An Ultra-Wide Overlay Cognitive Radio System for Wireless Backhauling for Small Cells

Michael Döring
Technische Universität Berlin
doering@tkn.tu-berlin.de

Anatolij Zubow
Technische Universität Berlin
zubow@tkn.tu-berlin.de

Pablo Leyva
AED Engineering GmbH
Munich, Germany
pablo.leyva@aed-engineering.com

Adam Wolisz
Technische Universität Berlin
wolisz@tkn.tu-berlin.de

ABSTRACT

During the last years WLAN (IEEE 802.11) has become the primary wireless access technology. However, the fast evolution of peak data rates and the wide deployment of WLAN hotspots results in the backhaul connecting such small cells becoming a bottleneck.

To provide a high capacity backhauling, we propose COUWBAT, a COgnitive Ultra-Wide BAckhaul Transmission system, featuring extremely flexible usage of a very wide range of non-contiguous, dynamically allocatable spectrum for backhauling in rural areas where a wired solution is not economically feasible. The proposed cognitive MAC layer supported by protocol in-band signaling, ensures the continuity of connectivity with high capacity even in case of fast changes in spectrum availability.

The proposed system was prototypically implemented and evaluated exhaustively analytically and also by means of network simulations using ns3. The source code of our simulation model is provided to the community as open source.

KEYWORDS

Cognitive Radio; Wireless Networks; Backhauling

1 INTRODUCTION

WLAN (IEEE 802.11) has become during last decade a highly successful wireless access technology. This success is driven on one hand by the integration of WLAN interfaces in all mobile devices (notebooks, tablets, smart phones) and on the other hand by the fast – matching the demand – growth of the peak data rates with every new generation, e.g., IEEE 802.11n, 802.11ac and 802.11ad. Which leads to the problem that the backhaul of these hotspots has become a bottleneck. Bitrates of more than 1 Gbps are necessary to meet the WLAN hotspots throughput requirements.
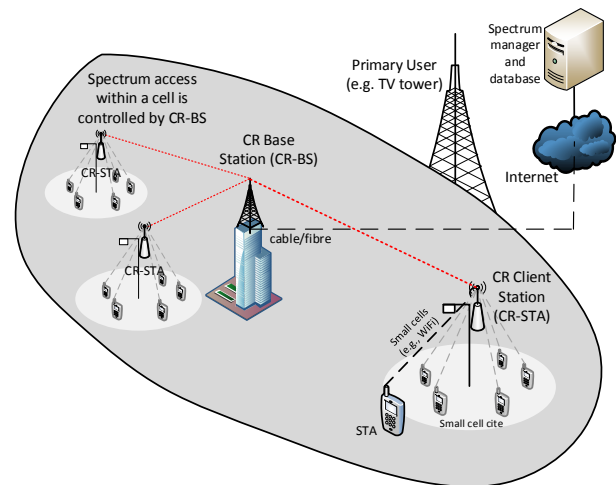
Figure 1: Envisioned wideband overlay cognitive wireless backhaul system.

Provision of such high data rates in the backhaul is possible using wired technologies, e.g., fiber or Gigabit Ethernet. Wired technologies are, however, often expensive, because of their cumbersome deployment and hence unsuitable for rural areas. Further, in some cases the hotspots are only build temporally, e.g., in the case of large events as festivals or fairs.

A promising solution is the usage of wireless technologies for the backhaul. Wireless links of the desired capacity can be provided in one of three ways: mm-Wave links (which have, however rather limited length), advanced multiple antenna systems (like TARANA solution – still under development [14]) or by using a rather large amount of spectrum. Unfortunately, the amount of spectrum necessary for the third solution is not ready available. Nevertheless, it was shown, e.g, in [9, 17], that most of the licensed frequencies are only used sporadically by their licensees. Thus, secondary usage of spectrum, i.e., utilizing spectrum of licensed users, which is currently not allocated by them could solve this issue. Cognitive Radio (CR) emerges as a viable solution for a wireless backhaul in spite of the spectrum crunch. Due to the availability of powerful Software Defined Radios (SDR) platforms it is now possible to efficiently implement dynamic allocation (of even highly fragmented spectrum) and vacation of licensed spectrum bands in very short time intervals.

Parameter	IEEE 802.22 (WRAN)	COUWBAT	IEEE 802.11ac (WLAN)
Cell size (typically)	17-30 km (<100 km)	<300 m	<20 m
Data rate	4.54-22.69 Mbps	up to 1.728 Gbps (512 MHz) 6 Mbps (8 MHz)	450 Mbps (MIMO 1x1) 1.3 Gbps (MIMO 3x3)
Bandwidth	6,7,8 MHz	parts of 8 - 512 MHz	20, 40, 80, (80+80) MHz
FFT size	2048	2048 (8192)	64, 128, 256, 512
Frequency range	54-698 MHz	20 MHz-1 GHz/ 1 GHz-2 GHz/ 2 GHz-3 GHz	5 GHz ISM band
Superframe size	160 ms	10 ms	–
Duplexing method	TDD	TDD (FDD between cells)	CSMA
Modulation types	QPSK, 16,64-QAM	QPSK, 16,64-QAM	BPSK, QPSK, 16,64,256-QAM
Coding rates	1/2, 2/3, 3/4, 5/6	1/2, 3/4	1/2, 2/3, 3/4, 5/6
Error correction coding	CTC/BTC	none	Convolutional or LPDC
Max power	36 dBm	17 dBm	17-36 dBm
Assumed noise figure	4-6 dB	4-9 dB	4-9 dB
Cyclic prefix mode	1/4	none (FBMC)	1/4
OFDM mapping	DL: vertical, UL: horizontal	DL/UL: horizontal	DL/UL: horizontal
Error protection	ARQ	ARQ	ARQ
Subcarrier spacing	3.348/3.906/4.464 kHz	250 kHz	312.5 kHz
Symbol duration	298.7/256/224 μs	4 μs	4.0/3.6 μs
Guard time (CP)	37.34/32/28 μs	none (FBMC)	0.4/0.8/1.6 μs
Symbols per superframe	26/30/34	variable	–
Used subcarriers	1680	1536	56, 114, 242, 484
Guard and null subcarriers	368	256	8, 14, 14, 28
Pilot subcarriers	DL/UL: 240	256	4, 6, 8, 16
Data subcarriers	DL/UL: 1440	1536	52, 108, 234, 468 (2×234)
Subcarriers/subchannel	DL/UL: 24	32	–
Subchannels	DL/UL: 60	64	–
MIMO	none	none	up to 4 spatial streams per client
Beamforming	not supported	not supported	supported

Table 1: Main system parameters of our proposed COUWBAT system compared to IEEE 802.22-2011 (from [5]) and IEEE 802.11ac [6]

In this paper we propose COUWBAT – a COgnitive Ultra-Wide BAckhaul Transmission system – designed to address the requirements of a centralized high bitrate backhauling for WLAN hotspots deployed in distances up to 300 m as shown in Fig. 1. COUWBAT follows the principle of overlay approaches for highly dynamic secondary usage of temporary available spectrum out of a very wide (order of GHz) spectrum range. Our solution does not require the spectrum to be either contiguous or adjacent. The signaling necessary for spectrum access control is supported by in-band control channels.

Our contributions are threefold:

1.) Designing a particular MAC which allows contention-free access, while providing fixed delay and high throughput.

2.) Integrating an in-band signaling scheme which can use different subchannels in distinct neighboring cells.

3.) Evaluating the performance of our MAC scheme both analytically and by means of network simulations with ns3.

The source code of our ns3 simulation model is available via github [3].

The rest of the paper is organized as follows. In the next section we present the related work. In Sec. 3 the design of our system is described in detail. The results of our performance evaluation are discussed in Sec. 4. Finally, Sec. 6 summarizes our main findings and concludes the paper.

2 RELATED WORK

2.1 Wireless Backhauling

Today wireless backhauling, particularly for small cells, is mostly done via directional radio using microwave transmissions [15]. Nevertheless, some approaches are using other technologies as 802.11ac, 802.22 in TV White Spaces (TVWS) or multi-antenna systems like the TARANA wireless [14]. Due to today's spectrum regulations, backhauling using unlicensed spectrum is currently only feasible using TVWS in sub-GHz bands, using higher bands as 3.5 GHz or ISM bands distributed over the whole spectrum range up to 60 GHz [12]. The usage of cognitive networks for backhauling was initially proposed in [16]. The authors in [7] and [13] propose the use of sub-GHz TVWS bands for backhauling by following the existing IEEE 802.22-2011 standard. While the link length is pretty high, the main drawback of this approach is the low data rate of up to 100 Mbps due to the limited channel bandwidth of only up to 8 MHz. Quite promising for backhauling is the usage of IEEE 802.11ac in ISM Bands as proposed in [8]. Due to the large bandwidth of up to 160 MHz and thus usage of MIMO transmission

(up to 8 spatial streams) a peak data rate of about 866 Mbps each multi-Mbps transmission becomes available over several 10's of meters. To extend the transmission range the use of directional antennas might a proper solution, too.

2.2 Cognitive MAC Protocols

Because Cognitive Radio (CR) has got a lot of attention in research, significant efforts has been made in the last years to define and develop MAC protocols for Cognitive Radio systems. A comprehensive overview of existing MAC protocols for CR networks is given by several authors as e.g., in [2, 4]. Based on these papers, it can be stated, that the main issues in designing MAC protocols for CR networks are channel sensing, mechanisms for spectrum assignment and recovery, as well as coexistence with other secondary users.

Here, let us remind a short description of C-MAC [1], as we re-use some of its ideas in our design. As most of the CR MAC protocols C-MAC is based on a superframe structure. Each node is assumed to have a single transceiver with supporting multi-channel operation. The main issue the authors tackle is the multi-channel hidden terminal, which means a node is not able to listen while it is transmitting, therefore the multi-channel hidden terminal effect is of fundamental importance. In C-MAC the superframe is divided in a beacon period and a data transfer period, in such a way beacon periods across different channels do not overlap. Further, they added the design feature rendezvous channel which can be seen as a common control channel. The rendezvous channel is used to exchange inter-channel coordination between certain nodes.

Table 1 shows the main parameters of our proposed system (COUWBAT) are compared with IEEE 802.22-2011 and IEEE 802.11ac.

3 PROPOSED SYSTEM AND MODELING

3.1 System Design

In Fig. 1 the architectural overview of our system is given. We envision a single-hop wireless backhauling system, which allocates non-contiguous chunks of spectrum within an upfront in hardware selected 1 GHz band, either in 20 MHz-1 GHz, 1-2 GHz or 2 GHz-3 GHz. These chunks of spectrum are dynamically selected pieces of frequencies combined to joint channels. Further, these chunks are non-deterministically vacated by licensees, a.k.a. Primary Users (PU). To ensure that there is always enough spectrum not blocked by PUs and thus available to provide high bitrates of up to 1 Gbps, the effectively available amount of spectrum for the envisioned system is > 500 MHz. We assume that the whole spectrum is licensed, but there exists a database of spectrum fragments available for secondary usage in a given time interval over a given spatial area (cf. Fig. 1). The available frequency bands might be strongly fragmented. Moreover, the permission of secondary usage can be revoked on short notice.

Each cell contains of a CR-Base Station (CR-BS), which is the cell head and many CR-Stations (CR-STA). Each CR-BS has a direct high bitrate connection to the Internet, while each CR-STA is co-located with e.g., a WLAN 802.11 access point. In addition the CR-BS has the possibility to access information stored in the spectrum database. We assume that each CR-BS has always an up-to-date knowledge of the data stored in the spectrum database. Fine grained channel selection within the selected 1 GHz block is performed by
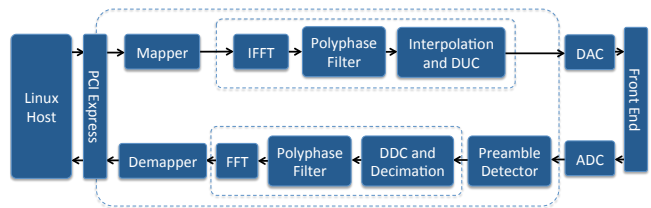

Figure 2: FPGA architecture

the CR-BS only. The network participants (CR-STAs) follow the decision of their CR-BS. Such a flexible CR system requires a very sophisticated signaling and resource management to provide a high level of service continuity. An extensive discussion can be found in our technical report [17].

The intended cell size, i.e., the maximal link length served by the wireless backhaul is up to 300 m. Please note, that the envisioned backhauling system is able to provide backhauling for arbitrary local technologies. WLAN is, due to its popularity, the research driving scenario.

3.2 COUWBAT PHY

To fulfill the requirements of a high bitrate and very flexible spectrum allocation a particular hardware has to be developed. To achieve the expected large bandwidth of > 500 MHz for the system and in spite of the limits imposed by the analog hardware working at 2.112 Gsps the implemented PHY has been designed to handle the whole digital bandwidth provided by this analog frontend. Although the processing is more demanding, it allows us to avoid the interpolation stage and its associated high order filters. This sample rate translates into 1056 MHz of simultaneously digital bandwidth. The developed PHY layer includes a high performance Fast Fourier Transform (FFT) as the core of the OFDM modulator/ demodulator.

To comply with the COUWBAT system specification this bandwidth is divided in two logical bands of 512 MHz bandwidth with 2048 subcarriers each, this implies a 4096 subcarrier OFDM modulator over 1.024 GHz bandwidth. This modulator is implemented as a 8192 points FFT. As shown in Table 1 the required processing time of each OFDM symbol is 4 μs, which splitted in each subcarrier, let us to less than 1 ns of processing time per subcarrier. To achieve this timing, eight FFT cores work in parallel combining their outputs and therefore eight samples are processed per clock cycle.

This implementation allows the upper layers to independently select which subcarriers of the 4096 will be used during the transmission. Each subcarrier can be assigned per OFDM symbol with a different constellation, as pilot or guard. A software configured transmission mask is applied before feeding the data to the FFT core. It indicates to the mapper module stage which modulation scheme should be used for each individual subcarrier and OFDM symbol. A PCI-Express subsystem allows high speed DMA communication with the host computer where the MAC layer is running.

To enable flexible spectrum access the transceiver is using non-contiguous Filter Bank MultiCarrier (FBMC). Another property of the designed radio is the skipping of something like a seperate Physical Layer Convergence Protocol (PLCP) header. The PHY holds all scheduled frames in a FIFO queue (TXQueue), where every frame has attached a radio tap header (TX descriptor) that includes all
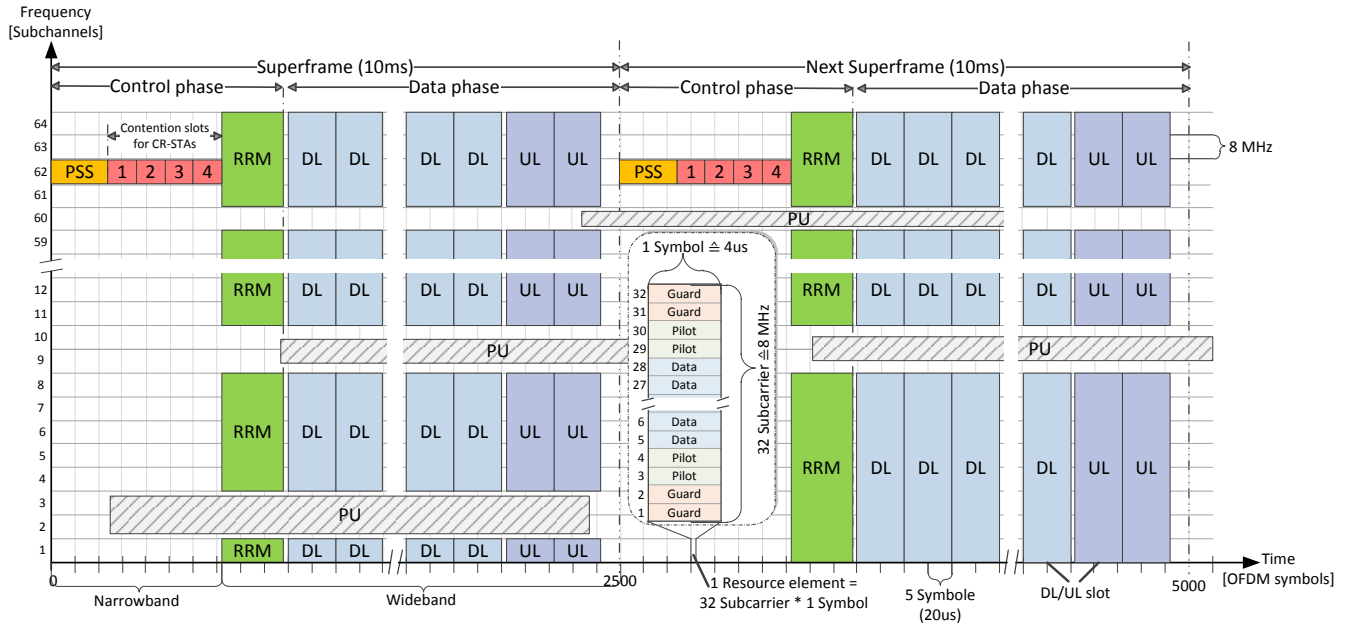
Figure 3: Proposed resource allocation grid exemplary for one CR-BS, one CR-STA and three Primary Users (PU).
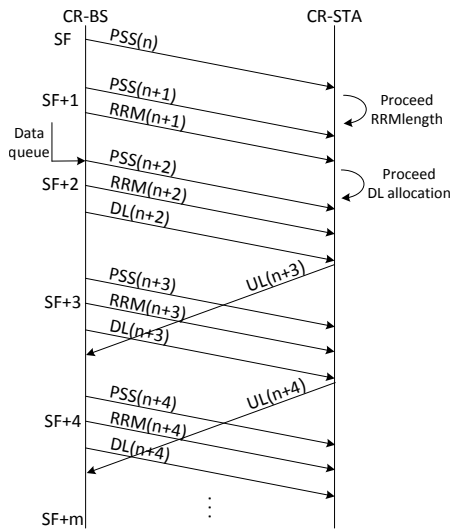

Figure 4: Message flow between CR-BS and CR-STA. A multi step process is necessary to transmit data between both entities.

meta information necessary for sending and receiving of frames as OFDM start symbol, number of allocated symbols, Modulation and Coding Scheme (MCS) etc. Packets are detected on upon recognition of their preamble that has to be known upfront by the receiver side. The introduced PHY is tested successfully on a FPGA implemented as shown in Fig. 2 with the given parameters.

3.3 COUWBAT MAC

The main difference to common MAC protocols is that the proposed MAC is solely responsible for the allocation of the OFDM symbols in time and subchannels in frequency during packet transmission and reception.

3.3.1 Channelization and Framing. In Fig. 3 our proposed radio resource grid is depicted. To lower the signaling overhead adjacent subcarriers (chunks of spectrum) are grouped into joint channels, so called subchannels. In the proposed system a subchannel width of 8 MHz per subchannel is targeted. We believe this to be a good partitioning, because it allows fine grained spectrum access, while reducing significantly the processing and signaling overhead. Therefore, in that way 2048 subcarriers are channelized into 64 subchannels, 32 subcarriers each. Each subchannel has two guard subcarriers on each edge to prevent interference between adjacent subchannels, which are being used by different CR-BSs. Further, four pilot subcarriers for synchronization and channel estimation purposes are added to each subchannel.

Resource allocation in time is organized on superframe basis, where the overall frame length of a superframe is based on the assumed coherence time of the channel of 10 ms. The superframe contains two mayor parts: a signaling and a data part. The signaling part in the beginning of each superframe starts with the narrowband control phase consisting of a Beacon called PSS – Primary Synchronization Signal. The PSS transmits spectrum information used by all Cognitive Radio-Base Stations (CR-BS), such as a binary mask of the available subchannels, the length in OFDM symbols of the next Radio Resource Map (RRM), as well as the CR-BS MAC address to identify the transmitter. This PSS is followed by four ALOHA random access slots. The ALOHA slots are used for managing association and disassociation requests from Cognitive Radio-STAtions (CR-STAs).

The narrowband part within each superframe is followed by a non-contiguous wideband frequency allocation. In the first part the wideband section contains signaling information, the Radio
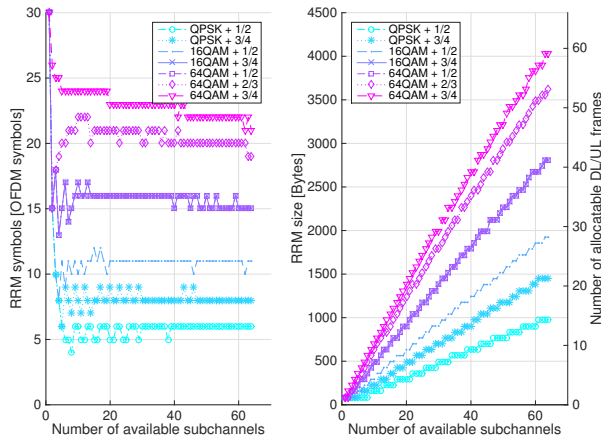
Figure 5: RRM size depended on all available MCS without any PU existence for one CR-STA

Figure 6: Association time of CR-STAs vs. the number of contention slots.

Figure 7: Overhead in percent for a certain number of contention slots.

Resource Map (RRM). The RRM is used to broadcast resource allocation information to all CR-STAs: the UL/ DL slot burst allocation and the MCS for the next data phase included in the next superframe.

The RRM is followed by the data downlink and uplink slots. The overall allocation information necessary for the downlink and uplink slots is thus splitted between the PSS and the RRM. As the the MCS information is pretty long, its transmission in the narrowband phase would require an extensive duration – which we avoid by placing this information in the RRM.

3.4 Information Flow

In Fig. 4 a simplified version of the link-setup process is shown as an example. In this example it is assumed that the CR-STA is already associated with the CR-BS. As in all cognitive systems, a rendezvous procedure is necessary to bring stations and base station together. It can be seen that four steps are necessary until the CR-STA can send UL data to CR-BS. This unfortunately adversely influences the throughput and increases the delay of the system when a fluctuating PU appears. Note that the step *Proceed RRMlength* is necessary because the PSS contains the length information of the RRM field.

3.5 Error Protection

For error control a modified Selective Repeat (SR) is proposed of the Automatic Repeat reQuest (ARQ) scheme. Every transmitted data frame is tagged with an individual sequence number. Every successful reception of a frame is acknowledged with an ACK containing the subsequent sequence number. In case the ACK was not received, the sender makes only a single retransmission attempt. The data from the retransmitted frame is enqueued at the front of the TxQueue. In case of multiple UL/DL bursts per CR-STA per superframe every burst is acknowledged individually.
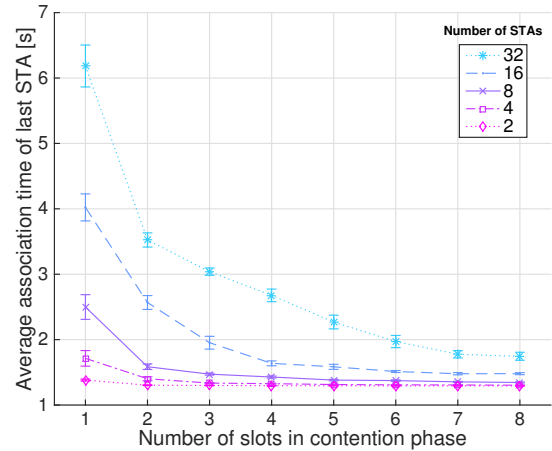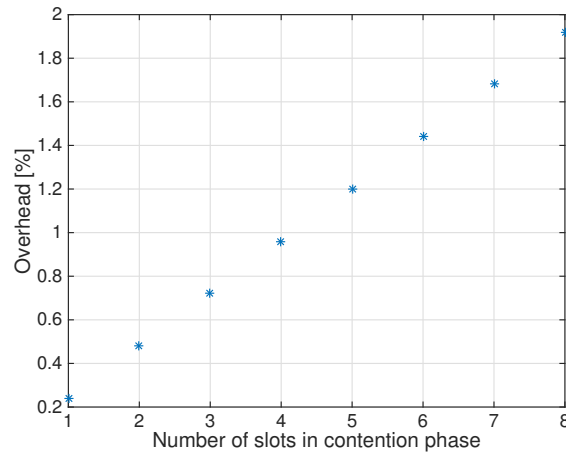
4 DESIGN CONSIDERATIONS

Following network model is assumed for the basic performance evaluation presented further-on: It is assumed that the whole spectrum is dedicated to licensed users, but there exists a database of available spectrum fragments for secondary usage in a given time interval over the given spacial area. The available spectrum might be strongly fragmented. Moreover, the allowance for secondary usage can be revoked on short notice. Every CR-BS has low latency access to the spectrum database, while the CR-STAs has no direct access to the database at all. To prevent disturbance of Primary Users, the CR-STA needs permission by the CR-BS to access the spectrum and remains a passive listener until a CR-BS is found. We will present now some design considerations which lead us to decision about system parametrization, and to evaluation of the performance limits.
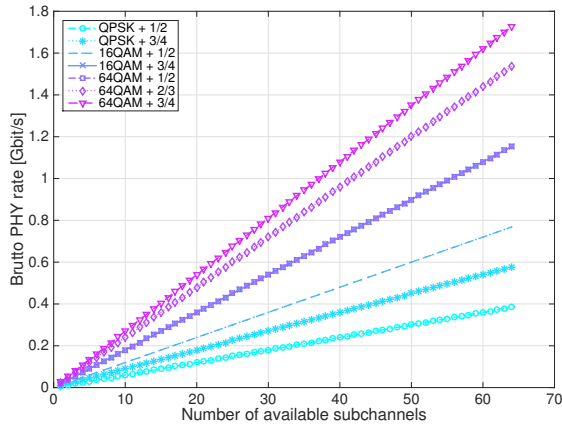
Figure 8: Brutto PHY throughput for different MCS level including puncturing in dependency to the number of available subchannels.
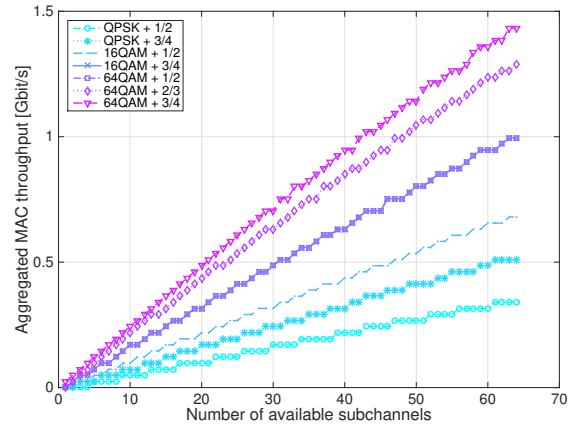

Figure 9: Aggregated MAC layer throughput between one CR-BS and one CR-STA for saturated traffic with 1500 Bytes per frame in dependency to the number of available subchannels.
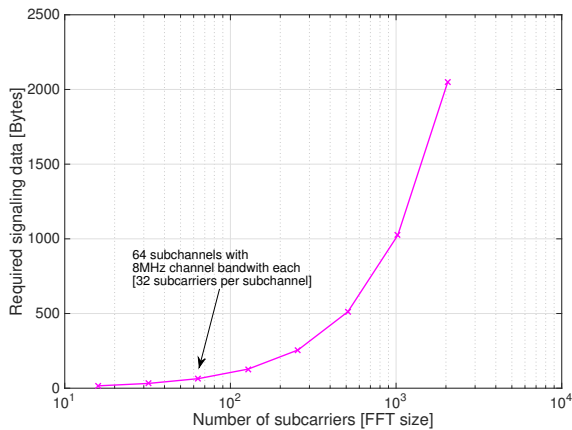

Figure 10: The signaling overhead depends strongly on the number of subchannels in use. The required signaling data for the MCS is 8 bit.

4.1 Radio Resource Map Size

The size of the Radio Resource Map (RRM) depends on the number of slots to be addressed in the data phase and on the number of subchannels which can be allocated. The RRM itself is always transmitted using the base MCS QPSK 1/2, where in the DL/UL phase adaptive MCS is used. Fig. 5 shows the number of necessary OFDM symbols the RRM needs to allocate in dependency of the number of available subchannels. With increasing MCS more slots can be added in the DL/UL part but need also be addressed in the RRM, therefore the size of the RRM increases. But apart from that, also the number of allocatable subchannels increase, which lowers the size of necessary OFDM symbols of the RRM.

4.2 Scanning Phase

After powering on each device (CR-BS and CR-STA) an initial scan for existing other CR-BSs has to be done. This phase takes always the same time. Every subchannel needs to be scanned for 20 ms to make sure that a given PSS will be observed. Therefore the initial scanning phase needs about 1.28 seconds (= 64 channels × 20 ms).

4.3 Association Phase

Association of new CR-STAs is done via the ALOHA contention slots shown in Fig. 3. The time, needed for the association process depends per cell on the number of contention slots and the number of CR-STAs. Therefore, we evaluated the number of contention slots to investigate the optimal number of slots in dependency of the introduced overhead. In Fig. 6 it can be seen that the average association time drops very fast with the number of contention slots. The four slots we have chosen for our system have an overhead of less than 1 % as depicted in Fig. 7.

4.4 Peak Rates

In Fig. 8 the maximum PHY rate depending on the number of available subchannels is shown. Under optimal conditions, which means 512 MHz are allocatable and a high SNR, which allows the maximal Modulation and Coding Scheme (MCS) of QAM-64 2/3, a PHY rate of up to 1.74 Gbps is achievable. Fig. 9 shows the aggregated MAC layer throughput for a connection between one CR-BS and one CR-STA. The maximum achievable throughput on the MAC layer is 1.433 Gbps. Therefore the MAC overhead is about 8 %.

4.5 Signaling Overhead as Function of Subchannel Width

As emphasized before the basic COUWBAT concept theoretically allows individual assignment of each subcarrier. This would, however create a huge overhead: For each subchannel the MCS needs to be transmitted during the signaling phase, otherwise the receiver is not able to decode the received information. Therefore it seems
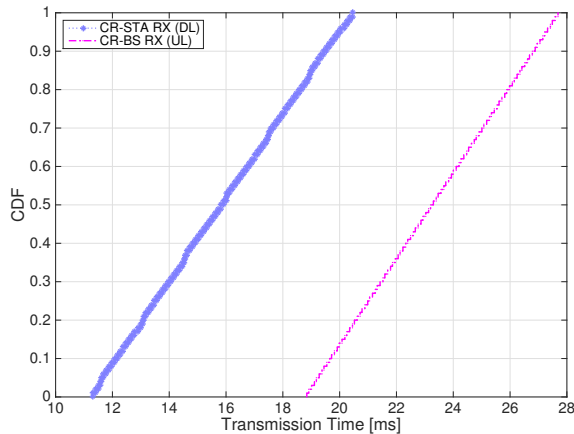
Figure 11: UDP end-to-end delay simulated with ns3.

Figure 12: Throughput of multiple STAs connected to one CR-BS in our ns3 model.

reasonable to group several subcarriers into a single subchannel assigned as whole. Btw. such grouping is also reasonable due to the necessity for guard bands between subcarriers assigned to different users. In Fig. 10 the signalling overhead necessary for different subchannel sizes is presented. We have chosen 8 MHz by clustering 32 subcarriers in one subchannel. The signaling overhead is in this case 64 Bytes.

5 PERFORMANCE EVALUATION

COUWBAT performance is, obviously, dependent on many operation conditions. To allow for a first insight into the achievable performance we have assumed some sample configurations and scenarios. We assume that within each cell CR-STAs are placed randomly or fixed according to the scenario. All devices are fixed at their certain locations, whereas the high of the CR-BS is assumed to be 30 m and the high of a CR-STA is 6 m because stations are assumed to be placed on lampposts. CR-BS and their related CR-STAs are in Line-Of-Sight (LOS), as well as in obstructed LOS. Each CR-BS forms a cell with a radius of up to 300 m. For the sake of performance studies we have used the widely applied ns3 simulation environment [10].

To model the propagation we have used the well known Okumura path loss model, configured for small city and urban environment. The transmit power of the CR-BS and the CR-STAs are set to 17 dBm low-power comparable to WLAN, whereas antenna gains are set to 0 dBm. To provide fading, the Okumura path loss model is combined with the Nakagami fading model. All former parameters are set per subchannel, which ensures the frequency dependency of the wideband system was considered accordingly.

Interference in the simulator is modeled by collecting all overlap of packets during a packet transmission and calculating the likelihood of the PER per chunk per packet. The integration of our COUWBAT protocol into ns3 can be downloaded from [3]. In this section the results taken from our proposed system modeled in ns3 are shown.
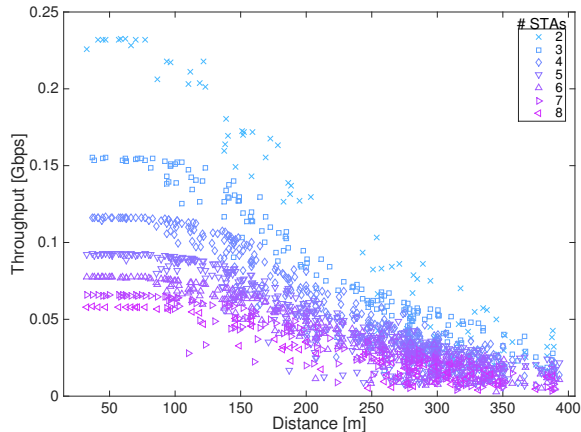
5.1 Performance Parameters – E2E Delay and Throughput

In Fig. 11 the CDF of the end-to-end (E2E) delay of an UDP packet flow is depicted. The delay is fix for each individual packet and depends strongly on the time when the packet was prepared and taken into the data queue. As already stated by Fig. 4 packets which arrive late have a smaller delay than packets which are scheduled earlier in the super frame.

Fig. 12 shows the estimated throughput of multiple CR-STAs connected to one CR-BS in dependency of the distance between sender and receiver. It can be observed that all stations share the channel in a fair and equal manner.

5.2 Instantaneous Impact of Different Primary User Behavior on COUWBAT Transmissions

In this paragraph we investigate the throughput of our intended backhaul system, because it is highly depended from the PU behavior. In Fig. 13 three different evaluations are shown. First, the base line (*No PU*) shows the maximum throughput achievable without the influence of any Primary User. Second, *Toggle PU* demonstrates the impact of an 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 third evaluation *Skopje Trace PU* is using a real PU source taken from the measurement campaign in [11]. The trace file itself is depicted in Fig. 14. 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. Downlink means transmissions from CR-BS to the corresponding CR-STA and uplink vice versa. Downlink and uplink are split 80 % to 20 %.

Please note that Fig. 14 has been computed using different frequencies! This has been done on purpose, as we wanted to use the worst condition. While for the SNR this means the pathloss is higher in higher frequencies the PU behavior exist. Analysis indicates that PUs with a higher fluctuation are to be expected mainly in the frequencies in the below 1 GHz (compare [17]).
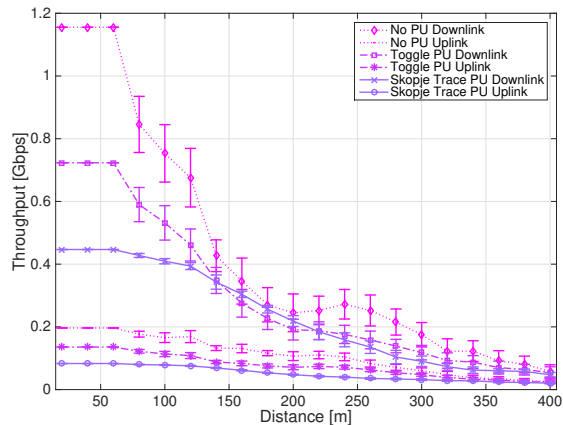
Figure 13: Aggregated MAC throughput between one CR-BS and one CR-STA for saturated traffic with 1500 Bytes per frame in dependency to the number of available subchannels.
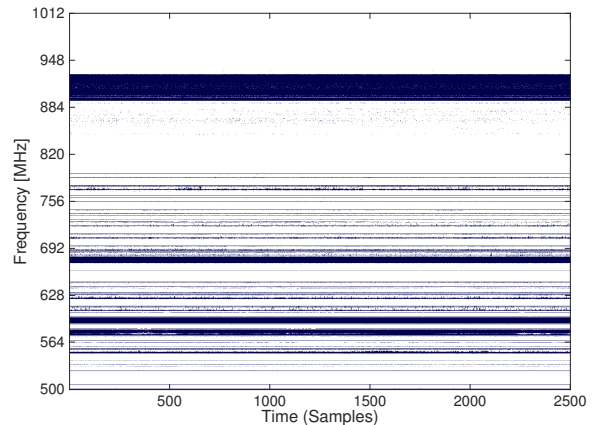

Figure 14: Sampled Primary User trace from a measurement campaign in Skopje [11] used in Fig. 13 to evaluate our protocol in terms of realistic spectrum changes. Originally the trace lasts four hours from 4pm until 8pm.

6 CONCLUSIONS

In this paper we have proposed COUWBAT the COgnitive Ultra-Wide BAckhaul Transmission system, which describes a new approach to backhauling. By the use of frequency bands which were "not available", because they are licensed to certain Primary Users (PU), we can gain bitrates of more than 1 Gbps, while ensuring that the original PUs are not disturbed. To provide continuously these high bitrates, the envisioned system operates in a very wide frequency range of larger than 500 MHz to ensuring that always enough unused spectrum can be found. Further we proposed a MAC protocol with a control signaling over inband control channels. The envisioned system was evaluated exhaustively analytically and via simulation in the well known network simulator ns3, were the source of our ns3 integration is available to the public under http://github.com/couwbat/couwbatns3.

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