 0x02, /* PSS phase started indicator */
    CW_CMD_WIFI_EXTRA_TX             = 0x03, /* Set receive subchannels */
    CW_CMD_WIFI_EXTRA_TX_ERR        = 0x04, /* Packet transmission */
    CW_CMD_WIFI_EXTRA_RX            = 0x05, /* Packet reception */
    CW_CMD_WIFI_EXTRA_RX_ERR        = 0x06, /* Transmission failed */
    CW_CMD_WIFI_EXTRA_NO_SEQ        = 0x07, /* Packet reception */
    CW_CMD_WIFI_EXTRA_RX_ERR        = 0x06, /* Failed CRC check */
    CW_CMD_WIFI_EXTRA_NO_SEQ        = 0x07, /* Sequence aborted, no sequence info */
    CW_CMD_DEBUG_DMA_START          = 0x08, /* DEBUG Command: Write to DMA */
    CW_CMD_DEBUG_DMA_STOP           = 0x09, /* DEBUG Command: Write to DMA */
    CW_CMD_DEBUG_DMA_WRITE          = 0x0A, /* DEBUG Command: Write to DMA */
    CW_CMD_DEBUG_DMA_READ           = 0x0B, /* DEBUG Command: Read from DMA */
    CW_CMD_DEBUG_DMA_STATUS         = 0x0C, /* DEBUG Command: Read DMA Status */
    CW_CMD_DEBUG_DMA_RESET          = 0x0D, /* DEBUG Command: Reset DMA */

    __CW_CMD_WIFI_EXTRA_AFTER_LAST, /* Arbitrary command, do not edit */
    __CW_CMD_WIFI_EXTRA_MAX = __CW_CMD_WIFI_EXTRA_AFTER_LAST - 1 /*Arbitrary command */
};

#define MAX_SUBCHANS 64 /* total number of subchannels each
    with 2048/64=32 subcarriers */

struct meta_header { /* exchanged between local MAC and PHY */
    uint32_t flags; /* see enums above */
    uint16_t frequency_band; /* sub-band (0-1GHz, 1-2GHz or 2-3GHz) */
    uint32_t ofdm_sym_sframe_count; /* absolute superframe counter */
    uint16_t ofdm_sym_offset; /* relative start (time) of MPDU */
    uint16_t ofdm_sym_len; /* duration (no. OFDM symbols) of MPDU */
    uint64_t allocatedSubChannels; /* bitarray of used logical subchannels */
    uint8_t MCS[MAX_SUBCHANS]; /* MCS/Bitrate for each subchannel */
    uint8_t CQI[MAX_SUBCHANS]; /* channel quality indicator per subchannel */
    uint16_t reserved; /* (reserved) */
}
```

The MAC frame header consists of the information shown in the following Listing 5.2. The given components of the *struct* are explained in the former Sec. 5.8.

Listing 5.2: MAC\_header frame format

```
#define WIFI_ADDR_LEN 6

struct mac_header {
    uint8_t i_fc; /* Frame control */
    uint8_t i_src[WIFI_ADDR_LEN]; /* Source address */
    uint8_t i_dst[WIFI_ADDR_LEN]; /* Destination address */
    uint16_t i_seq; /* Sequence number */
}
```

Fig. 5.21 shows the exchange of the multi-tiered transmission. Because information to receive following messages is stored in earlier ones, until the actual transmission of data several control

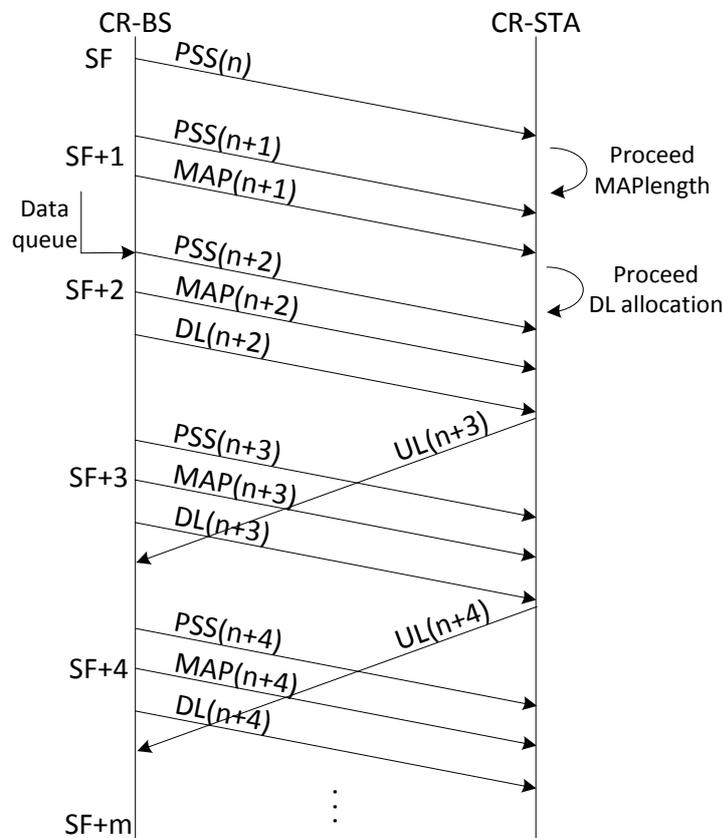


Figure 5.21.: Message flow between CR-BS and CR-STA. Up to four step process to transmit all necessary information for the UL slot.

channel messages needs to be exchanged. Starting with the PSS, which contains the MAP length in symbols. Followed by the MAP containing the DL and UL frame allocation in OFDM symbols. It can be seen, until the first uplink data is reaching at the CR-BS four superframes need to be passed.

Fig. 5.22 and 5.23 show the detailed message exchange between MAC and PHY layer of COUW-BAT entities, as well as the communication with external entities.

Because the CR-BS has to handle the spectrum access to, the messaging starts in Fig. 5.22 with the polling for spectrum allocation information. Now the CR-BS MAC is able to start the search for home channel procedure. This procedure is described in detail in Chap. 5. When the home channel is chosen, the CR-BS enters the main superframe loop, where the framing as described in Chap. 5 takes place.

The CR-STA has to start with the CR-BS scanning and association procedure. After a CR-BS is associated to the CR-STA also starts the main superframe loop according the description in Chap. 5.

The PHY has to know spectrum range (subchannels), when to send in OFDM symbols, which

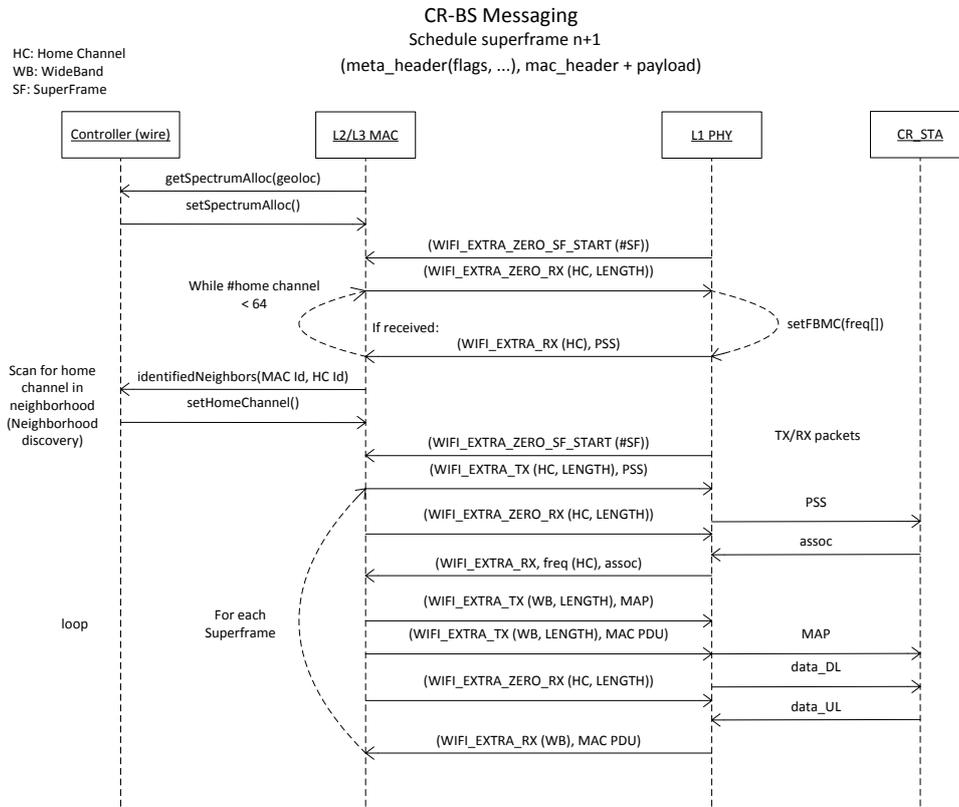


Figure 5.22.: Message exchange here for CR-BS between MAC and PHY layer, as well as external entities.

Modulation per subchannel for RX and TX. If the PHY is not transmitting it is in listening mode.

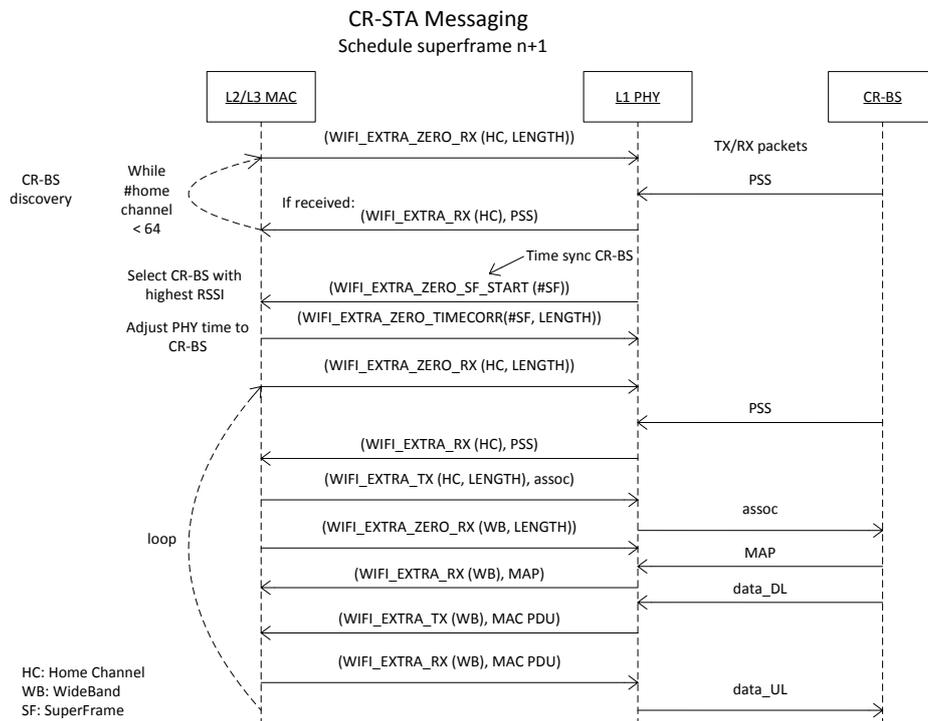


Figure 5.23.: Message exchange here for CR-STA between MAC and PHY layer, as well as external entities.

## 5.10. Automatic Repeat reQuest (ARQ)

Automatic Repeat reQuest (ARQ) is implemented as Selective Repeat (SR) scheme. The ACK scheme works as follows. A data frame (DL/UL) is sent with a certain SEQ number by MAC-A. After MAC-B receives this frame, it sends the highest SEQ it has successfully received so far in its next data frame. In case MAC-A does not receive the ACK (either data lost or ACK lost), it makes a SINGLE attempt to retransmit the same data. This is done by enqueueing that data (separate payload packets) to the front of the TxQueue. This is then sent with a new SEQ number as if it were fresh data and possibly together with actual fresh data. SEQ numbers increase continuously and the same SEQ number itself is never retransmitted.

Due to the COUWBAT protocol, the sent payloads of the 4 previous superframes (40 ms) must be kept/saved by the MAC for possible retransmission. This is the delay until the MAC receives back an ACK for a sent frame.

In case of multiple UL/DL bursts per superframe, the each n-th frame from the burst (1st, 2nd, etc.) in turn confirms/ACKs its corresponding n-th frame that was received in the previous superframe. One MAC's bursts use one single 8-bit SEQ counter.



## Chapter 6.

# Rendezvous Schemes for CR Networks

### 6.1. Introduction

CR has, in comparison to other communication systems, one more required step before a communication can be established. This step is to find the other communication node not only in space/ time as further in frequency, because channelization can be handled very flexible and is not bounded to fixed frequencies. Often a previously known static Common Control Channel (CCC) is used to signal frequency allocation information between communicating nodes. But to have such a static CCC available has, apart from limiting the difficulty of setting up a link, several drawbacks. First of all, a single control channel can be saturated if too many nodes use this channel (scalability), second this channel is prone to jamming attacks and third, mostly licensed frequency bands need to be used to avoid interruption caused by other communication systems. Licensed bands are very rare and very expensive too. If such a control channel exists, it is sometimes also called rendezvous channel [18]. Therefore rendezvous protocols play an important role in CR, especially if the control channel is established during the communication. Based on the recent hype of CR, a considerable number of MAC-protocols focusing on CR has been proposed recently. Most of these protocols assume a static CCC. In this work we focus only on dynamic approaches without a previously known CCC.

Initially connect two or more wireless nodes without a CCC in CR can be done via two different approaches: First, if the PHY layer uses (NC-)OFDM a mixture of sensing and precoded preambles can be used to establish an initial setup. Second, for any general PHY where channels are labeled similar for all participant nodes, Channel Hopping is the most applied scheme. Both options are called *blind rendezvous*. If a set of channels is available to certain nodes, but they do not share a common labeling this option is called *oblivious blind rendezvous*. While the first approach is mostly a PHY issue related to special OFDM-based PHY technologies, the second options are kind of general.

Whereas the limitations of the NC-OFDM related approach is deeply discussed in the first part of the following chapter, the second part investigates Channel Hopping based approaches and shows our selected method.

### 6.2. Related work

Setting up an initial channel between two or nodes is not new and not only related to CR systems. In former work it is also called *the telephone coordination game* [19, 20]. Here two persons are placed in two different rooms which are connected via  $n$  direct connected phone lines. During the game each player has to choose a socket to connect each other. The goal is to minimize the number of rounds until both players are connected. The optimal strategy, where one player chooses a random line and keeps it until the second player has it found, takes  $n/2$  rounds in expectation. The main issue here is,

who is the first player, who keeps the line? Other names of the rendezvous problem are *discovery or coordination problem* [21] and *network setup problem* [22].

The problem of rendezvous between several nodes is often related to the hidden node problem during the sensing phase [23]. We skip this issue here, because sensing is often error prone. Therefore, we have chosen a database approach. Nevertheless, spectrum databases are very reliable but they still waste spectrum, as there is a latency between the CR-nodes and the database, as well as an incumbent user might not be disturbed by a transmitting node as the propagation boundaries are of theoretical nature plus a safety margin.

Interestingly, the problem is the same for continuous and non-continuous spectrum schemes because when the link is whenever established, communication can be done.

An executive summary of setting up a CCC is given by Lo et al. [16]. His classification distinguishes CCC in in- and out-of-band approaches. He also shows that setting up a CCC is always based on channel hopping. The used sequences can be further distinguished in pseudo random, permutation-based, adaptive multiple rendezvous control channel-based or quorum-based.

Liu et al. [24] suggest a classification of rendezvous algorithms for centralized and decentralized systems from a link level perspective. The term *rendezvous* defines in their context 'the process of two or more radios of users to meet and establish a link on a common channel'. Rendezvous protocols can be divided either in protocols using an existing CCC, if no CCC is available they mostly use Channel Hopping (CH). Rendezvous protocols without using CCC can be further classified in protocols using random algorithms, w/ required time synchronization and applicable to symmetric and/ or asymmetric channels. As mentioned before in this work we focus only on approaches without a previously existing CCC.

For the sake of completeness we give further a short overview of PHY based rendezvous methods. Chowdhury et al. [25] approach is listed as dedicated CCC in the work of Lo et al. [16]. This is not entirely true because blind synchronization could also be used in in-band approaches. The main issue here is to design an OFDM preamble which is robust to wrong channelization, based on wrong sensing results or unexpected interference. Applying an OFDM based blind synchronization is studied in Section 6.5 of this chapter.

## 6.3. Model and Problem Description

### 6.3.1. Network Model

Our considered CRN consists of CR-Base Stations and CR-Stations which communicate over  $N$  orthogonal channels. The global channel set is denoted as  $C = \{0, 1, \dots, N - 1\}$ . Each channel in  $C$  represents one certain frequency band. The network time is divided into time slots of equal length (e.g.  $t = 10ms$  according to IEEE 802.22). As it is unrealistic that spatially dispersed CR-Stations have synchronized clocks with CR-Base Stations without message exchange, CR-Stations will start hopping according to their own local clocks. As a countermeasure, the duration of each time slot is prolonged to  $2t$  to ensure an overlap of  $t$  when the time slots are misaligned.

Then nodes can successfully complete the processes of beaconing, handshaking, establishing a link and so on if they access the same available channel in the same time slot.

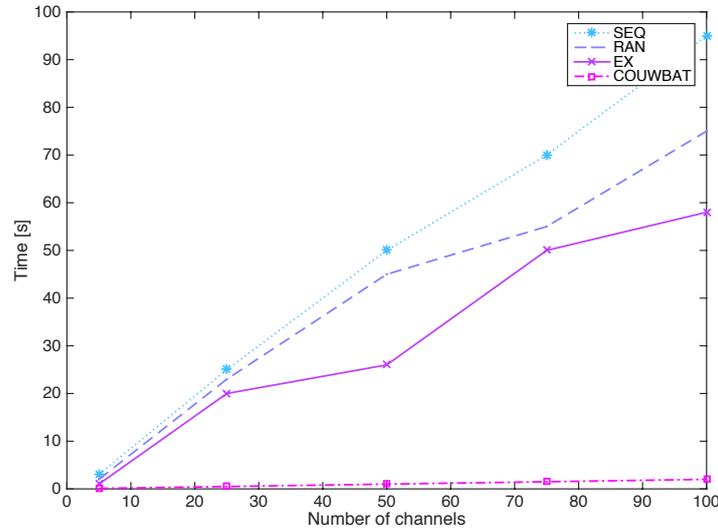


Figure 6.1.: Comparison of search times of three general rendezvous protocols proposed by Kondareddy et al. [22] vs. our proposed very specialized rendezvous scheme.

### 6.3.2. Approach

Our system has related to Yang et al. [26] following preconditions given: asynchronous clock, homogeneous model, symmetric role and known SU ID information.

Actually it is possible to assume that our system has 2048 channels, which equals the number of given subcarriers. Further we have a multi-channel system, as all subcarriers could be used synchronous. Such a large number of very small channels is not practical and easily to maintain. On PHY layer a preamble for every permutation of used and unused subcarriers has to be precalculated and stored. To have a more practical solution we grouped 32 subcarriers together to form 64 8 MHz wide channels. These channels are labeled in descend order. One 8 MHz wide channel is dedicated to a CR-BS, whom chose this channel during the setup phase.

## 6.4. Evaluation

### 6.4.1. Search Time

The *setup time* or Time-To-Rendezvous (TTR) is the crucial factor of any rendezvous protocol. This time is the time each Secondary User (SU), e.g., CR-STA needs to find an according CR-BS and establish a connection. Our system could be described as a special case of the proposed scheme from Kondareddy et al. in [22, 27]. Therefore we can compare our results with their results. As their approach is more general setting up a link between the SU and the CR-BS will take in maximum  $N^2 \times T_s$  seconds, which is would be in our case 81s. As we apply a decent order of channels and every CR-STA has to hop on all 64 channels before actually set up the connection our maximum rendezvous time is always 1.28 s ( $64 \times 20ms$ ).

## 6.5. On the Feasibility of Blind Synchronization of NC-OFDM in CRN

### 6.5.1. Overview

Non-contiguous OFDM (NC-OFDM) has the potential to be a successor technology in wideband Cognitive Radio Networks (CRN). One of its main challenges is the synchronization between sender and receiver, i.e., the secondary receiver needs perfect knowledge about the set of data subcarriers  $S$  being used temporarily by the sender. Otherwise the sender is not able to construct the proper preamble for the scattered non-contiguous spectrum allocation and the correlator on receiver side is likely to fail detecting the transmitted packet.

In this section we show the results of the evaluation. First, the limits of sensing-based blind synchronization schemes are examined and discussed. It is shown how interference from PUs and particularly from SUs influences the correctness of the estimated set of subcarriers on receiver side. Our findings lead us to the conclusion that for a reliable data communication the subcarrier set  $S$  needs to be directly transferred to the receiver. To optimize the systems performance the capacity of the CC must be well-matched with the granularity of subchannel assignment in the data channel.

### 6.5.2. Modeling and Problem Statement

### 6.5.3. Synchronization approaches for NC-OFDM

Fig. 6.4 depicts the two possible synchronization approaches for NC-OFDM. The first is the blind synchronization approach. Here the receiver has to guess, based on sensed spectrum information, the set of subcarriers being used by the transmitter,  $\tilde{S}$ . In contrast in the second approach the transmitter transfers the subcarrier set  $S$  to the receiver side using a separate CC. Next we give some details about both schemes.

#### Non-Blind Synchronization

In the non-blind approach the information about the resource allocation in the data channel  $S$  is exchanged in the CC. This guarantees that both transmitter and receiver perfectly agree on the same set of subcarriers to be used for the NC-OFDM transmission. The downside is the need for a, e.g., separate TX/RX chain for the CC.

#### Blind Synchronization

In blind NC-OFDM synchronization the receiver makes use of local spectrum sensing in order to detect the subcarriers being used by the transmitter [28]. Fig. 6.2 illustrates the approach where sensing is performed at two points in time: prior **(A)** and at the beginning of the NC-OFDM transmission **(B)**. The time interval between these two sensing points need to be very small, i.e., both the cycle time of PU activity and the channel coherence time (w.r.t. to fading) must be substantially larger. Moreover, the detector assumes that a subcarrier which is sensed as being used (busy) is either utilized by the SU transmitter or occupied by a PU but never both at the same time.

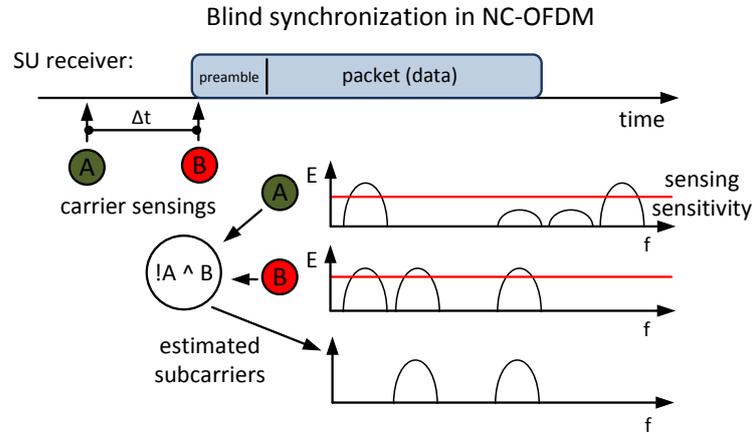


Figure 6.2.: **Blind synchronization in NC-OFDM.** The spectrum is sensed at two points in time: immediately prior (**A**) and at the beginning (**B**) of the NC-OFDM transmission. From **A** and **B** the SU receiver is able to estimate the set of subcarriers being used for the NC-OFDM transmission, i.e.,  $\neg A \wedge B$ .

#### 6.5.4. Cognitive Radio Model

We assume that PUs, which are licensed spectrum holders, are totally unaware of secondary spectrum usage and must be protected by any means. SUs have to be spectrum aware. The available unused spectrum can be estimated in two ways. First, by means of spectrum sensing. Second, using a lookup into a spectrum database which reveals the parts of the spectrum which are available for secondary usage. Note, that because of spatial separation each node detects different parts of the spectrum to be available for secondary usage.

The two options for a SU transmitter to estimate the secondary spectrum are shown in Fig. 6.3. First, lookup into PU spectrum database, which replies with a set of frequencies (i.e., NC-OFDM subcarriers) which can be used by SUs or second, detection of PUs by means of local sensing.

When the database approach is used, we can assume that there is no hidden PU problem [29]. The SU transmitter is able to ensure that from the selected secondary spectrum there is no interference towards other PUs. The available secondary spectrum is computed from the geographical location of the SU transmitter and the used transmission power (dBm/Hz). In contrast, the PU detection by means of sensing is imperfect and unreliable resulting in the well-known hidden PU problem, i.e., PUs outside transmission, but in interference range are not detected.

#### 6.5.5. Problem Statement

Our research focus is two-fold. First, we investigate the limitation of sensing-based blind synchronization methods for NC-OFDM in CRN. We want to investigate under which conditions such a synchronization is reliable in CRN, i.e., the estimated set of subcarriers at receiver side  $\tilde{S}$  equals those chosen by the transmitter side  $S$ , i.e.,  $S = \tilde{S}$ .

Second, in situations where a blind synchronization scheme fails a dedicated CC is required. Here, we are interested in the tradeoff between the available bitrate in the CC and the capacity of the data channel. Because with a low bitrate CC it is impossible to address a highly fragmented secondary

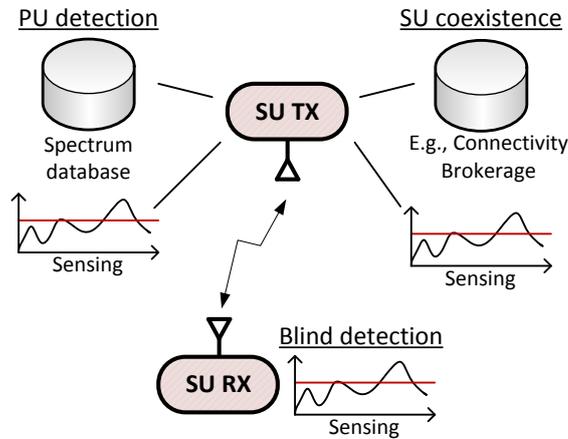


Figure 6.3.: **CR model:** Different settings are conceivable – **On TX side** PU detection via database or sensing and SU coexistence coordinated by e.g., Cognitive Brokerage (CB) [30] or via a control channel. At **receiver stations** blind synchronization by sensing only.

spectrum without wasting valuable spectrum resources. In particular, we are interested to what extent the available bitrate in the CC,  $R_{CC}$ , has an impact on the bitrate in the data channel,  $R_{DC}$  (see Fig. 6.4).

### 6.5.6. Limits of Blind Synchronization

In this section, we systematically examine under which conditions blind synchronization in NC-OFDM in a CRN is reliable, i.e.  $S = \tilde{S}$ .

#### Scenarios

We consider two different scenarios for a CRN: i) an isolated SU point-to-point (P2P) link and ii) multiple co-located SU P2P links which are in interference range. In the latter case we additionally analyze how cooperation between SU transmitters impacts the reliability of blind synchronization.

*Isolated SU Point-to-Point* In the first scenario we consider a single P2P link between one SU transmitter and one SU receiver. As depicted in Fig. 6.3 the SU transmitter is able to detect PUs via a Spectrum DataBase (SDB) or sensing. Because of the absence of a CC between the SU-TX and SU-RX and no access to the DB the SU receiver has to rely on sensing for the detection of PUs and SUs.

*Multiple co-located SU Point-to-Point links* In the second scenario multiple spatially co-located SU P2P links exist. Here, the discovery of PUs is done in the same way as in the isolated SU P2P scenario. In addition, SU co-existence must be considered as well. Fig. 6.3 illustrates the two possible options to manage SU co-existence. First, it can be realized using a Connectivity Brokerage (CB) approach or using a CC between SU transmitters to coordinate the spectrum access among SUs. Second, listen before talk like spectrum sensing is another option to coordinate spectrum access between co-located SUs.

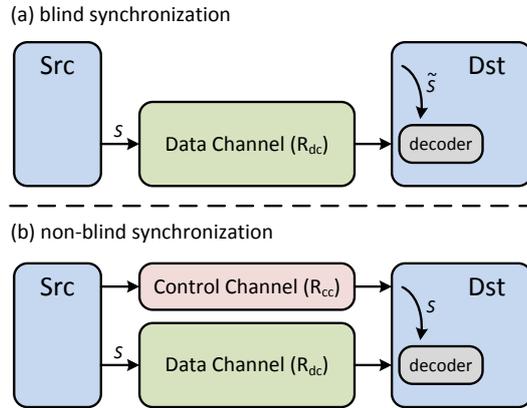


Figure 6.4.: **System model.** In blind synchronization schemes the allocated set of subcarrier,  $\tilde{S}$ , must be assessed by the receiver side, whereas in the non-blind approach the information about resource allocation in the data channel is exchanged in the control channel.

## Results

### ISOLATED SU-P2P COMMUNICATION

In the isolated SU-P2P communication scenario we have to consider whether the SU transmitter has access to a PU spectrum database or has to rely on local sensing (Fig. 6.3).

#### *Case I: SU-TX with access to spectrum database (Fig. 6.5(a))*

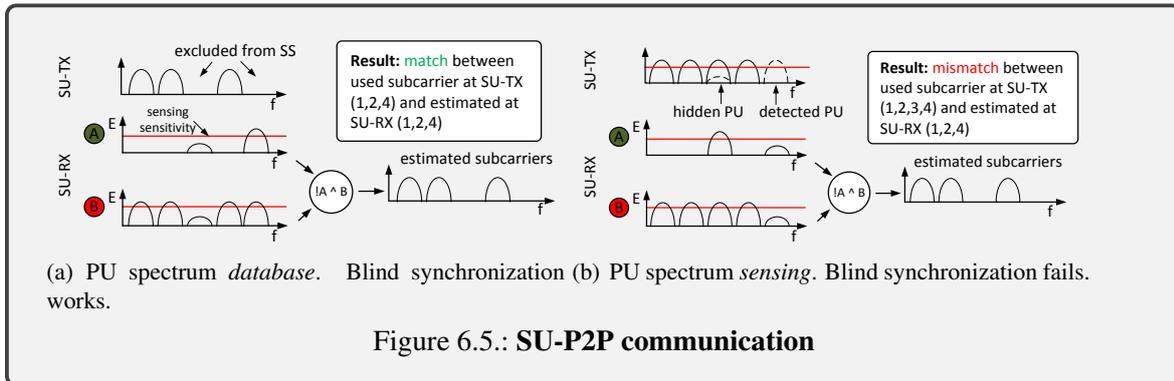
Here the SU transmitter access the PU spectrum database in order to estimate the available secondary spectrum. This approach ensures that there is no hidden PU problem, i.e., subcarriers allocated to a SU transmitter will not interfere with any PU using the same subcarrier. Moreover, all subcarriers from the available secondary spectrum are sensed to be idle.

**Result** From Fig. 6.5(a) we can see that the SU receiver is able to perfectly estimate the set of subcarriers being used by the SU transmitter. This is because in the absence of the hidden PU problem a subcarrier which is not used by the SU transmitter is sensed in both phases, **(A)** and **(B)** (Fig. 6.2), with the same value and is thus excluded from the set of estimated subcarriers as long as the channel coherence time is larger than  $\Delta t$ . In contrast, subcarriers which are allocated by the SU transmitter and received with sufficient high power are included in the set of estimated subcarriers. Hence a blind synchronization scheme works here.

#### *Case II: SU-TX with PU sensing (Fig. 6.5(b))*

SU transmitter estimates the available secondary spectrum by means of local sensing, which will fail because of the hidden PU problem.

**Result** From Fig. 6.5(b) we can see that there is a mismatch between the allocated subcarriers at the SU transmitter and the estimated subcarriers. This is due to the hidden PU problem, i.e., subcarriers being used by a PU are not sensed at the SU-TX but could be at the SU-RX side. Hence, a blind synchronization scheme is likely to fail.



### MULTIPLE CO-LOCATED SU-P2P COMMUNICATIONS

In the following we analyze whether blind synchronization for NC-OFDM is feasible in a scenario with multiple co-located SU-P2P communications links. The access to secondary spectrum must be coordinated if multiple SU transmitters are in inference range. In general there are two options, namely orthogonalization in i) time or ii) frequency. Here, we have to distinguish whether there is a cooperation between SUs in secondary spectrum access (e.g., using a CC) or not (i.e., spectrum being used by co-located SU transmitters are detected by means of local sensing). The latter approach leads to the hidden SU problem.

**Case I:** *SU-TX with access to spectrum database and cooperation between SU transmitters* (Fig. 6.6 & 6.6(b))

Here all SU transmitters have access to the PU spectrum database in order to estimate the available secondary spectrum without the risk of hidden PU problem. Moreover, the SU transmitters are cooperating with each other to coordinate the access to the secondary spectrum.

**Result** From Fig. 6.6(a) and 6.6(b) we can see that the estimated subcarriers at SU receiver side are correct as long as the medium access of co-located SUs is not aligned in time. This can be achieved by using a random access protocol like CSMA. However, if the medium access is aligned (e.g., strict TDMA) the SU receiver is unable to detect by means of sensing the subcarriers being used by co-located SU transmitters.

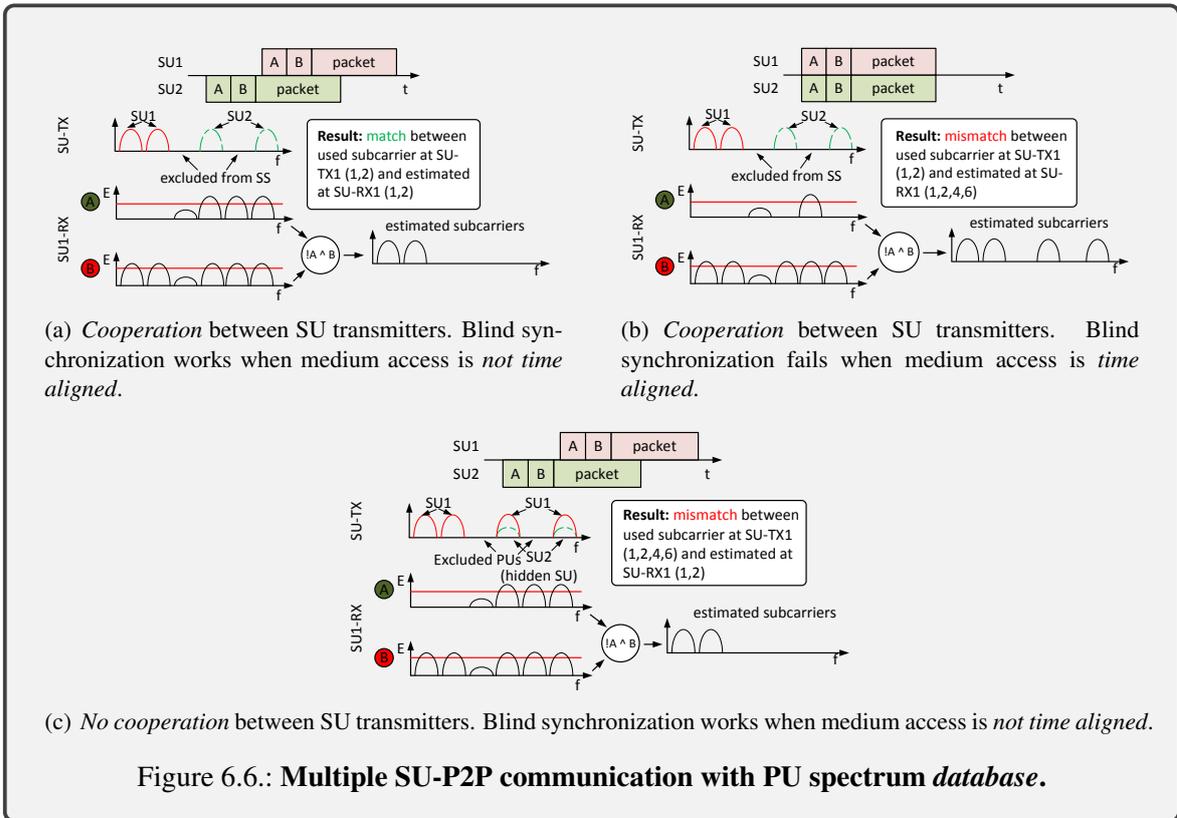
**Case II:** *SU-TX with access to spectrum database but no cooperation between SU transmitters* (Fig. 6.6(c))

Here again all SU transmitters have access to the PU spectrum database. However, due to the absence of a CC and/or CB the SU transmitters cannot cooperate with each other to coordinate the access to the secondary spectrum resulting in hidden SU problem.

**Result** From Fig. 6.6(c) we can observe that an uncoordinated access to the secondary spectrum among co-located SUs results not only in interference between them (hidden SU) but also causes that the SU receiver estimates an incorrect set of subcarriers. A blind synchronization would therefore fail.

**Case III:** *SU-TX with PU sensing and cooperation between SU transmitters* (Fig. 6.7(a))

All SU transmitters have to detect PUs using local sensing. However, there is a cooperation between SU transmitters regarding the usage of secondary spectrum.



**Result** From Fig. 6.7(a) we can derive that the detection of PUs using local sensing can cause hidden PU problems leading to incorrectly estimated subcarriers. A blind synchronization would therefore fail, too.

**Case IV: SU-TX with PU sensing but no cooperation between SU transmitters (Fig. 6.7(b))**

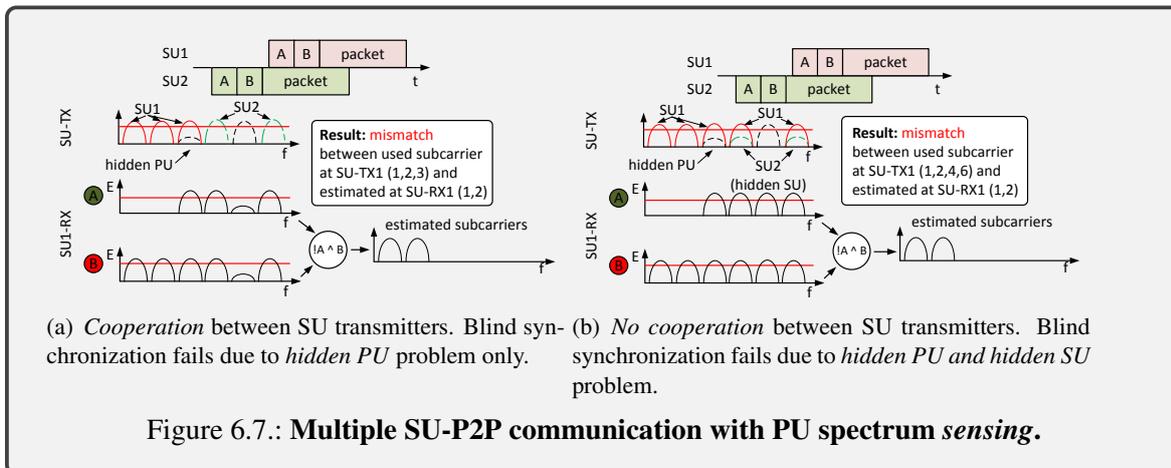
All SU transmitters have to detect PUs using local sensing. In addition there is no cooperation between SU transmitters regarding the usage of the secondary spectrum. Both PUs, as well as SUs need to be detected using local sensing.

**Result** From Fig. 6.7(b) we can see that both the hidden PU, as well as the hidden SU problem lead to incorrectly estimated subcarriers. A blind synchronization would therefore fail.

**6.5.7. Summary**

From our evaluation we can conclude that blind synchronization for NC-OFDM in a CRN is unreliable if the SU transmitter estimates the available secondary spectrum by means of sensing which is due to the hidden PU problem. In contrast, for an isolated SU P2P link where the SU-TX has access to PU spectrum database blind synchronization is feasible.

In a scenario with multiple co-located SU P2P links blind synchronization is reliable only if the SU-TX has access to a spectrum database and the medium access of co-located SUs are not time aligned. In a multi-user scenario sensing at SU-TX side leads to both hidden PU, as well as hidden SU problem resulting in incorrectly estimated secondary spectrum allocation information at SU-RX side thus making blind synchronization unfeasible.



	Multiple co-located SU-P2P	
	Cooperation between SU-TX	No cooperation between SU-TX
Isolated SU-P2P		
PU database	✓ (Fig. 6.5(a))	✗ (Fig. 6.6(b), if time aligned)
PU sensing	✗ (Fig. 6.5(b))	✗ (Fig. 6.7(a))

Table 6.1.: **Summary.** Scenarios in which blind synchronization for NC-OFDM is able to reliably estimate the set of subcarriers used for the NC-OFDM transmission.

Our observations lead to the summary that blind synchronization for NC-OFDM can only be used for Cognitive Radio Ad-hoc Networks (CRAN) where SUs allocate the medium in a random way, e.g., via CSMA, and PU detection is achieved via a lookup in a global spectrum database. Finally, if PU detection is limited to sensing, e.g., the SU transmitter has no access to a spectrum database, then blind synchronization becomes unfeasible and a CC between the SU transmitter and receiver is required.

# Chapter 7.

## Distributed Spectrum Broker

In this chapter, we provide a detailed description of the proposed algorithm for computing the spectrum share to be used by any Cognitive Radio – Base Station (CR-BS) and their associated CR-STAs. In order to manage interference between spatially co-located CR-BSs the algorithm ensures that neighboring CR-BSs use different parts of the spectrum and thus can co-exist. Note, that we aim for spectrum sharing between CR-BSs whereas the co-existence between CR-BSs and their associated CR-STAs was already described in Chap. 5.

### 7.1. Objective

The goal is to share the spectrum between CR-BSs and to make sure that i) in order to mitigate interference the same part of the spectrum (e.g., an OFDM subcarrier) is used only once in the two-hop neighborhood of any CR-BS node, ii) every CR-BS gets a minimum spectrum share which depends on the network density, iii) the algorithm for computing the spectrum share can be computed distributed without any centralized infrastructure.

### 7.2. System Model – Revisited

A wireless communication system is considered, in which a range of spectral frequencies from  $F_{min}$  to  $F_{max}$  can be used in Cognitive Radio manner. We assume that all the frequencies are licensed, but there exists a data base of spectrum fragments available for secondary usage in a given time interval over a given spacial area. The available spectrum might be strongly fragmented. Moreover, the allowance for secondary usage can be revoked on a short notice.

Furthermore, we assume that the secondary usage is claimed by a set of secondary networks. Each such secondary network is in fact a group of SU nodes with a designated cluster leader, referred further on as CR Base Station (CR-BS). The CR-BSs have the possibility to get information from a spectrum data base via the backbone. The remaining nodes, referred further on as CR Stations (CR-STA), are associated with the CR-BSs. Since the spectrum is selected by the CR-BS the remaining network participants (CR-STA) follow the spectrum selection done by the CR-BS.

All nodes are equipped with a half-duplex wideband NC-OFDM transceiver. The total spectrum, i.e.  $F_{min} \dots F_{max}$ , is divided into NSC subcarriers, which equals the size of the FFT. Adjacent subcarriers are grouped into physical subchannels resulting in a total number of SCH subchannels. The wireless communication between neighboring CR-BSs is limited to the in-band exchange of control messages (beacons). All nodes are time synchronized, i.e., the CR-BSs are synchronized with the help of Global Positioning System (GPS) or via network time protocol, whereas the CR-STAs are synchro-

nized through the control messages of the associated CR-BS. A coarse time synchronization is needed for in-band signaling (beacon exchange) due to the limitations of the half-duplex transceivers.

Finally, PUs which are licensed spectrum holders are assumed to be totally unaware of secondary spectrum usage and must be protected by any means.

### 7.3. Network Abstraction

The following network abstraction is used. The network of CR-BSs is represented as a undirected labeled graph  $G = (V, E)$  where the CR-BSs are represented as nodes and the wireless links between CR-BSs are respresented by vertices, i.e., only CR-BSs able to communicate with each other on the control channel are connected by a vertice in the graph.

The proposed algorithm assigns to every node  $v$  a ranking number  $r_v$  which references some part of the spectrum to be used. In order to avoid interference between nodes the following heuristic is used to assess the interference range. We assume that the interference range around a node is twice the communication range. Thus, to make sure that any part of the spectrum is used only once in the two-hop neighborhood of a node  $v$  the ranking number  $r_v$  must be unique in the two-hop neighborhood of  $v$ .

### 7.4. Problem Description

The spectrum allocation problem in the CRN is to find an optimal allocation of spectrum not claimed by PUs to CR-BSs, while making sure that there is no interference between CR-BSs, as well towards the PUs. This optimization problem can be formulated as follows:

**Instance:** A set of  $\mathcal{V}$  CR-BSs and an undirected graph  $I_{SU} = (V_{SU}, E_{SU})$  representing the interference between CR-BSs. Here CR-BSs in interference range are represented by vertices, which means, a link exists between two vertices  $v$  and  $u$ , if  $v$  and  $u$  interfere with each other. Moreover, a set of PUs and a directed graph  $I_{PU} = (V_{PU}, E_{PU})$  representing the interference from the CR-BSs towards the PUs.

**Objective:** The goal is to find a valid assignment of subcarriers for all CR-BS nodes:

$$A_{v,s} = \begin{cases} 1, & \text{if subcarrier } s \text{ is assigned to node } v \\ 0, & \text{otherwise} \end{cases} \quad (7.1)$$

such that the following term is maximized. This means that the available subcarriers are distributed among all nodes in order to achieve **max-min fairness** [31]:

$$A = \arg \max_A \min_{v \in V} \left( \sum_{s \in \mathcal{S}} A_{v,s} \right) \quad (7.2)$$

subject to:

(I) **Interference avoidance:** assignment of subcarrier  $s$  to node  $v$  does not cause interference to nodes in interference distance, i.e., if  $A_{v,s} = 1$  then  $\forall u : (v, u) \in E_{PU} \rightarrow A_{u,s} = 0$ .

(II) **Outage avoidance:** every CR-BS  $v$  gets a non-empty spectrum share, i.e.,  $\exists s : A_{v,s} = 1$ .

(III) **PU protection:** assignment of subcarrier  $s$  to node  $v$  does not cause interference towards any PU, i.e., if  $A_{v,s} = 1$  then  $\forall u \in \mathcal{P} : (v, u) \notin E_{PU}$ .

This optimization problem is a binary integer linear programming problem which is known to be *NP*-complete. *NP*C problems can be solved in exponential time only. Further if we could solve ANY *NP*-Complete problem in polynomial time, then we could solve all *NP*-Complete problems in polynomial time.

Table 7.1.: Definitions

$\mathcal{V}$	Set of CR-BS nodes
$\mathcal{V}_v$	Largest connected subgraph of node $v$
$v$ or $u$	CR-BS nodes
$r_v$	Ranking number of node $v$
$r_v^{\max}$	Highest ranking number in $\mathcal{V}_v$ as known by $v$
$G$	Network graph of CR-BS nodes
$A_{v,s}$	Assignment of $s$ subcarriers to node $v$
$V_{\text{PU}}$	Set of PUs
$E_{\text{PU}}$	Links in PU interference graph between CR-BSs and PUs
$V_{\text{SU}}$	Set of CR-BS nodes
$E_{\text{SU}}$	Links in SU interference graph between CR-BSs
NSC	Total number of OFDM subcarriers
GSC	Total number of guard carriers per subchannels
SCH	Number of physical/logical subchannels

## 7.5. Proposed Spectrum Allocation

The optimal solution to allocate spectrum in a CRN is a complex task to be efficiently implemented in practice. Therefore, in order to reduce complexity, we divide the overall optimization problem into two independent major tasks:

1. **Collision-free assignment** of subchannels to CR-BSs without considering any spectrum utilization by PUs.
2. **PU protection** by excluding OFDM subcarriers blocked by PUs from the set of assigned subcarriers.

### 7.5.1. Collision-free Assignment

In the following we present a fully distributed algorithm, which assigns each CR-BS node a collision-free portion of the spectrum with respect to other CR-BSs in interference range. The basic idea is that every CR-BS computes a so-called ranking number which is unique in its two-hop neighborhood. Furthermore, every node knows the highest, so far assigned, ranking number in the network. From both the actual and the highest assigned ranking number a CR-BS node is able to calculate the portion of the spectrum, i.e., set of subchannels, to be used.

### Estimating the Interference Graph

In order to avoid interference between CR-BSs the following widely used heuristic [32] is used to estimate the interference graph  $I_{\text{SU}}$  from the network graph of CR-BSs  $G$ . It follows the assumption

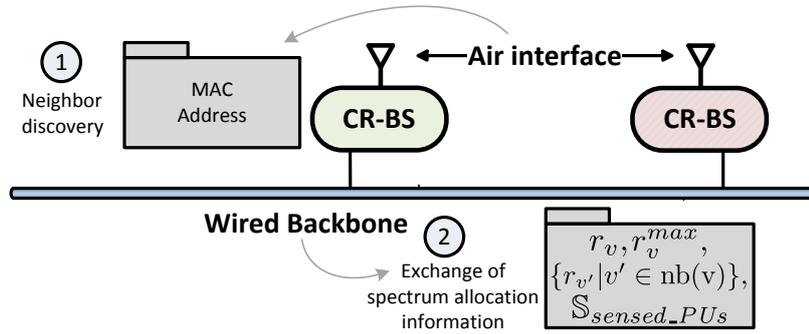


Figure 7.1.: Exchange of control messages via (1) air interface for neighbor discovery and (2) wired interface for calculating the spectrum share.

that the interference range around a CR-BS is twice the wireless communication range. Hence, we have to make sure that any subcarrier is used at most once in the two-hop neighborhood. Note, that  $G$  is estimated by sending beacon frames on the in-band control channel (Fig. 7.1). Hence,  $I_{SU}$  is constructed from  $G$  by adding an edge between two vertices having the same neighbor in common.

### Calculating the Spectrum Share

The prerequisite step is, that a new CR-BS node  $v$  is time synchronized with all its neighboring CR-BS nodes. By analyzing the received beacon frames node  $v$  knows the nodes addresses and assigned ranking numbers in its two-hop neighborhood as well as the highest, so far known, ranking number in the network<sup>1</sup> (Fig 7.1). With the help of this information node  $v$  calculates its own ranking number which is the smallest not already assigned ranking number in its two-hop neighborhood. The complete algorithm is shown in listing 1.

With the help of its ranking numbers  $r_v$  and the highest so far assigned ranking number  $r_v^{max}$  node  $v$  is able to calculate the size of the spectrum share to be used, i.e.,  $r_v/r_v^{max}$ . The exact part of the spectrum, i.e. set of subchannels, to be used is computed from the total number of available subchannels SCH which are in the interval  $\left(\lceil \frac{SCH \times (r_v - 1)}{r_v^{max}} \rceil + 1, \lceil \frac{SCH \times r_v}{r_v^{max}} \rceil\right)$ .

### Handling Ranking Collisions

Concurrent CR-BS node joins can cause problems, more precisely if two or more nodes located in the same two-hop neighborhood join the network simultaneously. In such a situation a ranking number collision occurs resulting in interference between SU cells due to the overlapping of allocated spectrum. However, such a collision can be detected locally by the joining nodes. The collision resolution is to re-run the algorithm for calculating the ranking number (listing 1) after a random waiting time (backoff).

Moreover, ranking number collisions can also be the result of network merging, i.e. two disconnected parts of the network are merged due to a joining node which connects both parts. Again,

<sup>1</sup>Precisely it is the highest rank number in the largest connected subgraph to which node  $v$  belongs to, i.e.  $r_v^{max} = \max\{r_{v'} | v' \in \mathcal{V}_v\}$  and  $\mathcal{V}_v \subseteq \mathcal{V}$ .

such a collision can be easily detected locally by the joining node  $v$  itself which executes a collision resolution algorithm as follows. Therefore, node  $v$  forces the  $n - 1$  nodes of those using the same ranking number, to recalculate their ranking numbers. This is achieved by sending a control message over the in-band control channel. Note, that the proposed scheme is robust with respect to spectrum re-allocation against merging of networks, because only the ranking numbers of the nodes at the edge between the merging networks need to be recalculated, resulting only in local spectrum re-allocation.

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**Algorithm 1** Calculate and set ranking number for a node.

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**Require:**  $v \in \mathcal{V}$  ▷ The node  $v$  for which ranking number is calculated.  
**Ensure:** ▷ Assigned ranking number  $r_v$  is unique in 2-hop neighborhood of node  $v$ .

- 1: **procedure** SELECTRANKNUMBER
- 2:     Semaphore mutex ▷ Semaphore for mutual exclusion.
- 3:     mutex.wait() ▷ Enter critical section.
- 4:      $\mathbb{R} \leftarrow \mathbb{N}$  ▷ Ranking numbers are natural numbers.
- 5:      $\mathbb{R}' \leftarrow \{r \in \mathbb{R} \wedge r \neq r_{v'}, v' \in \text{twohopnb}(v)\}$  ▷ Keep ranking numbers not already assigned in two-hop neighborhood.
- 6:      $r \leftarrow \min\{\mathbb{R}'\}$  ▷ Select the smallest free ranking number.
- 7:     assign( $v, r$ ) ▷ Assign ranking number  $r$  to node  $v$ .
- 8:     mutex.signal() ▷ Leave critical section.
- 9: **end procedure**

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### 7.5.2. PU Protection

By using algorithm 1 every CR-BS node is able to compute its spectrum share to be used within its cell. However, in a CR system an additional step is required. During this step those parts of the spectrum being used by PUs need to be excluded which is achieved by exploiting the flexible spectrum shaping capabilities of NC-OFDM. To avoid the situation that the assigned spectrum of some CR-BS is fully blocked by PUs, a distributed subchannel permutation scheme, which randomly maps the logical subchannels to physical subchannels is applied. This results in a scattering of adjacent subcarriers being blocked by a PU over the whole spectrum range, thus, avoiding the situation of hurting just a single CR-BS (Fig. 5.6). Note, due to the applied distributed subchannel permutation scheme, adjacent subchannels can be assigned to different CR-BS nodes. This results in subcarrier interference. Therefore, from the block of adjacent subcarriers, which are grouped as subchannel, edge subcarriers need to be used as guard carriers.

Listing 2 shows how from the set of assigned resource units subcarriers being blocked by co-located PUs are excluded. An illustrative example was given in Fig. 5.7 in Chapter. 5.

### 7.5.3. Optimization – Utilizing Unused Spectrum

The size of the spectrum share assigned to a CR-BS node depends on the highest assigned ranking number,  $r^{\max}$ , in the network. Every CR-BS node gets  $1/r^{\max}$  of the total spectrum share. However, in a realistic network we have dense, as well as sparse network parts, i.e. some node (e.g., network edge nodes) will have only a few neighboring CR-BSs, while others might have lots of neighbors. So, after spectrum assignment in the sparse parts of network, some parts of the spectrum, i.e., ranking numbers, remain unused. The objective of the following algorithm extension is to utilize this unused spectrum, which is achieved as follows.

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**Algorithm 2** Calculating the set of resource units to be used by a CR-BS node.

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**Require:**  $r_v, r_v^{\max}$   $\triangleright$  The ranking number of node  $v$  as computed by algorithm 1 and the highest known ranking number assigned in the network.

**Ensure:**  $\triangleright$  The assigned set of subcarriers (RUs) to node  $v$ ,  $\mathbb{S}_v \subseteq \mathbb{S}$ , are used only once in two-hop neighborhood of node  $v$  and are not blocked by any detected PU.

1: **procedure** ASSIGNRESOURCEUNITS

2:  $\mathbb{L}_v \leftarrow \{l \mid \lceil \frac{\text{SCH} \times (r_v - 1)}{r_v^{\max}} \rceil + 1 \leq l \leq \lceil \frac{\text{SCH} \times r_v}{r_v^{\max}} \rceil\}$   $\triangleright$  Set of logical subchannels to be used.

3:  $\mathbb{P}_v \leftarrow \{\text{perm}(l) \mid l \in \mathbb{L}_v\}$   $\triangleright$  Distributed subchannelization – random mapping of logical to physical subchannels.

4:  $\mathbb{S}_v \leftarrow (s_1, \dots, s_{\text{NSC}}) \mid s_i = \begin{cases} 1 & \text{if } \exists p \in \mathbb{P}_v : (p-1) \times \frac{\text{NSC}}{\text{SCH}} + 1 + \frac{\text{GSC}}{2} \leq i \leq p \times \frac{\text{NSC}}{\text{SCH}} - \frac{\text{GSC}}{2} \\ 0 & \text{otherwise} \end{cases}, \forall i \in \{1 \dots \text{NSC}\}$   $\triangleright$  Bit vector indicating which data subcarriers are assigned to node  $v$ .

5:  $\mathbb{S}_v \leftarrow \text{AND}(\mathbb{S}_v, \text{NOT}(\mathbb{S}_{\text{sensed\_PUs}}))$   $\triangleright$  Remove RUs blocked by detected PUs.

6:  $\mathbb{S}_v \leftarrow \text{AND}(\mathbb{S}_v, \text{DBSpectrumMask}(\text{geoLoc}(v)))$   $\triangleright$  Excluded RUs using data from spectrum database.

7: **return**  $\mathbb{S}_v$

8: **end procedure**

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In addition to the ranking number, every node  $v$  calculates a set of additional ranking numbers  $T_v$ .  $T_v$  contains the ranking numbers not being used in its two-hop neighborhood. To avoid collisions on these additional ranking numbers, every node  $v$  has to report the set  $T_v$  to its two-hop neighbors, which is calculated as follows:

$T_v = \{t \mid t \in \{1, \dots, r_v^{\max}\} \wedge t \neq r_{v'} \wedge t \notin T_{v'}, v' \in \text{twohopnb}(v)\}$ . Therefore, in listing 2 line two needs to be replaced by the instructions given in listing 3.

### 7.5.4. Discussion

In the absence of any PUs the proposed algorithm ensures that every CR-BS gets a fair spectrum share which depends on the density of the network. In a CRN some parts of the assigned spectrum can be blocked by PUs and thus have to be excluded from SU usage. The proposed random subchannel permutation scheme ensures that every CR-BS node gets a free fraction of spectrum with high probability. The chance, that a node gets no spectrum, i.e. its assigned part of the spectrum is completely shaded by PUs, is very small and can be decreased by raising the total number of subchannels.

The proposed algorithm is robust with respect to the appearance and disappearance of PUs, i.e. only the allocated spectrum of the SUs in interference range of a particular PU need to be reallocated, specifically only the second task must be performed (Sec. 7.5.2). The algorithm is also robust with respect to the appearance and disappearance of SUs (CR-BS), i.e. the spectrum needs to be reallocated only if the maximum ranking number  $r_v^{\max}$  in the largest connected subgraph changes. Finally, the proposed algorithm is able to deal with network merges, i.e. the merging of two networks results only in the recomputation of the ranking numbers of the edge nodes between the two networks.

Finally, the proposed algorithm is fully distributed and requires only local messaging, which means, the exchange of the actual and the highest known ranking number between spatially co-located CR-BSs. Thus, the control message overhead is very low.

**Algorithm 3** Calculating the set of resource units to be used by a CR-BS node using the algorithm extension.

**Require:**  $r_v, r_v^{\max}$   $\triangleright$  The ranking number of node  $v$  and the highest known ranking number in the network.

**Ensure:**  $\triangleright$  The assigned set of RUs to node  $v$ ,  $\mathbb{S}_v \subseteq \mathbb{S}$ , are used only once in two-hop neighborhood of node  $v$  and are not blocked by any detected PU.

```

1: procedure ASSIGNRESOURCEUNITSEXTENSION
2:   Semaphore mutex  $\triangleright$  Semaphore for mutual exclusion.
3:   mutex.wait()  $\triangleright$  Enter critical section.
4:    $T_v = \{t | t \in \{1, \dots, r_v^{\max}\} \wedge t \neq r_{v'} \wedge t \notin T_{v'}, v' \in \text{twohopnb}(v)\}$   $\triangleright$  Set of unused ranking numbers in 2-hop nb.
5:   assign( $v, T_v$ )  $\triangleright$  Assign additional ranking numbers  $T_v$  to node  $v$ .
6:   mutex.signal()  $\triangleright$  Leave critical section.
7:    $\mathbb{L}_v \leftarrow \{l | \lceil \frac{\text{SCH} \times (r_v - 1)}{r_v^{\max}} \rceil + 1 \leq l \leq \lceil \frac{\text{SCH} \times r_v}{r_v^{\max}} \rceil\}$   $\triangleright$  Set of logical subchannels according to primary ranking number.
8:   for all  $x \in T_v$  do  $\triangleright$  For every additional ranking number.
9:      $\mathbb{L}_v \leftarrow \mathbb{L}_v \cup \{l | \lceil \frac{\text{SCH} \times (x - 1)}{r_v^{\max}} \rceil + 1 \leq l \leq \lceil \frac{\text{SCH} \times x}{r_v^{\max}} \rceil\}$   $\triangleright$  Add additional logical subchannels.
10:  end for
11:   $\mathbb{P}_v \leftarrow \{\text{perm}(l) | l \in \mathbb{L}_v\}$   $\triangleright$  Distributed subchannelization – random mapping of logical to physical subchannels.
12:   $\mathbb{S}_v \leftarrow (s_1, \dots, s_{\text{NSC}}) | s_i = \begin{cases} 1 & \text{if } \exists p \in \mathbb{P}_v : (p - 1) \times \frac{\text{NSC}}{\text{SCH}} + 1 + \frac{\text{GSC}}{2} \leq i \leq p \times \frac{\text{NSC}}{\text{SCH}} - \frac{\text{GSC}}{2}, \forall i \in \{1 \dots \text{NSC}\} \\ 0 & \text{otherwise} \end{cases}$   $\triangleright$  Bit vector indicating which data subcarriers are assigned to node  $v$ .
13:   $\mathbb{S}_v \leftarrow \text{AND}(\mathbb{S}_v, \text{NOT}(\mathbb{S}_{\text{sensed\_PUs}}))$   $\triangleright$  Remove RUs blocked by detected PUs.
14:   $\mathbb{S}_v \leftarrow \text{AND}(\mathbb{S}_v, \text{DBSpectrumMask}(\text{geoLoc}(v)))$   $\triangleright$  Excluded RUs using data from spectrum database.
15:  return  $\mathbb{S}_v$ 
16: end procedure

```



# Chapter 8.

## Evaluation

In this chapter the results of a wide range of evaluations is shown and discussed. Different aspects of control channel design are evaluated. Then the data channel properties are elucidated and the distributed spectrum broker, proposed in the former chapter is analyzed in detail by means of simulations as well as analytically.

### 8.1. Control Channel

In this section different aspects of control channel design are evaluated.

#### 8.1.1. Control Channel Information

For designing a CC the expected traffic in the CC needs to be estimated. For the downlink, i.e. CR-BS to CR-STA the set of addressed Resource Blocks (RB) must be signaled. The size of this information depends on different parameters: spectrum allocation based on information from a spectrum broker, the intra-SU co-existence protocol and the channel coherence bandwidth. Beyond that, the Adaptive Modulation and Coding Scheme (MCS) per RB needs to be exchanged.

In the uplink direction, i.e. CR-STA to CR-BS, the Channel Quality Indicator (CQI) per RB needs to be signaled. Optionally sensing data information obtained by the CR-STA can be exchanged, too.

In the multiple cells scenario the wireless interface is only used for exchanging neighbor discovery information between CR-BSs. The signaling information itself is sent over the wired backbone.

Fig. 8.1 shows the logical signaling and communication flow between CR-BS and its corresponding CR-STA. The left figure 8.1(a) indicates the bootstrapping process, while on the right the one 8.1(b) the main loop is shown. The CR-BS starts with estimating available the Resource Blocks (RB) based on different sources as e.g., the Spectrum DataBase (SDB). This information needs to be signaled to the CR-STA so that the CR-STA is able to decode the information during the data channel phase. For every transmitted RB the CQI is now estimated on receiver (CR-STA) side and sent back to the CR-BS. With this closed loop information a subset of RBs with good channel quality and the related MCS are chosen. After this bootstrapping phase the main loop is entered. The main loop is similar to the bootstrapping process but now also MCS information is sent from CR-BS to the CR-STA.

#### 8.1.2. Out-of-band Signaling: Control Channel Data Rate vs. Efficiency in the Data Channel

The expected control channel data rate is directly depended from the efficiency in the data channel. To estimate the usage of a certain technology an analysis by means of simulations was done.

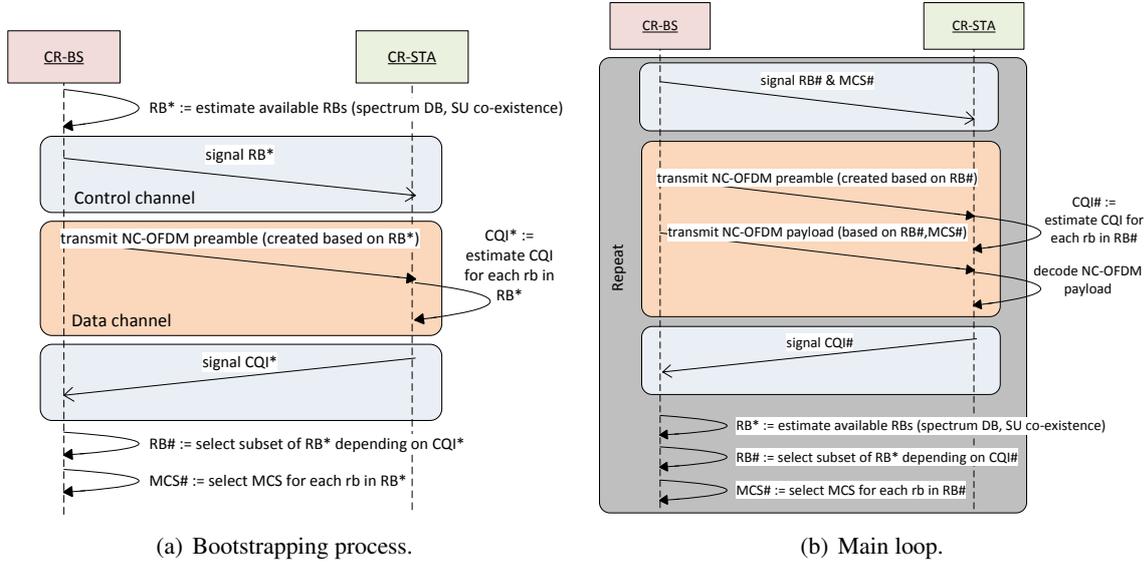


Figure 8.1.: Logical signaling and communication flow.

### Methodology

For the analysis we assume a wide-band data channel using NC-OFDM. The total spectrum, i.e.,  $F_{min}$  to  $F_{max}$ , is divided into NSC subcarriers, which equals the FFT size of 8192. This is the maximum FFT size achievable from PHY perspective. Moreover, we assume that co-located cells are orthogonalized in the frequency domain as discussed in the former sections and proposed by the algorithm in [33] and Chap. 7. To efficiently use even a highly fragmented radio spectrum a large NSC is advisable. Unfortunately, this requires a higher bitrate in the CC to be able to address each subcarrier individually. To be able to quickly react to changes in the secondary spectrum, i.e., due to the appearance of new PUs, and thus to guarantee the protection of PUs the allocation of subcarriers need to be updated frequently which further increases the required bitrate for the signaling in the CC.

To reduce the signaling overhead we pursue the following approach. Instead of addressing each individual subcarrier the addressing overhead can be easily reduced by grouping  $NSC/R$  adjacent subcarriers in Resource Blocks (RBs). To protect PUs a complete RB is excluded from spectrum allocation if at least one of its subcarriers is utilized by a PU. The drawback is a decreased efficiency especially in a highly fragmented spectrum. The simulation parameters for this setup are listed in Tab. 8.1.

### Results

During this experiment the number of usable RBs depending on the maximal available CC bitrate is observed. The exemplary result is given in Fig. 8.2. It can be observed, that a CC bitrate up to  $6.25 \text{ kbit/s}$  is too low because the addressable resource blocks in the data channel are too large and have to be left unused because some SC are affected by PUs. Which means some nodes (CR-BS) can not allocate any spectrum in the data channel.

Table 8.1.: Simulation parameters

Parameters	Value
# of SU nodes	25
# of neighboring SUs per SU nodes	5 (mean)
# of neighboring PUs per SU nodes	35 (mean)
# subcarrier per subchannel	$2^p$ , where $p = 0 \dots 9$
# of PUs	100
PU occupancy	1 - 40 subcarriers (uniform random)
PU placement	uniformly distributed
NSC (FFT)	8192 (scaled version of 802.11 OFDM)
Bandwidth	512 MHz
Update rate of subcarrier allocation	100 Hz

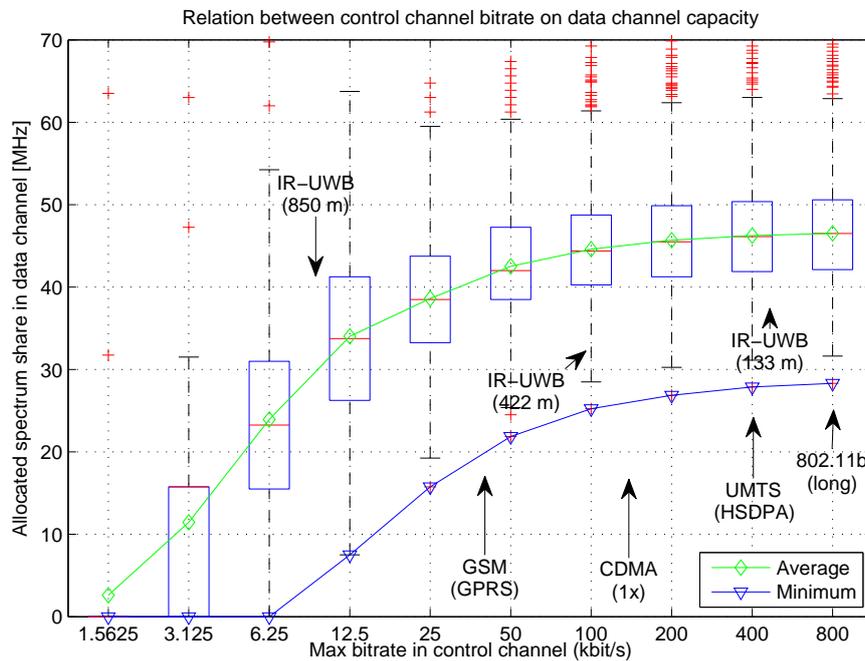


Figure 8.2.: **Control channel.** Impact of CC bitrate on data channel matched with various potential technologies ((see [34, 35] for detailed technology description).

### 8.1.3. Feasibility on Application of Impulse-UWB for Control Channel

In this section we evaluate Impulse-Ultra-WideBand (UWB) as out-of-band control channel for our envisioned system [36]. The requirement in terms of data rate of the control channel is pretty low, as a data rate of about 10-100 kbit/s is necessary. Such a CC requires only a small bitrate, large enough to reference the scattered spectrum (subcarriers) in use. Further an update interval within the channel coherence time and below the maximum time to leave the primary spectrum. In a practical system the required bitrate for signaling the spectrum allocation is in the order of a few 10 kbit/s and depends on several PU properties as e.g., occurrence, quantity and channel width. More important is an always available and robust CC with a delay below the channel coherence time, otherwise the spectrum allocation information will become outdated.

A candidate wireless technology for the CC could be Impulse-Radio-Ultra-WideBand (IR-UWB) [37]. This technology allows transmission below the noise floor of other wireless transmission techniques and can therefore be used in parallel without interfering with PUs and therefore without requiring additional dedicated spectrum resources. The idea is not new and was originally proposed by Čabrić et al. in [38] to be used for dissemination of spectrum sensing information in CR networks. Unfortunately there is a lack of practical studies showing the performance of IR-UWB in real-world testbeds. Moreover, we believe it is important to analyze whether the two wireless technologies, IR-UWB and NC-OFDM as envisioned in this paper, can co-exist together in a multi-technology CR transceiver station without mutual interference.

Usually IR-UWB technology is used in short range communication with high bitrates, whereas its use for medium and long range communications was only studied in theory so far. Therefore, we conducted experiments using a commercial off-the-shelf IR-UWB transceiver to evaluate IR-UWB in a realistic outdoor scenario.

The rest of this chapter is organized as follows. First, with the help of measurements in our IR-UWB testbed, we found out that under real conditions IR-UWB can achieve the required communication range of a few hundreds of meters in LOS only. Any form of propagation obstruction made a communication impossible. Second, although IR-UWB is a wideband technology it is severely affected by narrow-band interference in close proximity, which is the case in the envisioned multi-technology CR station.

#### Primer on IR-UWB

UWB is a rather simple wireless communication technology and was originally introduced in 1901 by Marconi to transmit Morse codes. As shown in Fig. 8.3 the pulses are very short in time, but occupy a very large bandwidth in the frequency domain. Signals with an instantaneous bandwidth exceeding 500 MHz or with a fractional bandwidth larger than 0.2 are considered as UWB [37]. The main advantages beside its very simple transceiver structure is, that radio frequency profiles are very low and the transmission is robust in the face of multipath. Because of the increasing spectrum scarcity the FCC approved in 2002 unlicensed operation in the frequency ranges from 3.1 GHz to 10.6 GHz with a very low transmit power of about -41.3 dBm/MHz. Following this decision the standardization group IEEE 802.15.3a was formed to provide a high speed UWB-PHY. The groups split up in 2006 because no agreement between the main PHY technologies Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM) and Direct Sequence UWB (DS-UWB aka. IR-UWB) could be found. Currently MB-OFDM is a successor technology for short-range high-speed wireless USB,

while IR-UWB is today mainly used for ranging.

In UWB a trade-off between communication range and data rate exist. This trade-off was analytically evaluated for long-range IR-UWB communication by Nascimento et al. [34]. Their results show that from theoretical point of view a communication range of up to 1 km with a data rate of  $10 \text{ kbit/s}$  using the free space path loss model is possible. By applying the lognormal shadowing path loss model a data rate of  $10 \text{ kbit/s}$  can be achieved in ranges up to 200 m.

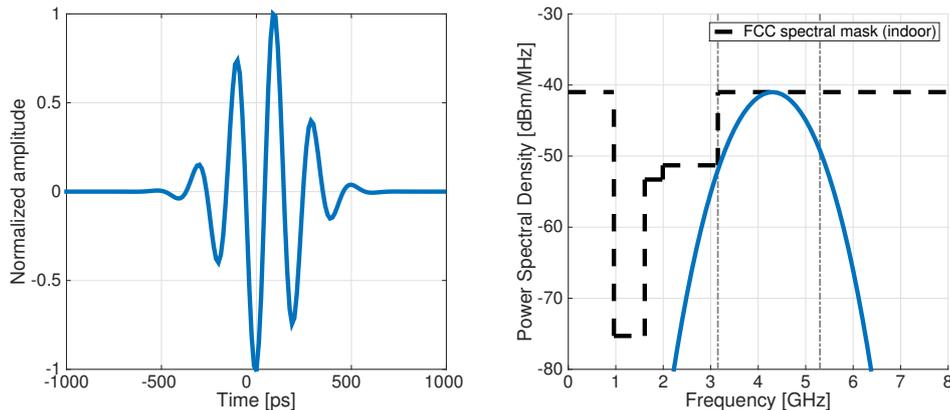


Figure 8.3.: UWB waveform shown in time domain (left) and frequency domain (right). (source: [39])

## Problem Statement

This section is a measurement study from an outdoor IR-UWB testbed. The research question is to find out whether IR-UWB meets the requirements for a CC in CR networks. In particular, we are interested in whether IR-UWB is able to provide a reliable, low latency, always available but low bitrate ( $\approx 10 \text{ kbit/s}$ ) communication over the required communication range of a few hundred of meters outdoors (small cells). Moreover, we are interested whether the envisioned multi-technology station equipped with two air interfaces, IR-UWB and NC-OFDM, is feasible, i.e., there is no significant mutual disturbance between both technologies.

## Evaluation of IR-UWB for Control Channel Usage

We have performed a variety of experiments in our outdoor IR-UWB testbed to investigate the suitability of the IR-UWB technology as CC in CR networks. First, we measured the maximum communication range outdoors. Second, we studied whether the two wireless technologies, IR-UWB and NC-OFDM, can co-exist in a multi-technology station.

*IR-UWB Hardware* The state-of-the-art IR-UWB transceiver for long range data communication and ranging, the TimeDomain P410 [40] (depicted in Fig. 8.4), is used in our experiments. The most important parameters are summarized in Tab. 8.2. The advantage of the coherent receiver is that increasing the number of pulses per bit results directly in a SNR gain and therefore in higher communication ranges, but at the cost of decreased data throughput. This means the Pulse Integration Rate (PII) affects the communication range significantly. The P410 is using a low duty cycle transmission, with coherent signal processing and a fixed pulse rate of 10 MHz, but different PII in the range of 4(16:1) to 10(1024:1) pulses per bit. According to the vendors specification for a PII of 4 the

Parameter	Value
Operating band	3.1 - 5.3 GHz
Center frequency	4.3 GHz
Transmit power	-12.64 dBm
Noise figure	4.8 dB
Dynamic range (PII=10)	60 dB
Transmit pulse repetition rate	10.1 MHz
Pulse Integration Rate (PII)	10 (1024 pulses per bit)

Table 8.2.: Specification of TimeDomain P410 transceiver.

maximum communication range is 35 m with a peak data rate of  $632 \text{ kbit/s}$  is feasible. For the highest PII of 10 the maximum range is 354 m with a peak data rate of  $9.86 \text{ kbit/s}$  [40], which still meets our requirements for the CC.



Figure 8.4.: P410 RCM with BroadSpec antenna (source: [40])

### Packet Delivery Ratio Measurements

As mentioned in Sec. 8.1.3 the communication range of the CC for CR should correspond to the communication range of the used data channel. Therefore, the objective of this section is to study the propagation characteristics of the IR-UWB communication system in a real-world outdoor environment. Here we were especially interested in investigating the influence of obstructed Line-of-Sight (LOS) on the communication link. Because it is also stated in the P410 datasheet that NLOS is working for very short distances only.

#### *Methodology*

The evaluation was carried out on the campus of the Technische Universität Berlin. The IR-UWB transmitter was placed on the edge of the roof of our building (approx. 25 m above the ground) and had direct LOS with the receiver located at the ground floor. The receiver was further mounted on a tripod in a height of 1.20 m and was moved in a random walk over the campus. For every point in space, every received IR-UWB frame was GPS tagged and time stamped. The most robust modulation and coding was used all time. This means the PII was set to 10, which means that 1024 IR-UWB pulses are transmitted per symbol, which equals one bit. The resulting data rate is around  $10 \text{ kbit/s}$

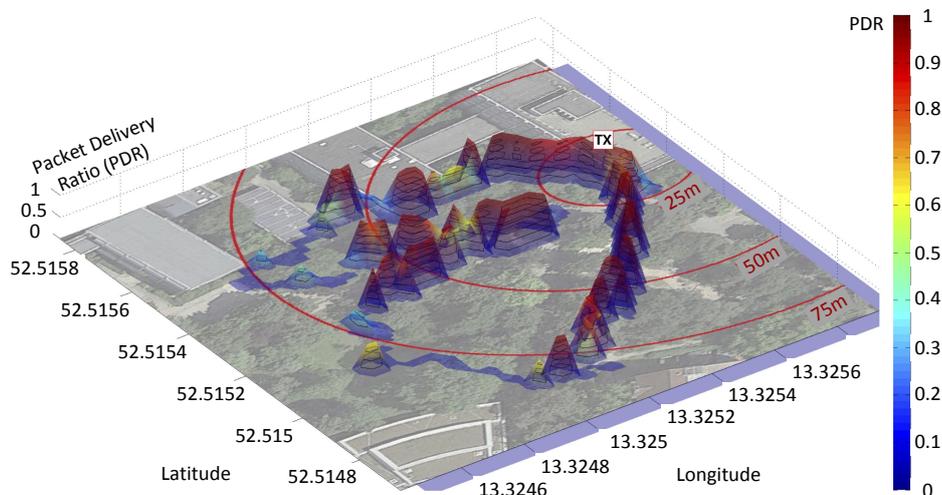


Figure 8.5.: Measured Packet Delivery Ratio (PDR) at IR-UWB receiver at different spatial locations on university campus (TUB).

which meets our requirements for the CC. As performance metrics the Packet Delivery Ratio (PDR) was measured.

#### Results

Fig. 8.5 shows the PDR at different spatial locations on our campus. It can be seen that a communication is only possible in unobstructed LOS. Even minor shadowing from e.g., leaves of trees leads to a severe drop in the PDR. A NLOS communication is only possible for very short ranges up to a few meters. Our results show that under real urban conditions with shadowing and obstacles a communication over more than 75 m in general is not feasible.

### SNR, Noise and Signal Strength Measurements in LOS

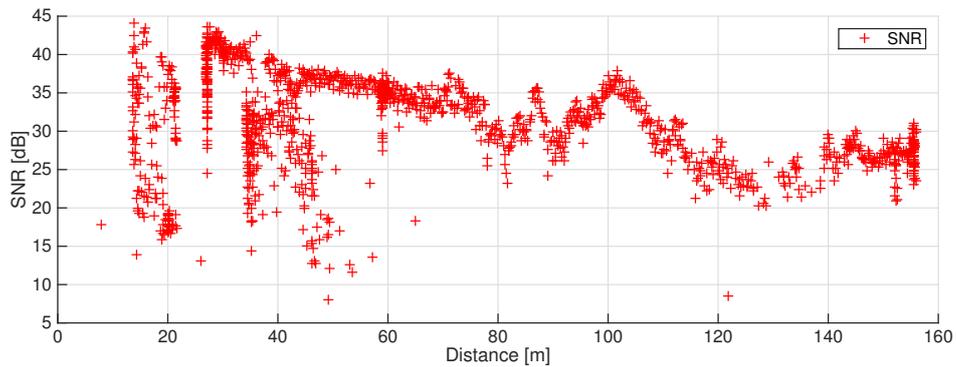
With clear LOS propagation very long links are feasible. The datasheet claims that links of 300 m and more are possible. Therefore, we restricted our study on LOS links only.

#### Methodology

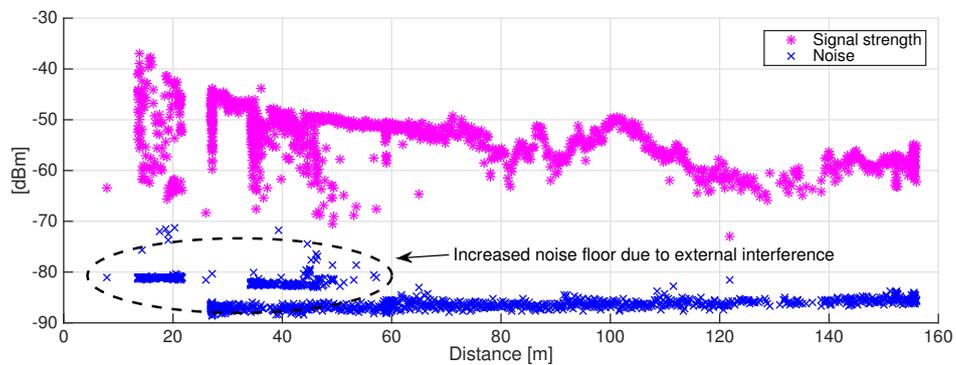
The methodology was similar to the previous experiment, but making sure that always a clear LOS propagation between transmitter and receiver exists. In addition to PDR we also evaluated the Signal-to-Noise Ratio (SNR), noise floor and signal strength. These values were calculated from the channel impulse response as described in the API documentation [41, p.49ff].

#### Results

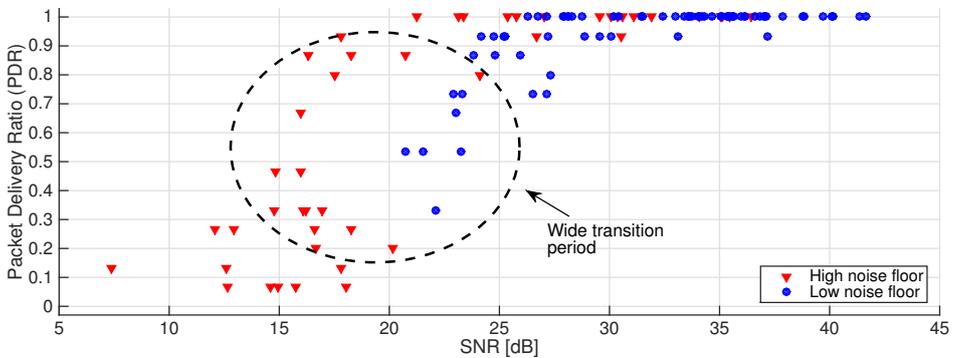
From Fig. 8.6 we can observe that under LOS conditions links of more than 150 m are feasible. If LOS can be ensured even longer links might be established, which is unfortunately not the case on our campus. Moreover, we can observe that there is no clear relationship between link length and SNR. In our experiments we found lots of short links (< 60 m) having an unusual low SNR. However, the propagation characteristics are not solely responsible for the large variations in the SNR. Indeed from Fig. 8.6(a) and 8.6(b) we see that there are lots of short links suffering from an unusual high noise floor which is about 8 to 17 dB higher than usual. Local sources of interference like WLAN or



(a) Distance vs. SNR



(b) Distance vs. noise and signal strength



(c) SNR vs. PDR

Figure 8.6.: LOS measurements

other wireless technologies which are widely used on our campus may be responsible for that. Hence, their impact is studied in great detail in the next section.

Finally, the relationship between SNR and PDR is given in Fig. 8.6(c). We can identify a bi-modal distribution which is due to the different noise floor levels. The weak relationship between SNR and PDR makes the SNR a poor indicator for the link quality. Note, that each point in Fig. 8.6(a) and 8.6(b) represents a received packet from which SNR, noise and signal power is calculated.

## Co-existence of IR-UWB and NC-OFDM

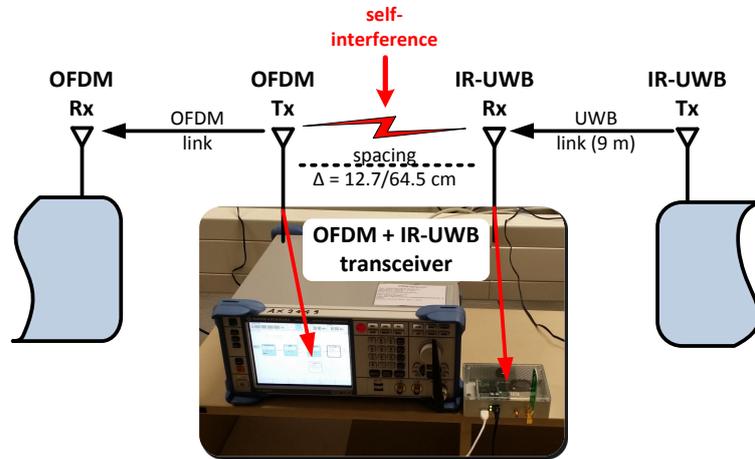


Figure 8.7.: Experimental setup with signal generator emulating the NC-OFDM transmission and the co-located IR-UWB receiver.

As stated in the former *Sec. Problem Statement* we envision a multi-technology CR transceiver having two air interfaces: i) an IR-UWB for control signaling and ii) a NC-OFDM air interface for data transmission. The idea is to use the two interfaces simultaneously without mutual disturbance. Hence, in this section we study the self-interference between both wireless technologies with focus on the underlay IR-UWB transmission, because the influence of IR-UWB interference onto WLAN was already shown in [42].

### Theory

The narrowband interference problem in IR-UWB systems is well studied in theory, e.g., [37, Chap. 11]. IR-UWB has a high probability to be affected by narrowband interference. Because of its ultra wide transmission band a large number of possible narrowband interferers will be in same frequency range. Further, the restricted transmission power leads to a limited dynamic range. Therefore, a single strong interferer can be diminish the receivers performance seriously. The state-of-the-art IR-UWB transceiver in our testbed has a very wide bandwidth of about 2.2 GHz and high dynamic range of 60 dB. Theoretically, this receiver should be able to deal with narrowband interference. This was reviewed in this experiment.

### Methodology

Fig. 8.7 shows the experimental setup. To mimic the envisioned multi-technology station two wireless links were set-up and used simultaneously, namely i) an UWB link and ii) a narrow-band OFDM link. Without loss of generality the narrow-band OFDM transmission, i.e., IEEE 802.11 WLAN, is used to emulate the envisioned NC-OFDM wideband transceiver. In particular an 802.11a similar signal with a bandwidth of 20 MHz and a transmit power of 10 dBm is generated with a R&S SMBV100A vector signal generator [43]. The UWB link was 9 m long, the transmitter is using the most robust modulation (PII=10) and the highest allowed transmission power (-12.64 dBm).

To investigate the impact of the OFDM transmission on the IR-UWB link the center frequency

of the OFDM signal was swept from 1 GHz to 6 GHz with a step size of 50 MHz. For each center frequency 40 IR-UWB frames were transmitted and timestamped at the IR-UWB receiver side for later offline processing. Two different measurement series with different spacings between the two air interfaces (OFDM TX and IR-UWB RX), namely, i) 64.5 cm which is a mockup for an outdoor setup and ii) 12.7 cm emulating an indoor multi-technology CR device, were conducted.

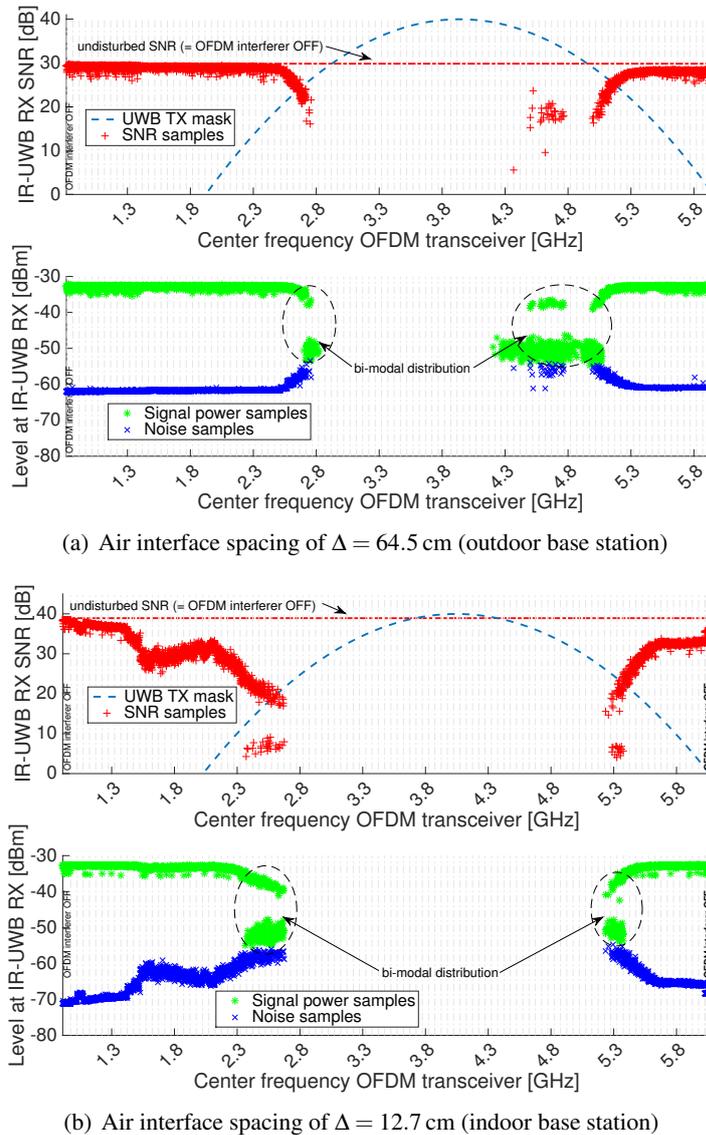


Figure 8.8.: SNR degradation on the IR-UWB link due to interference from narrow-band OFDM transmission for different spatial spacings.

*Results*

Fig. 8.8 shows the results for the two different air interface spacings. On the x-axis the center frequency of the OFDM narrowband transmitter is depicted. In each frequency bin the result of a complete measurement run is shown, i.e., each successfully received IR-UWB frame is marked by a red

cross showing its SNR value. The blue dashed curve is only for clarity and shows the transmit mask of the UWB transmitter. Moreover, both bottom plots shows also the received signal power and noise floor of each packet.

Fig. 8.8(a) shows the results where the spacing between the air interfaces was  $\Delta = 64.5$  cm. Here we can see that as long as the OFDM link is not using frequencies which are within the UWB transmit mask, its impact on the UWB link is small. Nevertheless, any narrow-band OFDM transmission (here 20 MHz) within the UWB transmit mask causes a full outage on the UWB link, i.e., PDR = 0. The used IR-UWB transceiver hardware has a dynamic range of 60 dB at maximum PII = 10. If we consider free space propagation the SNR is around -50 dB. This means the IR-UWB link is jammed by the OFDM transmission.

In Fig. 8.8(b) we see the results for the typical multi-technology setup for the envisioned indoor multi-technology CR transceiver with a very small separation between the two air interfaces  $\Delta = 12.7$  cm. Here even narrowband OFDM transmissions outside the transmit IR-UWB mask have a severe impact on the performance of the IR-UWB link. An OFDM transmission with a much lower center frequency  $f_c = 1.5$  GHz significantly influences the IR-UWB transmission, i.e., the SNR drops by more than 10 dB whereas the noise floor increases. For some OFDM center frequencies we can observe a bi-modal distribution of the signal power which might be an indication of an insufficient dynamic range and therefore the saturation of the IR-UWB receiver. A better RF shielding, applying analog (notch) filtering before the pulse correlation [44] or pulse shaping [45] might improve the co-existence in this case.

The main challenge of any interference rejection technique is the requirement of the exact knowledge about the center frequency of the narrowband interferer. Theoretically, such information can be obtained by means of sensing or lookup in databases as they are common in the CR context, but even if the complete knowledge about all the narrowband interferers is available, the high number of interferers make methods like notch filtering or pulse shaping practically impossible.

## Discussion

Our results have following practical implications. TVWS are in the frequency range below 1 GHz, although there is no spectrum overlap, a severe mismatch between the communication ranges of the control and data channel exist. Therefore, the use of the envisioned IR-UWB system for the control channel in TV White Spaces (TVWS) is not recommended.

## Conclusion

Because COUWBAT aims for two frequency ranges with 20-1500 MHz and 1500-3000 MHz, the first range will be feasible with impulse-UWB while the second range causes UWB outage. Simultaneous operation of impulse-UWB and 802.11 b, g and a in a multi-technology BS (with small spacing) is not feasible. But increasing the spatial separation between both air interfaces will help here. 2.4 GHz ISM bands and higher frequencies of 5 GHz ISM band become available. Nevertheless, the higher frequency band will be in COUWBAT still not usable. An alternative might be orthogonalization in time to omit self-interference.

### 8.1.4. Control Channel Overhead in In-Band Signaling

#### Outage Probability

As shown in Fig. 8.9(a) the CC overhead in in-band signaling is more a problem than in out-of-band signaling because the same resources are shared between control and data channel. The ratio between control and data channel is assumed to be fix, i.e.,  $\Delta f \times \Delta t = const$ . This means the control channel overhead can be lowered when the relative length of the CC is shorten and also when the relative width of the CC is as wide as possible. Fig. 8.9(b) shows the limitations of this approach. When the CC is widen in frequency the outage probability of the CC raise with the number of PUs. For this estimation 32 control channels are uniformly distributed in a frequency range of 500 MHz and every node (CR-BS) who requires a CC has about 12 neighbors in its proximity. The numbers are the maximum values of our considered system. It can be clearly seen, that with the raise of the PU usage and the CC width the probability of not getting a CC is raises, too. If we assume a channel width of 7 MHz as applied in TV White Spaces (TVWS) an PU appearance of 30% is enough that 10% of all nodes will not get a CC. This needs to be carefully considered in the later implementation.

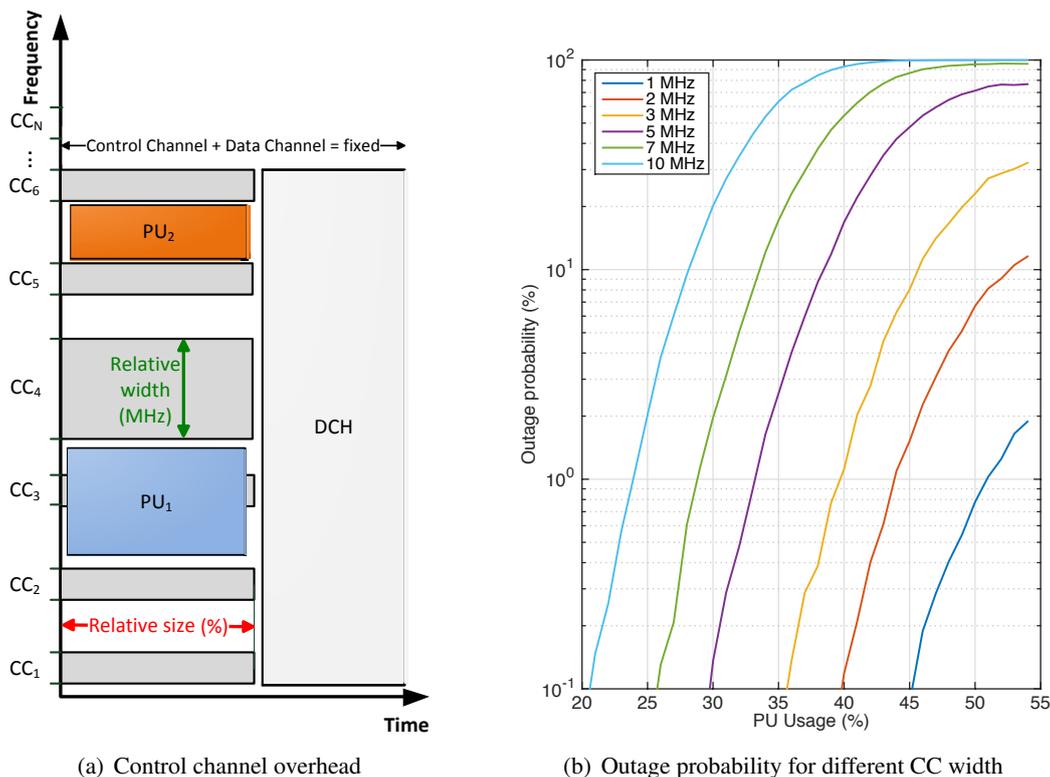


Figure 8.9.: Trade-off between efficiency and outage probability.

#### Signaling Overhead

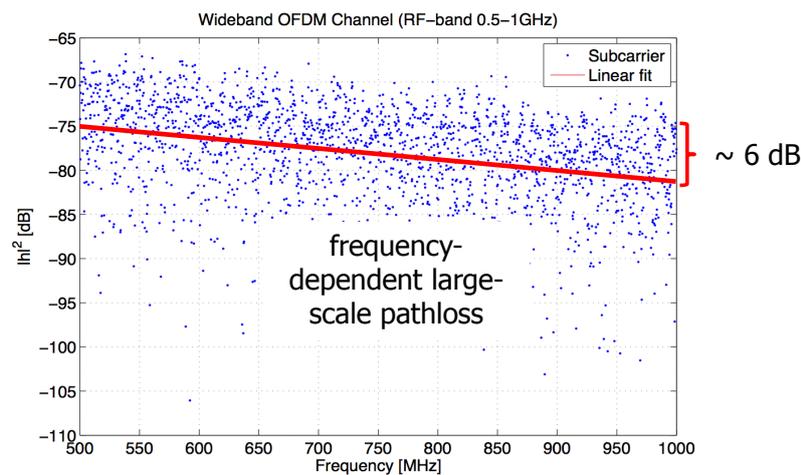
Our suggested protocol has a fixed overhead dependent on the number of used subchannels. Every subchannel consists of a fixed number of subcarriers. The FFT of our system is fixed to 2048, which

equals the number of subcarriers. If subcarriers are grouped into subchannels the resolution decreases. This means gaps of occupiable spectrum need to be larger.

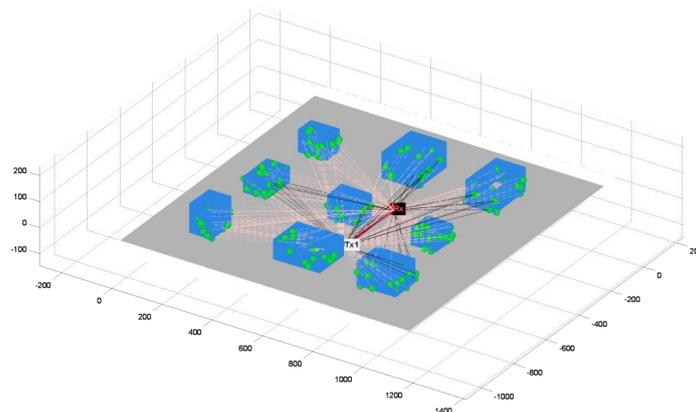
## 8.2. Data Channel Properties

Fig. 8.10(a) shows the frequency-dependent large-scale pathloss of the intended data channel. The properties of this wideband data channel are 500 MHz in the range of 0.5-1 GHz. The pathloss is generated using the geometry-based propagation model *IlmProp*<sup>1</sup> from TU Ilmenau. The modeling parameters are, as depicted in Fig. 8.10(b), obstructed line-of-sight and a distance of about 300 m.

Because the pathloss is about 6 dB over the whole range of 500 MHz the usage of a Modulation and Coding Scheme (MCS) selection per resource block is necessary.



(a) Wideband OFDM System using RF frequency < 1.5 GHz, bandwidth 512 MHz, i.e. frequency-dependent large-scale pathloss/shadowing



(b) Geometry-based propagation model (IlmProp).

Figure 8.10.: Properties of the COUWBAT data channel. Snapshot generated using a geometry-based propagation model (IlmProp, TU Ilmenau).

<sup>1</sup><http://www2.tu-ilmenau.de/nt/en/ilmprop/>

### 8.3. Statistical Multiplexing

**Experiment:** From Fig. 8.11 we see the expected number of end-user terminals per CR-STA and the number of CR-STA per CR-BS. Our objective is to evaluate the effect of statistical multiplexing in our system. The following network traffic models were used [46]: i) traffic mix using IEEE 802.16m models (40% HTTP, 30% FTP, 30% video), ii) Web browsing (HTTP) traffic model, ii) File Transfer Protocol model, iii) near real time video streaming model.

**Results:** Fig. 8.12 shows a sample trace for the downlink network load at the three different levels of the hierarchy - STA (user), CR-STA and CR-BS. The following observations can be made. The network load is very bursty at the level of STAs where there are long idle periods common. At the level of the CR-BS the traffic becomes more predictable.

For a deeper insight we calculated the Coefficient of Variation (CoV) for the four different traffic mixes (Fig. 8.13). The total number of STAs connected via their CR-STAs to a single CR-BS was varied. Note, that a number of 100-200 corresponds to our scenario. We can observe that the network load is very bursty when the number of STAs is small. As the number of STAs increases the variation of the network load decreases as indicated by the CoV value.

Finally, we can also see the expected network load at the CR-BS in the downlink (Fig. 8.11).

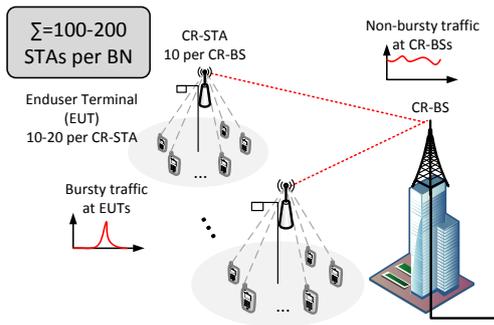


Figure 8.11.: The expected number of end-user terminals per CR-STA and the number of CR-STA per CR-BS.

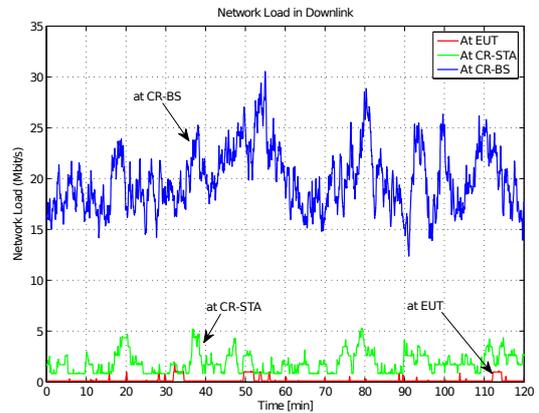


Figure 8.12.: Sample trace shows the network load at the different levels of the hierarchy - user, CR-STA and CR-BS.

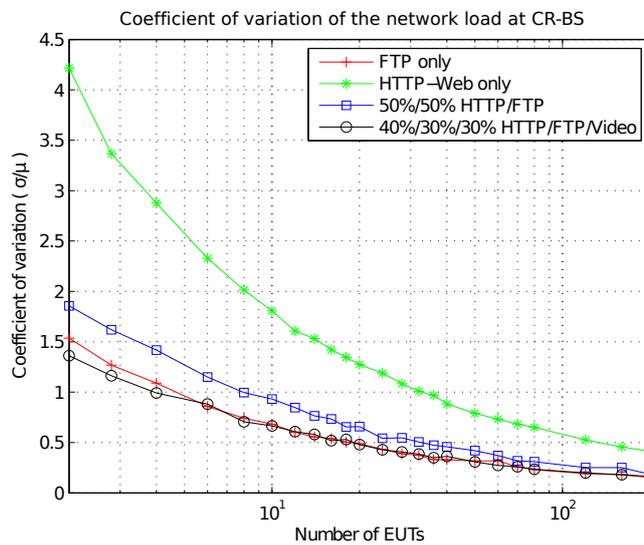


Figure 8.13.: Coefficient of variation for different traffic mixes.

## 8.4. Distributed Spectrum Broker

The performance of the proposed overlay CR scheme is analyzed by means of simulations as well as analytically. First, we describe our methodology. Second, we present selected results from our evaluations.

### 8.4.1. Methodology

The performance of the proposed algorithm in Chap. 7 is analyzed by means of simulations. Two different random network topologies were considered. First, we consider a random network topology with fixed node degree  $\alpha$  of 2,4,6 and 8 respectively. Second, we consider a random network where every node has at least one neighbor. This results in a network with variable node degree. In both cases the nodes joined the network as follows. In each round, from the set of not already joined nodes, a single node was randomly selected to join the network. The presented results show the spectrum allocation after all  $\mathcal{V}$  nodes have joined the network.

As the performance metric, we calculated the number of available data subcarriers at every node excluding guard carriers, as well as subcarriers blocked by PUs. As stated in Eq. 7.2 our main objective is to find a spectrum allocation where the minimum number of assigned subcarriers to CR-BSs is maximized. Finally, an FFT size of  $S = 8192$  was used.

### 8.4.2. Simulation Results

**Experiment 1: (Impact from PUs)** To evaluate the impact from PUs on the proposed allocation scheme we considered the random network topology with a fixed node degree of  $\alpha$ . The number of subcarriers per subchannel ( $N_{SC}/SCH$ ) was set to 32 whereas the number of guard carriers per subchannel was 2 resulting in 256 subchannels in total. A single global PU was simulated whose occupied spectrum share was varied from 0 to 50% of the total available spectrum.

**Result 1:** From Fig. 8.14(a) we can observe that the proposed scheme ensures that every CR-BN gets a free share of the spectrum. The difference between those nodes who are getting the most and the least subcarriers is small even in the case where the PU occupies a large part of the spectrum. This is possible because the proposed subchannelization scheme scatters the adjacent subcarriers blocked by PUs over the whole spectrum.

Moreover, a raising number of neighbors ( $\alpha$ ) narrows the size of the assigned spectrum. This is due to the enforced strict interference avoidance strategy.

**Experiment 2: (Optimal number of subcarriers per subchannel)** According to the proposed subchannelization scheme adjacent subcarriers are grouped into subchannels. Because adjacent subchannels can be assigned to different CR-BS nodes we have to insert guard carriers resulting in wastage of spectrum. In the following we evaluate the optimal number of subcarriers (incl. two guards) in each subchannel, which is a trade-off between efficiency (small guard carrier overhead) and probability of being blocked by PUs. The latter can be explained as follows. The scattering is done on the subchannel level, i.e. the mapping of physical subchannels to logical subchannels is random. The larger the number of subchannels the larger the effect of scattering the adjacent subcarriers being blocked by PUs because the subcarriers within a subchannel are adjacent. For this purpose a single global PU was simulated whose spectrum share was fixed to 50% of the total available spectrum. Further, a random network topology with a fixed node degree of  $\alpha$  was considered.

**Result 2:** From Fig. 8.14(b) we observe that node degree  $\alpha$  has only a minor impact on the optimal number of subcarriers per subchannel. The larger the number of subcarriers per subchannel, i.e. the smaller the number of subchannels, the higher the variation of assigned subcarriers becomes. If only a few subchannels are used, it can happen that some nodes will not get no free spectrum, i.e. all assigned subcarriers are blocked by PUs. Thus, a good trade-off between fairness among CR-BS nodes and efficiency is achieved with 32 subcarriers per subchannel and thus 256 subchannels in total.

**Experiment 3: (Impact of proposed algorithm extension)** In the following we will quantify the improvement to our spectrum sharing algorithm proposed in Sec. 7.5.3. Therefore a random network topology with variable node degree and different number of nodes is considered. The number of placed PUs is 12, 25 and 50 for a network of 50, 100, 200 nodes respectively. The PUs are placed uniform randomly. Each PU occupies a small random part of the spectrum, i.e. 2%, 1% and 0.5% for a network with 50, 100, 200 nodes.

**Result 3:** From Fig. 8.14(c) we can observe that with the proposed algorithm extension there are CR-BSs having significantly more spectrum assigned which otherwise would be unused. In particular the gain is especially high for nodes at network edges or in the sparse parts of the network. The median of the assigned number of subcarriers over all CR-BSs remains nearly the same whereas the mean value increases by 40-52%.

**Experiment 4: (Comparison with global optimum)** Finally, we compare the results of our proposed heuristic with the global optimal solution. The latter was computed using ZIMPL<sup>2</sup> and the Gurobi<sup>3</sup> solver for computing the mixed-integer problem given in Sec. 7.4. Again, a random network topology with a fixed node degree of  $\alpha$  was considered.

**Result 4:** Fig. 8.14(d) shows the minimum number of allocated data subcarrier as computed by the proposed algorithm relative to the global optimal solution for networks with different node degrees and available secondary spectrum. The following observation can be made. First, in the absence of any PUs the performance of our approach is 60-70% of the optimum. This is a good value since we considered the worst case scenario where the random joining of nodes resulted in lots of network merges.

In contrast to the optimum solution with a complexity of  $NPC$  our heuristic has only a constant complexity,  $\mathcal{O}(1)$ , which only depends on the number of nodes in the local two-hop neighborhood around a node and thus is independent from the network size. The computation of the optimal solution on a modern Intel i7 with 3.4 GHz took between 10s and multiple days. The second important observation is, that in the presence of PUs, the relative performance of the heuristic worsens to just 45% of the optimum. This is based on the proposed decomposition of the problem in two sub-tasks (Sec. 7.5). First, we assign the spectrum shares to SUs independent from any PUs. Afterwards we exclude any subcarriers being blocked by PUs. The stochastic subchannel permutation scheme cannot guarantee that all SUs are equally affected by PUs.

<sup>2</sup>Zuse Institute Mathematical Programming Language, <http://zimpl.zib.de/>

<sup>3</sup>Gurobi Optimizer, <http://www.gurobi.com>

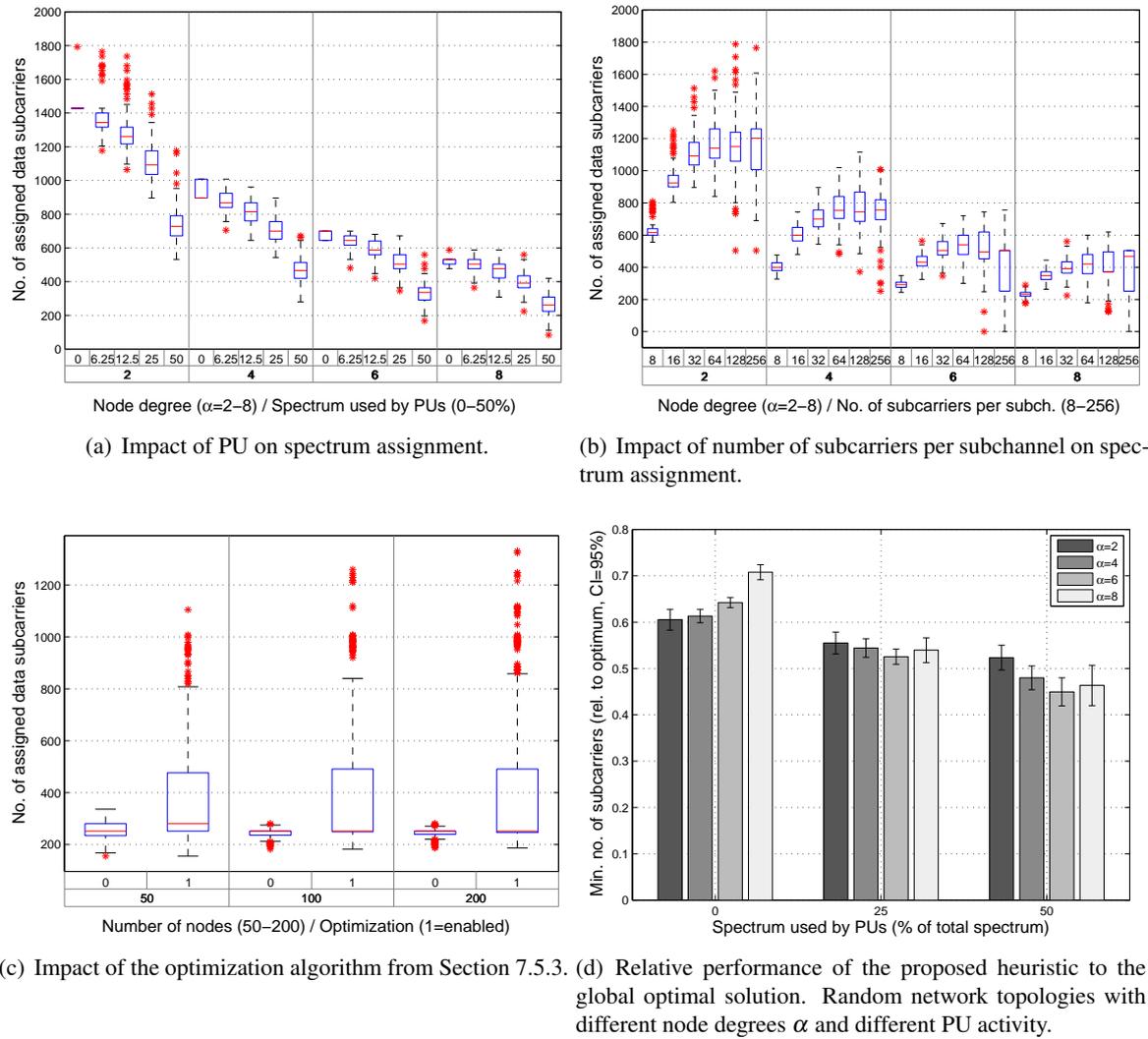


Figure 8.14.: Simulation results of the spectrum sharing algorithm explained in Chap. 7.

## 8.5. Evaluation of the Proposed In-Band Control Channel

In this section various control channel improvement opportunities are discussed and evaluated.

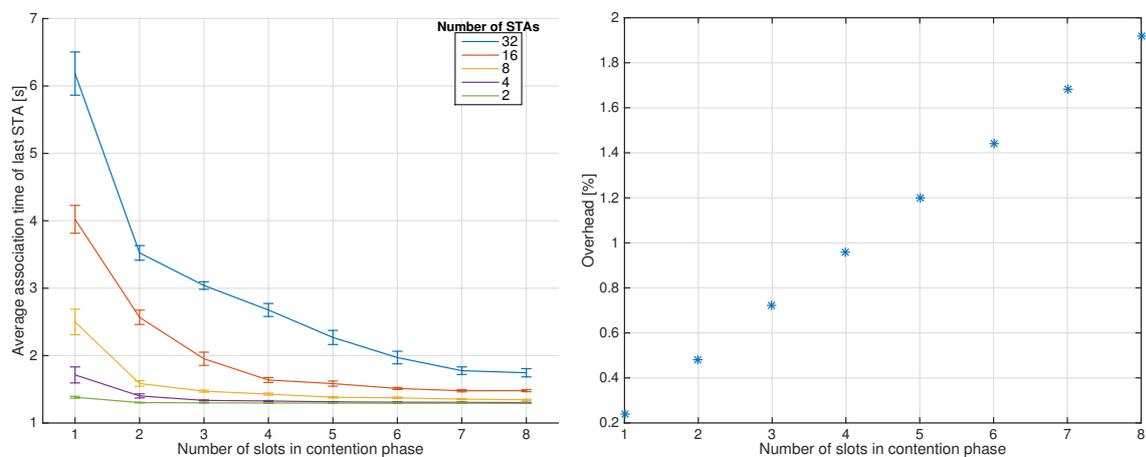
### 8.5.1. Number of contention slots

#### Methodology

To investigate the necessary number of contention slots for our developed MAC protocol the MAC protocol is implemented in ns3. We analyzed the rendezvous time for a certain number of CR-STAs to one CR-BS by varying the number of CR-STAs which due a connect attempt to one CR-BS. To avoid bias no primary user is active. To resolve congestion of competitive contentions slot access the former introduced exponential backoff per CR-STA is enabled.

#### Results

As described in the former section, a full scan of all channels needs about 1.28 seconds ( $= 64\text{channels} \times 20\text{msec}$ ), this is the baseline of the association time in Fig. 8.15(a). In Fig. 8.15(b) the percentage of overhead per number of contention slots is given. It can be seen that the maximum percental overhead with eight contention slots is below 2 %.



(a) Association time of CR-STAs vs. the number of contention slots (b) Overhead in percent for a certain number of contention slots

Figure 8.15.: Results from ns3 simulation

### 8.5.2. Backup channels

Due to the dynamic properties of the spectrum it is likely that a control channel will be blocked by primary transmission. If this happens, all CR-STAs have to rescan for the new control channel of their CR-BS which takes at least 1.28 seconds. With backup channels we can tackle the problem: How does a cell recover from an incumbent appearance in a timely fashion?

## Methodology

If backup channels are introduced the overhead is now twofold. First, as long a backup channel is available the hopping and re-association procedure will take only a very short time. But we have to reserve the spectrum for these backup channels in order to ensure their existence, which results in a less number of overall available control channels. Second, if no backup channel is available the re-association procedure will take its at least 1.28 seconds as in the former approach.

## Results

In Fig. 8.16 we investigated the probability that no backup channel can be found in the whole spectrum range, i.e. all backup channels are blocked by PUs. It can be seen that it is very unlikely that no backup channel can be found. Only for a high number of 7 backup channels and a high probability of subchannel blocking the control channel is in outage.

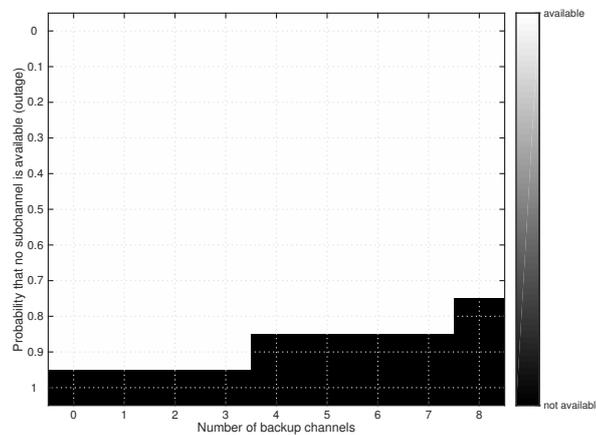


Figure 8.16.: Outage probability for 64 subchannels with up to 8 backup channels. One cell. No spectrum claimed by PUs.

The switching from the current control channel to a backup channel takes about 60 ms. We defined a channel holding time of five slots (50 ms) to avoid channel switching in the case of fading before a switch to the backup channel is initiated (channel coherence time). The switching itself can be done within one slot and takes therefore 10 ms. With these numbers it can be seen that introducing backup channels has a huge potential to speed up the control channel switching process if a PU appears. Only in the unlikely event that no backup channel is available a full scan must be initiated. In the worst case with a maximum of seven backup channels this operation takes now  $8 \times 60 \text{ ms} = 480 \text{ ms}$  plus the time for the full scan as shown in the former paragraph.

### 8.5.3. Channel switching announcement

In the former paragraph it has been shown that the passive approach of introducing backup channels can speed up the control channel switching up to 20 times. Now we want to study a reactive approach by adding a channel switching announcement. Because we get our allowed spectrum allocation from a data base, we know about the future when a lease ends. Therefore an channel switching announcement

should be entered to further speed up the channel switching to within one superframe. To implement that PSS has to be extended by an extra field of 2 Bytes.

To optimize the introduced overhead the channel switching announcement control information is further used to signal available backup channels. If the channel switch active is set to zero, the remaining bits are used to announce two backup channels.

- 1 bit: Channel switch active - Indicates that a channel switch is announced, otherwise the following fields are backup channel numbers.
- 6 bit: New channel number - 64 channels.
- 9 bit: Channel switch counter - Counts the superframes until the channel switch will be initiated or backup channel number if channel switch active is set to zero.

## 8.6. Simulation with NS3

### 8.6.1. NS3 - Model

Our implementation of the ns3 model is based on the existing well known IEEE 802.11 wireless LAN model integrated in the core version of ns3. We changed large parts of the model to be compliant with the proposed MAC and PHY specifications. As shown in Fig. 8.17 and 8.18, the ns3 module is prepared to work either as simulation only or via the formerly described interface with real hardware.

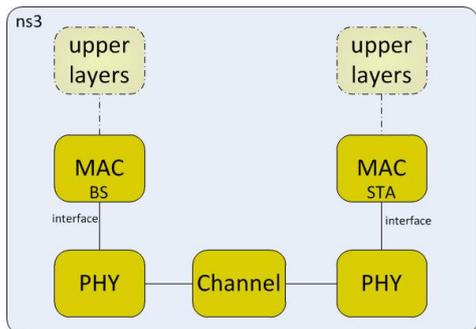


Figure 8.17.: Current implementation in ns3, where MAC and PHY layer are completely modeled in ns3.

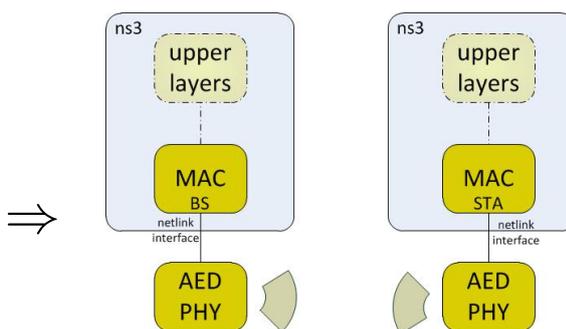


Figure 8.18.: Future implementation, where the PHY layer is exchanged with real hardware.

Simulation is possible in various settings, but only one CR-Basestation can be used. The applied parameters are listed in table 8.3.

Table 8.3.: NS3 simulation parameters

Number of CR-BS	1
Number of CR-STAs	varied
Placement	random and fixed
Heights	CR-BS 30m, CR-STA 6m
Bandwidth	512MHz (2048 subcarrier)
Subchannels	64
Subcarrier per subchannel	32
Total number of subcarriers (FFT size)	2048
Propagation model	Okumura Propagation Model (small city, urban environment) per subchannel
Fading model	Nakagami Fading Model per subchannel
Transmit power	17 dBm
Modulation & coding scheme	QPSK $1/2, 3/4$ ; 16-QAM $1/2, 3/4$ ; 64-QAM $1/2, 2/3, 3/4$
PU model	Trace-based PU, but not interfering (Data base)

### 8.6.2. NS3 - Evaluation Results

In this section the results taken from our proposed system modeled in ns3 are shown.

### 8.6.3. End-to-end delay

In Fig. 8.19 the CDF of the end-to-end delay of UDP packets is shown. The delay is fixed for every packet and depends strongly on the time when the packet was created and send to the data queue. As already stated in the former chapter in Fig. 5.21 packets which arrive late have a smaller delay than packets which are scheduled earlier in the super frame.

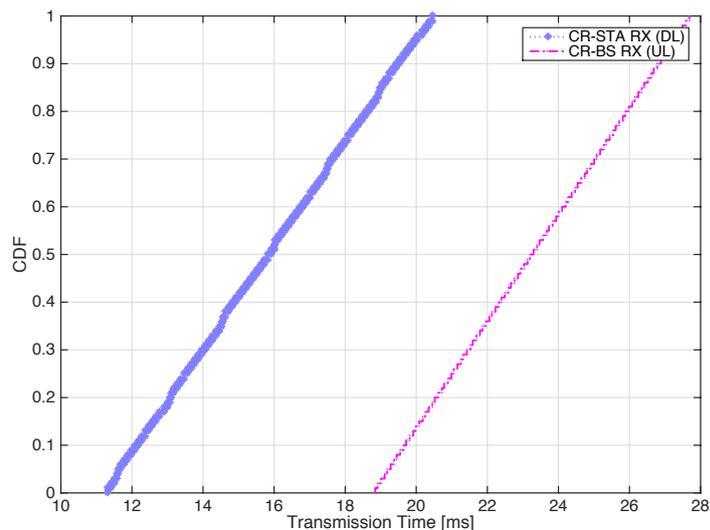


Figure 8.19.: UDP end-to-end delay simulated with ns3.

### 8.6.4. Instantaneous Impact of different Primary User behavior on COUWBAT transmissions

In Fig. 8.20 three different evaluations are shown. Downlink means transmissions from CR-BS to the corresponding CR-STA and uplink vice versa. Downlink and uplink are split 80 % to 20 %.

The base line (*No PU*) shows the maximum throughput of our ns3 system without the influence of any Primary User. *Toggle PU* uses a very artificial PU which allocates 50 % of the whole spectrum in 50 % of the overall time. It further swaps his 50 % spectrum chunk to force a control channel reset. The last *Skopje Trace PU* is using the trace file depicted in Fig. 8.23. It can be seen in the trace file snapshot that it is very unlikely that a control channel reset is forced, only differences in the wideband phase appear.

Please note that Fig. 8.22 and Fig. 8.23 using different frequency ranges! The reason is that we always want to use the worse condition. For the SNR this means in higher frequencies the pathloss is higher and for the PU behavior exist more PU with a higher fluctuation in the below 1 GHz band. Between 1 GHz and 1.5 GHz there are a lot of empty measured bands because of GPS and similar techniques with a very low power footprint.

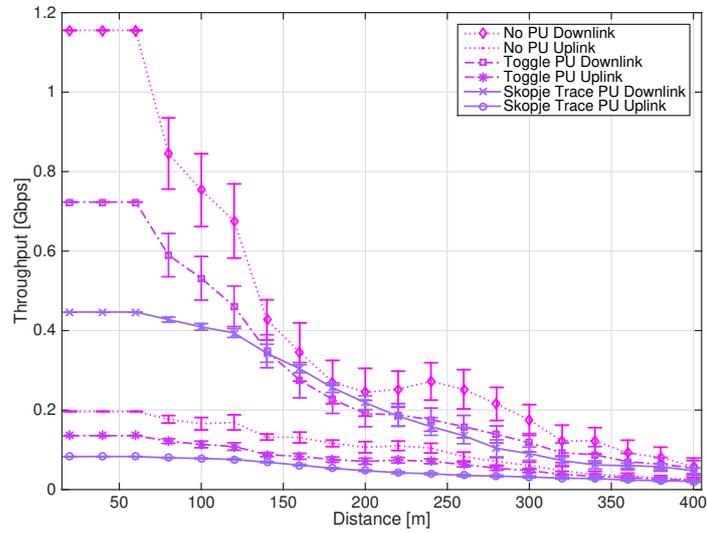


Figure 8.20.: Aggregated MAC throughput between one CR-BS and one CR-STA for saturated traffic with 1500 Bytes per frame in dependency to the number of available subchannels.

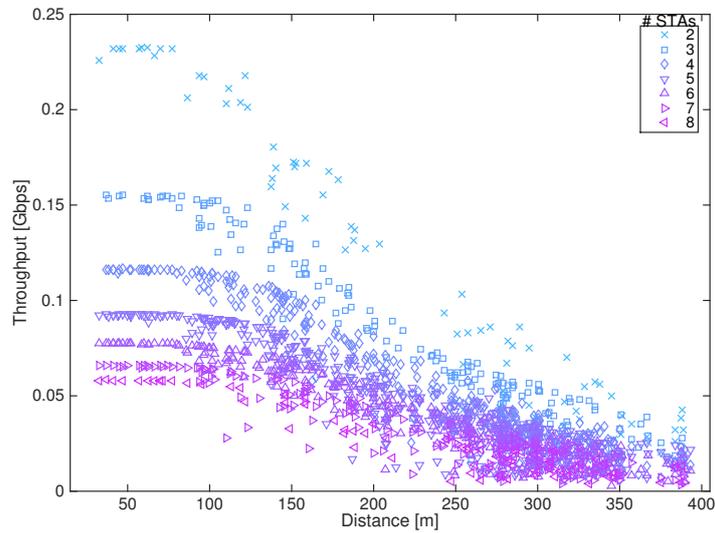


Figure 8.21.: Aggregated MAC throughput between one CR-BS and  $n$  CR-STA for saturated traffic with 1500 Bytes per frame in dependency to the number of available subchannels.

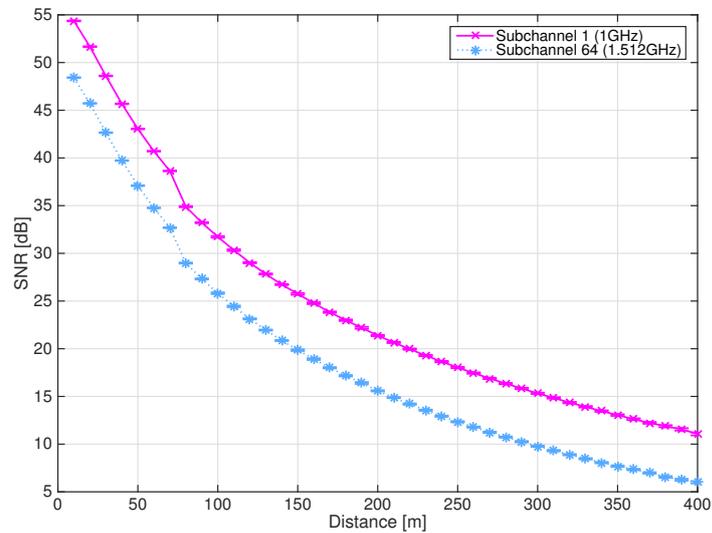


Figure 8.22.: SNR value of each subchannel in dependency of various distances in our ns3 model.

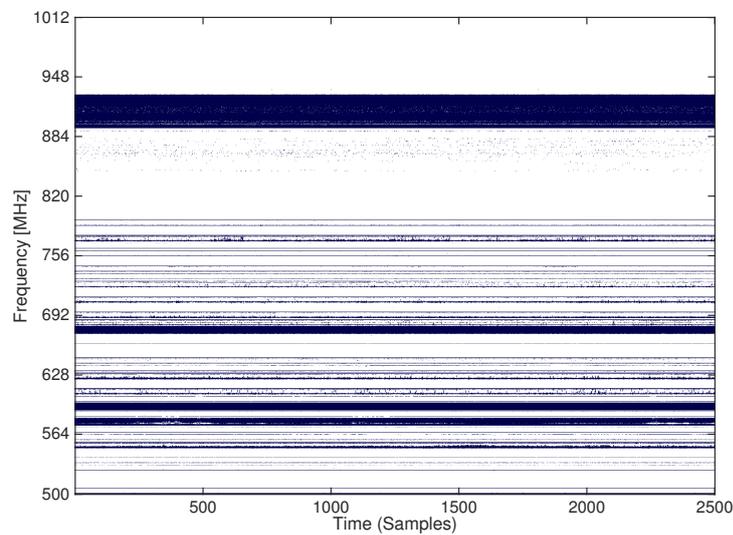


Figure 8.23.: Primary User trace from a measurement campaign in Skopje [47] used in Fig. 8.20 to evaluate our protocol in terms of realistic spectrum changes. Originally the trace lasts four hours from 4pm until 8pm. In our simulation we increased the sampling rate and use one sample every 400 ms.

## Chapter 9.

# Physical Layer

The goal of this section is to give a brief overview about the COUWBAT PHYsical layer (PHY). Both, control and data channel, are using the full flexibility of NC-OFDM, which allows to aggregate spectrum snippets scattered over a wideband spectrum.

### 9.1. NC-OFDM Primer

Non-Continuous OFDM (NC-OFDM) transmission technique allows the efficient utilization of available, even fragmented, spectrum. As depicted in Fig. 9.1 subcarriers affected by a Primary User (PU) transmission can be switched off, while the remaining subcarriers are still usable for Secondary User (SU) transmission. This flexibility has a drawback: because blind synchronization approaches still lack in reliability, the NC-OFDM receiver has to get the allocation of currently used subcarriers somewhere. Therefore, for the signaling of the subcarrier allocation a side or control channel is required.

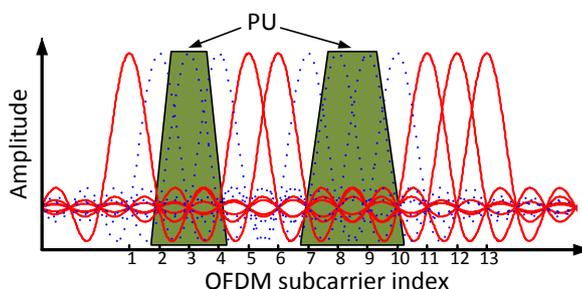


Figure 9.1.: **Spectrum shaping using OFDM.** Subcarriers being blocked by PUs are disabled (dotted curve).

NC-OFDM has a lot of advantages and disadvantages which are similar to ordinary OFDM systems and here are briefly listed only:

#### Advantages

- Very high spectral efficiency
- Robust against narrow-band co-channel interference
- Robust against Inter Symbol Interference (ISI)

## Disadvantages

- Sensitive to frequency offset
- High Peak-to-Average Power Ratio (PAPR)
- Need of cyclic prefix/ guard interval

### 9.1.1. Synchronization in NC-OFDM

The synchronization of the NC-OFDM transmission at the receiver is a challenging task because in a Cognitive Radio (CR) system the receiver does not have any information on the used set of OFDM subcarriers. A blind synchronization schemes for NC-OFDM based CR proposed in the literature [48] rely on very accurate sensing information at receiver side to be able to derive the set of data subcarriers used by the transmitter. However, this requires a very high sensing sensitivity which is not feasible in a practical system e.g., due to the hidden PU node problem or very weak PUs (e.g. GPS). Hence, an incorrect sensing increases the preamble misdetection rate and leads also to a very high packet error rate of the NC-OFDM transmission.

Therefore we follow an approach where the receiving CR-STA has perfect knowledge on the set of used OFDM subcarriers of the NC-OFDM transmission. This information is transmitted using an inband NC-OFDM transmission during the control phase by using the PSS frames. So the NC-OFDM synchronization at receiver side can be accomplished with perfect information on the subcarriers used by transmitter side. Our proposed synchronization scheme for NC-OFDM was inspired by [48, 49] and is given in Fig. 9.2. The receiver uses information on the used subcarriers from the control phase to reconstruct the transmitted preamble which is used for the preamble detection. After the detection of a preamble the samples are processed using FFT while the unused subcarriers are removed before demodulation. Note, that reconstructed preamble can be pre-computed and cached.

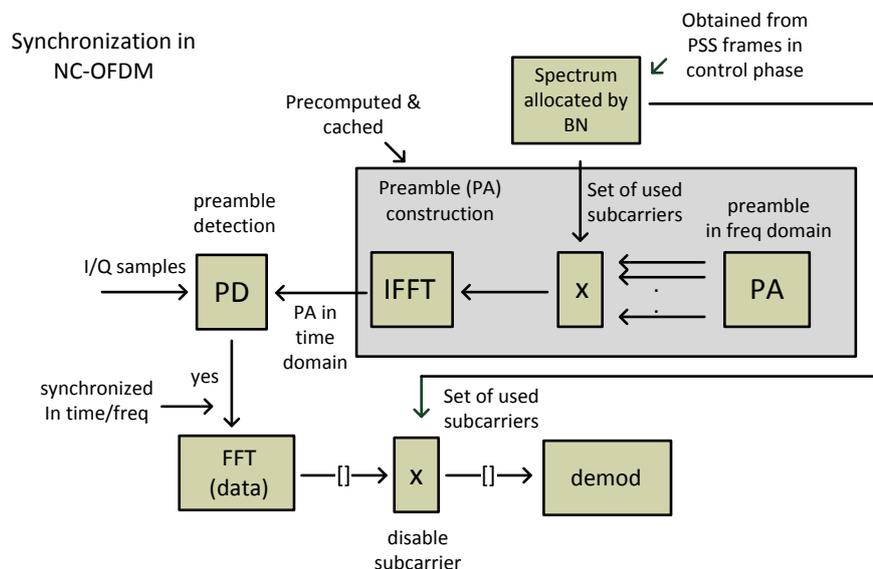


Figure 9.2.: Synchronization in NC-OFDM - i) preamble detection on unfiltered signal using reconstructed preamble using information on the used subcarriers from the control phase, ii) disabling the subcarriers not being used before demodulation.

The preamble shown in Fig. 9.3 is placed at the start of every transmitted downlink and uplink frame. Short Training Field (STF) and Long Training Field (LTF) consist of a sequence of 32 OFDM symbols. This sequence is used to assist the receiver in identifying that a COUWBAT frame is about to start. The Signal Field (SIG) is used to describe the data rate and length (in Bytes) of the frame. The receiver is able to calculate the time duration based on this information. This preamble information is modulated with BPSK.

The preamble is followed by the Physical Layer Convergence Procedure (PLCP) header, which is QPSK modulated and has the length of two NC-OFDM symbols.

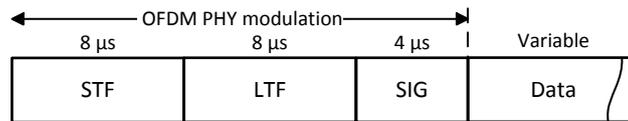


Figure 9.3.: Physical layer frame format (PLCP Preamble + PLCP Header).

Table 9.1.: PHY parameters: On top the general parameters are shown, then the specific adaption for the control and data channel are listed.

Frequency range	20 MHz - 1.056 GHz 1.056 MHz - 2.112 GHz 2.112 MHz - 3.168 GHz
Bandwidth	2 × 528 MHz
Center frequencies	264 MHz, 792 MHz
Physical layer	FBMC
Total number of subcarriers (FFT size)	2048
Total number of subcarriers used	2048
Subcarrier frequency spacing	250 kHz
IFFT and FFT period	4 μs
Symbol interval	4 μs
Symbol rate	250 kHz
Total number of samples per symbol	2048
Total number of subchannels	64
Number of subcarriers per subchannel	32
Number of data subcarriers per subchannel	24
Number of pilot subcarriers per subchannel	4
Number of guards per subchannel	2 + 2 = 4
<b>Control channel</b>	
Modulation & coding scheme	QPSK 1/2
<b>Data channel</b>	
Modulation & coding scheme	QPSK 1/2, 3/4; 16-QAM 1/2, 3/4; 64-QAM 1/2, 2/3, 3/4



## Chapter 10.

# Related Work and Standardization Efforts

### 10.1. Dynamic Spectrum Access Protocols

In this section a short overview of recently proposed Dynamic Spectrum Access (DSA) and Media Access Control layer (MAC) protocols is given.

#### 10.1.1. Overview Papers

Dynamic spectrum access (DSA) schemes are in the research focus since over a decade. A comprehensive survey of spectrum assignment strategies is given by Tragos et al. [50]. A large number of papers propose their own classification scheme for the main functions of DSA protocols. *Ren et al.* [15] identified the following main functions:

- **Transparency for PUs** No interaction or coordination between SUs and PUs should exist, which means SUs will be transparent to PUs.
- **Collision avoidance** This process has two aspects. Collision between SUs and PUs which must be avoided at any time and secondly spectrum sharing and collision avoidance between SUs.
- **Accurate spectrum sensing** Sensing is the weakest point of most CR systems. Its accuracy significantly affects the performance of the CR system. A lot of different approaches exist, but path loss, channel fading, shadowing, noise uncertainty, etc. make it still uncertain. Therefore mechanisms such as cooperative spectrum sensing or database approaches are proposed.
- **Efficient dynamic spectrum allocation** In distributed network architectures it is fairly hard to allocate resources efficiently, nevertheless DSA protocols should provide efficient dynamic spectrum allocation.

*Lu et al.* [51] provide in their overview paper a very good insight of the state-of-the-art in spectrum managing. They evaluated about 140 different sources. Started with spectrum sensing schemes including local spectrum techniques like energy detector, matched filter, feature detectors etc., towards sensing scheduling with silent periods. They give also an introduction about challenges faced in wideband sensing and synchronization. Furthermore, they provided an overview of cooperative approaches incl. data fusion techniques as hard- or soft-combining.

*Vamsi and Das* [52] give an overview and classification of medium access control (MAC) protocols in Open Spectrum Access (OSA) networks with the focus on ad hoc networks.

*Cormio et al.* [53] provide an introduction of differences between MAC and Cognitive MAC (CMAC) schemes. Their focus is on optimization of spectrum sensing and transmission duration. Moreover, they provide a classification of CMAC protocols.

### 10.1.2. Distributed Dynamic Spectrum Access

This classification of distributed dynamic spectrum access protocols is proposed by [15]. It can further be distinct in MAC Protocols for CR infrastructure-based networks and MAC protocols for CR ad hoc networks [53]. Here we give some overview examples of these three different types of distributed dynamic spectrum access protocols.

### 10.1.3. Contention-Based Access

As many protocols suffer from hidden or exposed node problems Dynamic Open Spectrum Sharing (DOSS) [54] solves this issue by applying multiple transceivers and busy tones at distinct frequencies. The busy tone is always send if a data transmission appears (RTS/CTS scheme). PU detection is done by contiguous local sensing on one of the transceivers.

### 10.1.4. Time-Slotted Access

*Cordeiro et al.* [55] proposed the Cognitive MAC (C-MAC) scheme. This scheme is similar to our approach. The spectrum access is organized by a superframe structure and uses a single radio transceiver. The superframe is split into a Beacon Period (BP) and a Data Transfer Period (DTP). For exchanging control information, one of the available channels is selected as Rendezvous Channel (RC). It is used for broadcasting channel information, PU detection and resource reservation. Via beacon packets the two-hop information like communication slots and beacon information of every node is distributed.

For spectrum sensing the superframe includes quiet periods, which are further used to perform load measurements.

### 10.1.5. Hybrid Access

*Hamdaoui et al.* [56] proposed the Opportunistic spectrum MAC (OS-MAC). The OS-MAC protocol is a cluster based approach. The spectrum between SUs is shared by using pre-determined window periods. During a window period the spectrum access is random. The MAC assumes a single radio which has a switching functionality, to switch between control channel and the data channel.

*Kondareddy et al.* [27] proposed the SYNchronized MAC (SYN-MAC). This MAC scheme assumes a multi-radio to assign non-overlapping time slots at each of all available channels. Every device has now the possibility of sensing during quiet periods, but is strongly related to the channel schedule, where it can transmit.

## 10.2. Related Standardization Efforts

This section gives a short overview about related standardization efforts. All currently existing standards targeting the exploitation of TV White Spaces (TVWS), only.

### 10.2.1. IEEE 802.22

IEEE 802.22 [57] is the first Cognitive Radio standard that covers the dynamic spectrum access of TV white spaces. It is intended to serve Wireless Regional Area Networks (WRANs), especially in

rural areas, with distances up to 100 km using the frequency bands from 54 to 864 MHz.

The 802.22 system is organized as centralized point-to-multipoint connection where the Base Station (BS) manages its associated Consumer Premise Equipments (CPEs). The maximum power is limited to 4 Watt EIRP. To protect Primary Users, here called incumbent equipment, the BS has common Cognitive Radio functionalities implemented. These are incumbent database access, spectrum-sensing, geolocation, regulatory domain dependent policies and coexistence with other SUs. Spectrum access is entirely controlled by the BS to ensure protection of incumbent services as TV and wireless microphones. A CPE needs proper authorization from its BS before a transmission can be achieved. Mobility is possible but limited. Each device has to know its location via GPS and has to poll the database according to its mobility pattern. Further needs each CPE a directional and an omnidirectional antenna. First one is for communication between the CPE and the BS, while the second antenna is used for spectrum sensing. The air-interface is based on OFDMA with 2048 carriers, supporting three different channel bandwidths of 6, 7 and 8 MHz.

The spectrum access is organized by a hierarchical frame and superframe structure with an overall length of 160 ms (see Fig. 10.1). Each superframe is further split into 16 frames of 10 ms each. The first frame contains the superframe preamble, a frame preamble and the Superframe Control Header (SCH). The 15 remaining frames contain only the frame preamble and are divided in the Downlink Subframe (DS) data from the BS to CPEs and the Uplink Subframe (US) channel from CPEs to the BS. The CPEs share their resources on demand base (Demand-Assigned Multiple Access (DAMA)).

In the DS subframe the DS/US MAP provides the scheduling information for CPE bursts. The US- and DS Channel Descriptor (UCD and DCD) is used to carry the PHY characteristics of the bursts (modulation, coding).

The US subframe contains information about ranging (distance to BS), bandwidth requests and the Urgent Coexistence Situation (UCS). The latter notifies the BS that the CPE has sensed signal of an incumbent device. Subsequent to the US subframe the Self-Coexistence Window (SCW) follows. This window gives multiple BS the opportunity to talk with each other in order to resolve self-coexistence issues and is part of the Coexistence Beacon Protocol (CBP). During a synchronized SCW, a BS or a CPE can either transmit CBP packets on its operating channel or receive CBP packets on any channel. By knowing their SCW pattern a WRAN can capture CBP packets from neighboring WRANs. The standard also suggest to deploy a WRAN database to solve coexistence of multiple IEEE 802.22 systems.

For protecting incumbent devices Quiet Period (QP) are temporally added. During this periods BS and CPE sense the spectrum and the CPE reports its spectrum-sensing result to the BS.

In the standard no dedicated common control channel is envisaged. The BS broadcasts its vacant channel information in the SCH slots, so every CPE which appears can scan passively the used channels. Therefore the initial scanning takes at least 160 ms per channel. The SCH contains all channel and network information for initialization. Regarding the information given in the DS/US MAP, a CPE can transmit and receive data without contention.

## **Co-existence with COUWBAT**

Co-existence of COUWBAT devices with 802.22 is handled by the self co-existence sensing procedure of 802.22.

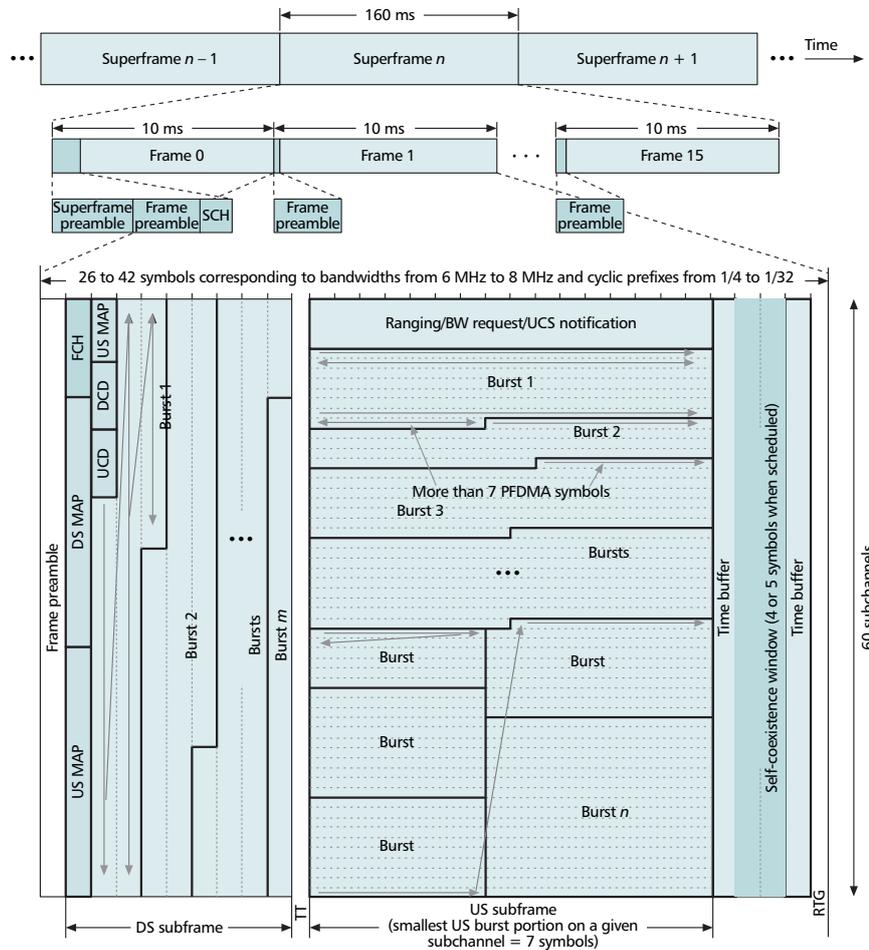


Figure 10.1.: Frame structure in 802.22 (source: [58])

### 10.2.2. IEEE 802.11af

IEEE 802.11af [59] is the WLAN extension for the usage of TV White Spaces between 54 and 790 MHz. The main concepts as channel spacing between 6 and 8 MHz, as well as the channel access are similar to the IEEE 802.22 standard. The main difference is the intended link distance and the PHY technology. WLAN 802.11af is designed for ranges up to 1 km and uses smaller channels as other WLANs.

The spectrum access is fundamentally based on the spectrum information from a geolocation database (GDB). The Access Point (AP) has to have access to the GDB. If a station has no access to the GDB it can only passively listen for a so called enabling signal. Only if access to the GDB exists, the station is allowed to send packets. Spectrum sharing between 802.22 WRAN and 802.11af WLAN is handled by listen-before-talk (CSMA) from WLAN side, while 802.22 devices are not aware of parallel usage.

The physical layer still uses OFDM, but the channel size is adapted to TVWS channel size with 6, 7, and 8 MHz depending on the regulatory domain.

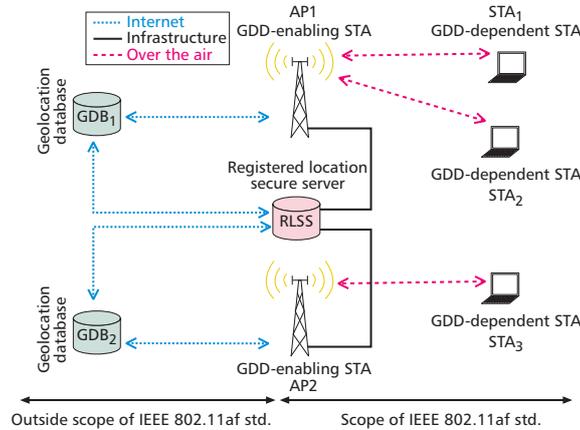


Figure 10.2.: 802.11af architecture (source: [60])

**Co-existence with COUWBAT**

From COUWBAT side there is no need to protect 802.11af in a special way, because 802.11af handles co-existence in the same way as common WLAN 802.11 namely CSMA.

**10.2.3. Standard ECMA-392 MAC and PHY for Operation in TV**

The ECMA-392 standard was originally published in 2009 with a second edition in June 2012 by European Telecommunications Standards Institute (ETSI) and specifies the Media Access Control layer (MAC) sub-layer, as well as the PHY layer for personal or portable cognitive wireless networks operating in TV white spaces [61].

Networks could be formed flexible with three types of devices: master, peer and slave. Different networks topologies including master-slave, peer-to-peer and even mesh are supported. The master node is responsible for coordinating Dynamic Frequency Selection (DFS), Transmit Power Control (TPC) and channel measurements for the slaves, too. Whereas, peer devices are allowed to access the channel by distributed reservation to form ad-hoc networks. An adjacent master node is hereby not intervened. ECMA-392 targets the same applications as WLAN 802.11, which are home networks, hotspots or campus environments. To be applicable in different regulatory domains the specified PHY has to support different bandwidths of 6 MHz, 7 MHz and 8 MHz) and may support MIMO. The maximum data rate of ECMA-392 is 31.64 Mbit/s in an 8 MHz channel. The protocol overhead of PHY and MAC layer is about 19% or less.

The standard specifies a number of incumbent protection strategies that may be used to protect PUs, which include DFS, TPC and spectrum sensing. A spectrum database access is not part of the standard, but information as available channel lists can be obtained to protect incumbents. Further, the above mechanisms to protect incumbent devices will also be used for self-coexistence and mitigation of interference between of nearby networks.

The MAC timing structure is based on a superframe. One superframe is composed of 256 Medium Access Slots (MAS). As depicted in Fig. 10.3 the superframe contains of five different periods, particularly a Beacon Period (BP), Reservation-based Signaling Window (RSW), Data Transfer Period (DTP), Quiet Period (QP) and the Contention Signaling Window (CSW). The RSW is not

mandatory, but should be included after the BP to support signaling between master and slave devices in a master–slave setting.

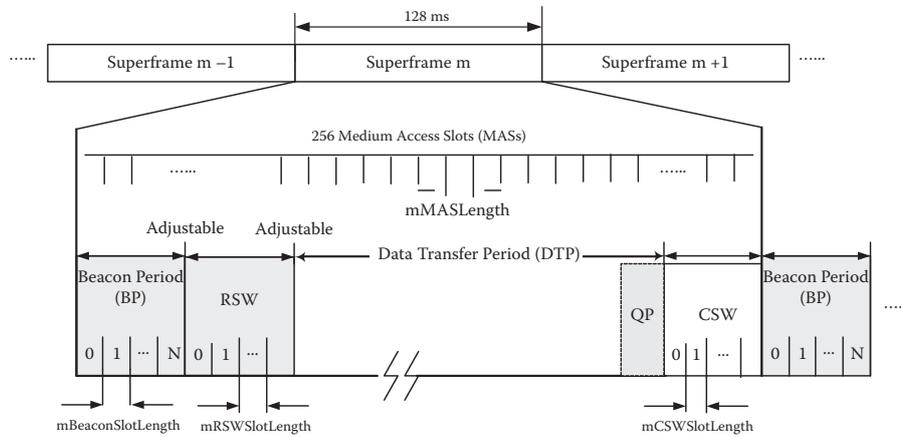


Figure 10.3.: Standard ECMA-392 MAC superframe structure (source: [62])

### Co-existence with COUWBAT

From COUWBAT perspective there is no need to protect ECMA-392 devices, because co-existence with non-ECMA-392 devices is handled by sensing.

## Chapter 11.

# Conclusions & Future Work

### 11.1. Conclusions

Wireless small cell networking is a promising approach to address future wireless networks forecasted growth in wireless traffic volume. In this technical report we propose a wireless backhauling for small-cells based on overlay Cognitive Radio technology. At first the proposed architecture is presented, thereafter a detailed description of the protocols on the data link layer are given. A novel fully distributed spectrum sharing algorithm was proposed and evaluated by means of simulations. Moreover, we present results from spectrum measurements analyzing the occupancy of spectrum in frequency and time.

### 11.2. Future Work

As future work we consider the following steps. First, we extend our research towards an appropriate physical layer abstraction model for wideband NC-OFDM. Second, we want to conduct system-level simulations for the single as well as multiple cells scenario.



# Appendices



# Appendix A.

## Spectrum Measurements

The goal of this section is to analyze the the radio spectrum in the 22 MHz to 3/6 GHz band regarding aspects like occupancy of spectrum in frequency and time, the size of the spectrum holes, noise floor as well as dynamic range. The results will show that there is a plenty of free spectrum available which can be opportunistically used by our overlay CR system.

### A.1. Methodology

We conducted a short term spectrum measurements on the roof of our building at TU Berlin, Germany. We used R&S FSV Spectrum Analyser connected to the Multi-Polarized Ultra Wide Band antenna<sup>1</sup>. The measurements were performed on the roof of HFT building at TU Berlin campus. More detailed specification can be found in Table A.1.

Frequency range	22MHz - 3GHz	22MHz - 6GHz
Measurement duration	3.3min	7.4min
Radio Bandwidth	200kHz	500kHz
Video Bandwidth	20kHz	50kHz
Sweep Time	0.582s	0.0033s
Trace Mode	Clr/Write	
Detector	Sample	
Values per sweep	14900	

Table A.1.: Measurement setup

### A.2. Results

#### A.2.1. Occupancy in Frequency & Time

In Figure A.2 we can see the spectrogram of the collected data. Already here we can see that given frequencies are either used all the time or practically not at all. There are only few frequencies that are used only partially. The best example here is the 2.4GHz ISM band.

#### A.2.2. Noise Floor

The first step was to calculate the noise floor of the data. We have taken the average power received during measurement time and passed the result through the Rank-Order Filter as proposed in [63].

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<sup>1</sup>SUPER-M ULTRA BASE (08-ANT-0861) covers the frequency range from 25 MHz to 6 GHz, see [www.mpantenna.com](http://www.mpantenna.com)



Figure A.1.: Multi-polarized ultra wide band antenna used in measurements (SUPER-M ULTRA BASE (08-ANT-0861) covers the frequency range from 25 MHz to 6 GHz, see [www.mpantenna.com](http://www.mpantenna.com)).

The kernel size was in the current version set manually, thus it may be not optimal but still gives the idea of the real noise floor. The results are shown in Figure A.4. Worth noting is that the overall noise floor is pretty low and is also result of the spectrum analyzer settings. It is possible to lower the noise floor by increasing the sweep time. We can see higher noise floor on the frequencies lower than 500 MHz.

On the Figure A.4 there is also shown average power over the whole experiment time and the heat map of the values. More red dot on the image means that the given power level for given frequency was reported more often than green and blue dots.

The last part of the Figure A.4 are two line denoting the detection thresholds. First one is arbitrarily set to  $-95$  dBm and is meant as the regulatory rule that everything below this line is noise and we do not have to care about that signal. The second one was set to be exactly 5 dBm above the calculated noise floor. For the rest of the document the sample value that is below either of this lines is treated as noise and the value that above both is treated as PU signal.

The same analysis for the frequency band up to 6 GHz can be seen on Figure A.5. We can see that the noise floor goes higher with the increase of frequency. The increase is not very large but can already influence the required detection thresholds.

### A.2.3. Dynamic Range

On both figures we can also see that the received signal strength for the PU transmissions like GSM is going up to  $-30$  dBm. On the other hand the regulatory  $-95$  dBm sensitivity threshold gives the

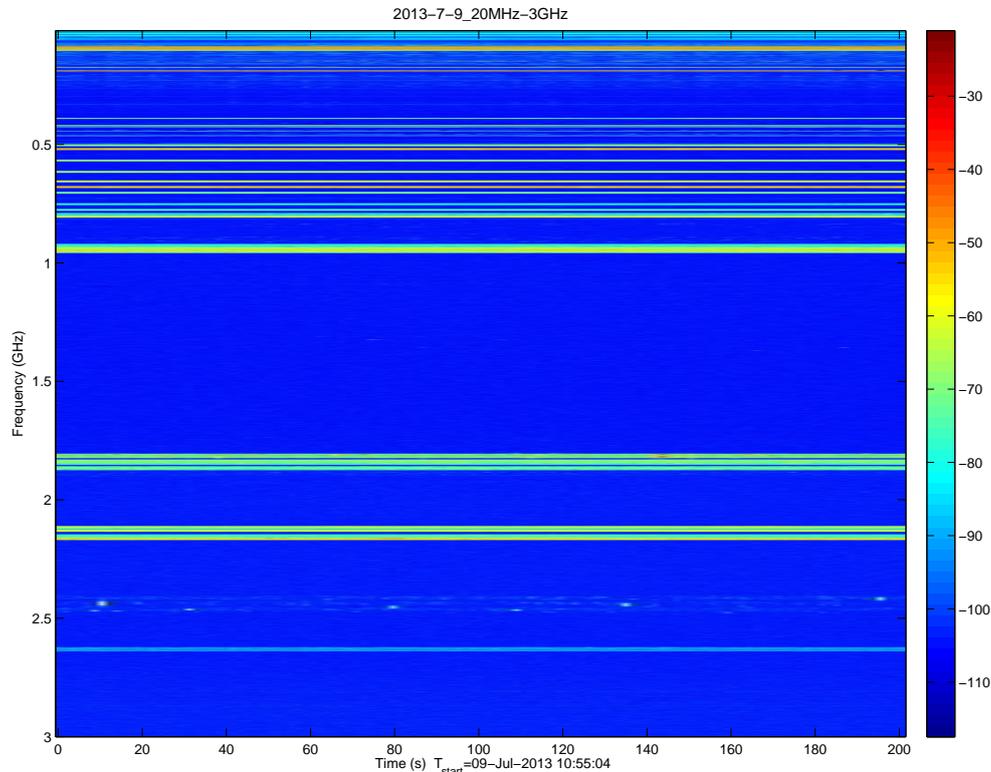


Figure A.2.: Spectrogram of 3 GHz measurements

required noise floor of  $-100\text{ dBm}$  for any successful PU detection. Both numbers together give over  $70\text{ dB}$  of required dynamic range. This is very challenging for the design of the RF frontend and the digital processing.

If we consider only the above defined detection thresholds we can calculate that there is  $2.62\text{ GHz}$  and  $5.50\text{ GHz}$  (in the  $3\text{ GHz}$  and  $6\text{ GHz}$  span respectively) free spectrum available all the time. This is a large number but it does not consider the minimal usable amounts of spectrum. It is also considering perfect reuse when we can use spectrum immediately after it was detected free.

#### A.2.4. Spectrum Allocation

From the previous analysis it look like the spectrum usage is pretty low. On the other hand if we look at the spectrum allocation from the regulatory point of view it is completely opposite. Every piece of spectrum is allocated couple of times (it goes up to 17 allocations for one band in the  $3\text{ GHz}$  range). The spectrum allocation data can be found in [64] or under the link: <http://www.efis.dk/>.

The descriptions of the spectrum applications assigned to the bands can be seen in Fig. A.6. It is definitely divided into small parts any frequency reuse has to be analyzed in the case by case basis. Also it is not enough to look only on the spectrum sensing information. It looks like it is even more challenging to disable spectrum usage due to the regulatory spectrum allocation. This has to be done manually with big care on the systems, like EPIRBs (emergency position-indicating radio beacons).

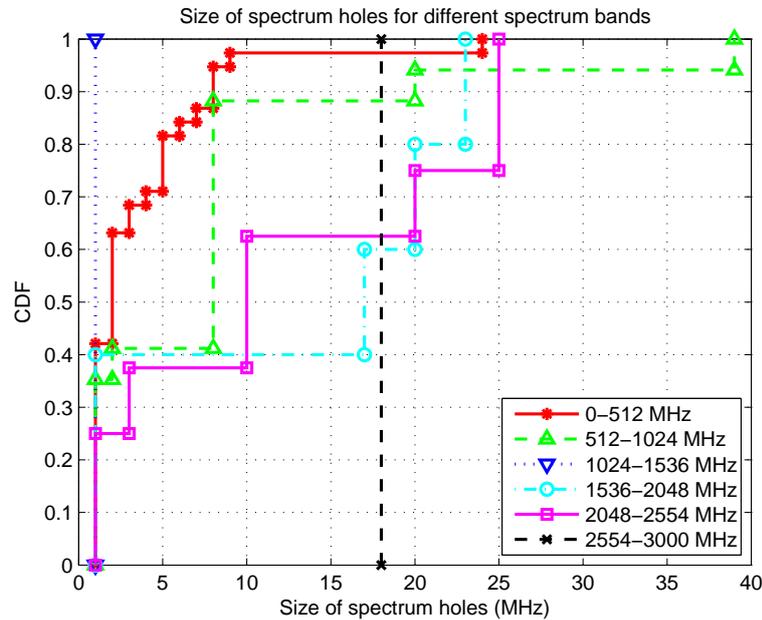


Figure A.3.: CDF of spectrum holes from Fig. A.4.

### A.2.5. Size of Spectrum Holes

Our project goal is to use spectrum chunks of 512 MHz. Therefore, it would be interesting to see the distribution of the spectrum holes (Fig. A.3) which gives us the requirement on the subcarrier spacing (Hz). From Fig. A.3 we can see that e.g. in the 0-512 MHz band 30% of the spectrum holes are larger than 5 MHz.

### A.3. Summary & Conclusion

From our results we can conclude that there is a plenty of spectrum available also in the below 1 GHz spectrum band. Furthermore, the spectrum holes are sufficient large in frequency so they can be used by the proposed CR system.

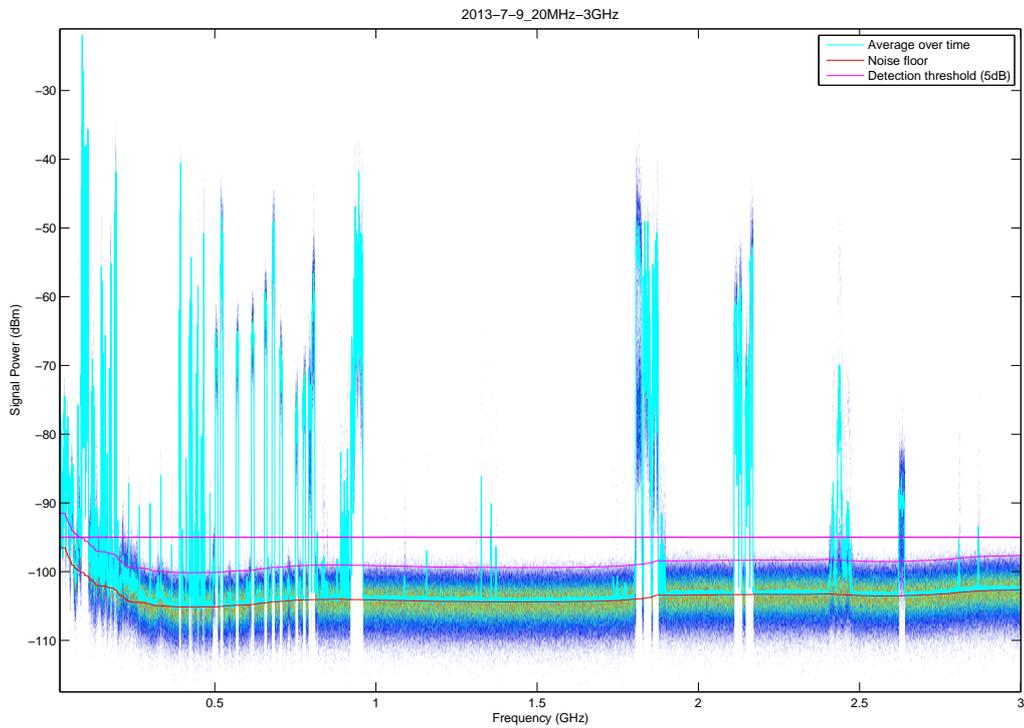


Figure A.4.: Noise floor analysis up to 3GHz

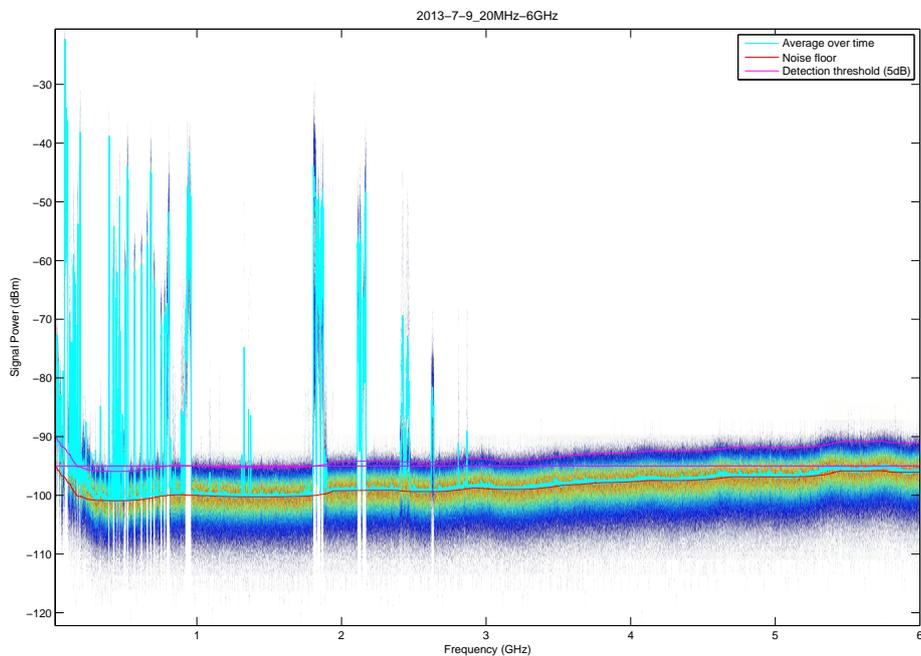


Figure A.5.: Noise floor analysis up to 6 GHz



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