# Coexistence Study of Different Medium Access Mechanisms Using a Software Defined Radio Testbed

## Alexander Pastor

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**Examiners**

Prof. Dr. Petri Mähönen
Prof. Dr.-Ing. Marina Petrova

**Supervisors**

Prof. Dr. Petri Mähönen
Peng Wang, M.Sc.
Andra Voicu, M.Sc.

Institute for Networked Systems
RWTH Aachen University

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presented by
Alexander Pastor

Prof. Dr. Petri Mähönen
Prof. Dr.-Ing. Marina Petrova

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(Alexander Pastor)

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We thank. . .

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# ABSTRACT

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## INTRODUCTION

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# BACKGROUND

In this chapter the theoretical foundations for the succeeding work are treated. Firstly, the Medium Access Control (MAC) layer is introduced in the context of the OSI reference model. Successively, a glance on a number of different MAC protocols and mechanisms is taken, while discussing performance with respect to the challenges and goals in wireless transmission. The chapter concludes with describing the advantages of software-defined radio (SDR) and how GNU (GNU is not Unix) Radio can be used to support SDR.

## 2.1 MAC PROTOCOLS

### 2.1.1 MAC Layer in the OSI Model

The OSI (Open Systems Interconnection) model is a layered architecture that divides a telecommunication system into several manageable layers. It features seven layers, where the second layer - the Data Link Layer (DLL) - can be split into two sublayers. The focus of this thesis lies on the lower sublayer, which is MAC. The upper sublayer is Logical Link Control (LLC). Table 2.1 gives a short overview of the layers' responsibilities.

**MAC Responsibilities** These are some placeholder words for the actual content.

### 2.1.2 Challenges for Wireless MAC Protocols

Wireless MAC protocols have to tackle a few problems that do not occur in wired data exchange. Among them are the hidden node and the exposed node problem, which will be discussed by reference to Figure 2.1. Further challenges, such as energy limitations will also be delineated.

#### 2.1.2.1 The Hidden Node and the Exposed Node Problem

Suppose that the radio range of the nodes in 2.1 is limited to the neighboring nodes and $A$ would like to transmit to $B$. If $C$ just started transmitting $A$ does not hear $C$ and falsely assume that the channel is idle and start transmitting, which leads to a collision. This is the hidden node problem.

For the same configuration, in another scenario $B$ would like to send to $A$ and $C$ is already transmitting to $D$. $B$ refrains from sending although collisions would only take place between $B$ and $C$, where it does not matter as both $B$ and $C$ are transmitters. This is the exposed node problem.
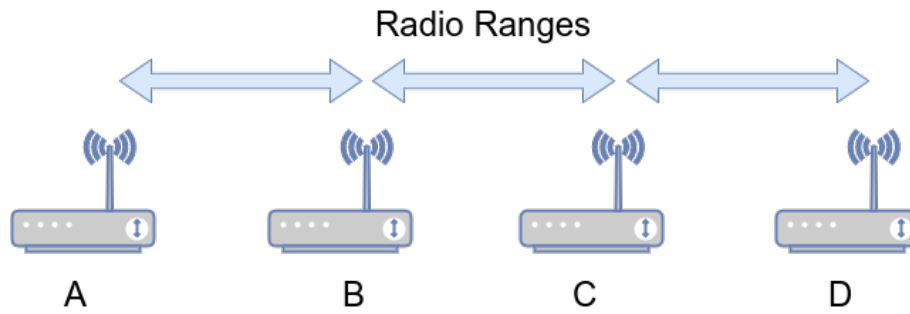
FIGURE 2.1: Setup to explain the hidden and exposed node problem. Each node can only reach its direct neighbors.

### 2.1.2.2 Power Problems

Further challenges when designing MAC protocols include the power conservation when faced with constrained power resources, as e.g. in wireless sensor networks (WSN) where devices rely on batteries for their power supply. Attempts to reduce energy consumption have been made in several specialized, duty-cycle based MAC protocols for WSN such as Sensor MAC, Timeout MAC and Berkeley MAC as in more detail shown in Section 2.1.6.

As a consequence of the constrained energy resources, WSN are especially susceptible to denial of sleep attacks, a special form of denial of service (DoS) attack, drastically increasing energy consumption and thus reducing the system lifetime.

| Level | Layer | Responsibilities |
|---|---|---|
| 1 | Physical Layer | dealing with mechanical, electrical and timing interfaces of data transmission |
| 2 | DLL: MAC Sublayer | controlling medium access and frame synchronization |
| 2 | DLL: LLC Sublayer | multiplexing to enable different network protocols coexist, flow control and error control |
| 3 | Network Layer | routing and congestion control |
| 4 | Transport Layer | transmission reliability, same-order-delivery, congestion avoidance |
| 5 | Session Layer | token management, dialog control, synchronization |
| 6 | Presentation Layer | abstracting syntax and semantics of transmission, encryption |
| 7 | Application Layer | user application protocols, such as http, ftp, smtp and many more |

TABLE 2.1: Layers in the OSI model
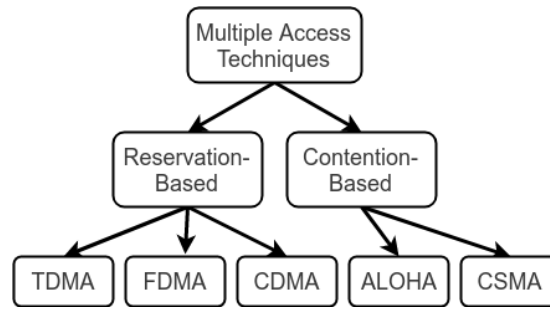
FIGURE 2.2: Classification of MAC techniques

It is due to this fact that security is paramount in biomedical or military fields of application [4].

### 2.1.3 Classification of MAC Protocols

Traditional MAC protocols can be classified into one of two groups: reservation-based and contention-based as depicted in Figure 2.2 [1]. The difference between them is that in reservation-based protocols a coordinator prevents collisions by assigning physical resources to devices, whereas in contention-based protocols no such infrastructure exists and nodes have to contend for channel utilization, hence the name. Another technique independent from these categories is to employ duty cycles (DC), where nodes continuously alternate between active and inactive periods. According to [2] the appropriate choice of MAC protocol depends on a plethora of design-drivers such as requirements concerning throughput, latency, energy consumption and traffic patterns.

We will proceed with discussing representative protocols of the two categories. Thereafter, we will take a look at a few protocols that use DC mechanism.

### 2.1.4 Reservation-Based MAC Protocols

Reservation-based protocols may implement an array of desirable features, but require knowledge of network topology in order to allow each node to communicate with every other on the basis of a centrally coordinated schedule. These features include reduced collisions, fairness among nodes or multiple transmissions at the same time. Owing to the fact that we do not incorporate reservation-based protocols in our experiments we will only briefly describe the basic principles of the time-division multiple access (TDMA), frequency-division multiple access (FDMA) and code-division multiple access (CDMA).

TDMA is a representative protocol in this group, which divides time into slots. Each node is assigned to a unique slot during which it may transmit. As a result we obtain collision-free transmission, predictable scheduling delays, high throughput in heavy load situations and fairness among nodes. However, both the knowledge of topology and tight synchronization require large overheads or expensive hardware [2].

FDMA (FDMA) divides a frequency band into a number of channels. One or more may be assigned to each node. Receivers use bandpass filters to obtain the transmitted signal.

CDMA is a digital spread-spectrum technique where multiple transmitters share the same frequency band and transmissions may occur at the same time. In this method transmitted signals are combined (XORed) with special [1] sequences making the transmitted signal's frequency vary in order to avoid interference. The receiver has to follow along this variation of frequency (that is to say know the spreading code) when decoding to retrieve the original data signal, resulting in increasing security as a side effect.

It is also possible to combine several of these techniques. Making use of this, the base station (eNB) of LTE in the licensed band coordinates traffic by assigning physical resource blocks (PRB) to devices. A PRB is a combination of a frequency and a time slot based on the reservation techniques of orthogonal FDMA (OFDMA) and TDMA.

### 2.1.5 Contention-Based MAC Protocols

#### 2.1.5.1 ALOHA

ALOHA is arguably the most simple MAC protocol. Whenever a user wants to send data he just does so. The higher the channel load, i.e. transmissions per time unit, the more likely collisions will occur, which render all transmitted information useless.

The question is how likely it is that a collision does not occur. In other words, how efficient is an ALOHA channel? Making a statement requires a few preliminary assumptions as shown in [3]:

1. We simplify the calculation by assuming a fixed frame length.

2. The number of packets generated during a frame time is a Poisson-distributed random variable $X$.

3. The channel load $G$ comprises of two portions: "new" and retransmitted frames.

The probability mass function of the Poisson distribution and thus the probability of $k$ frames being generated during a given frame time amounts to:

$$Pr(X = k) = \frac{G^k \cdot e^{-G}}{k!} \tag{2.1}$$

The probability of zero frames being generated during the transmission of the frame is $Pr(X = 0) = e^{-G}$ (assumption 3). If no collision occurs during the transmission of frame $F$, no other frame was sent during that transmission. Conversely, $F$ itself did not collide with a frame sent off prior to $F$. We conclude that the vulnerability period during which collisions may corrupt data is two frame times (assumption 2).

The probability that no frame other than the frame to be transmitted is generated during the two-frame-time vulnerability period is $P_0 = e^{-2G}$. The throughput $S$ is given by $S = GP_0 = Ge^{-2G}$.

---

[1]by special we mean that the signal has certain properties such as orthogonality and in some cases pseudo-randomness

The maximum throughput is achieved when $\frac{\partial S}{\partial G} \stackrel{!}{=} 0$:

$$\frac{\partial S}{\partial G} \quad = \frac{\partial}{\partial G} G e^{-2G} \tag{2.2}$$

$$= e^{-2G}(1 - 2G) \tag{2.3}$$

$$\stackrel{!}{=} 0 \tag{2.4}$$

$$\Leftrightarrow \quad G \quad = 0.5 \tag{2.5}$$

This means that for $G = 0.5$ the throughput S reaches its maximum $S_{\text{ALOHA,max}} = \frac{1}{2e} \approx 0.18$. This result is very reasonable, since the transmission of a frame is vulnerable for the duration of two frame times, so the maximum is achieved when sending exactly every second slot, where a slot is equivalent to the frame time.

We note that, the throughput can be doubled with slotted ALOHA. In contrast to pure ALOHA, slotted ALOHA divides time into slots, where transmissions are may only commence at the beginning of slots, which effectively halves the vulnerability period to only one slot, since frames transmitted prior to a frame $F$ cannot interfere with $F$ anymore. Thus, $S_{\text{ALOHA,max}} = \frac{1}{e} \approx 0.36$, reached at $G = 1$. However, this comes at the cost of an additional frame delay of $t_{\text{slot}}$ in the worst case and $\frac{t_{\text{slot}}}{2}$ in the average case and the need for synchronization.

As shown in Figure 2.3, ALOHA's performance is discouraging and improvements over ALOHA were found.

### 2.1.5.2   CSMA

Main problem of ALOHA is the negligence of concurrent traffic in the channel. A solution to this problem is offered by "listen before talk" (LBT) mechanisms, which means in order to avoid collisions we make a clear channel assessment (CCA) and refrain from sending should it be busy. This is the simple, yet effective basic idea of carrier sensing multiple access (CSMA) which comes in three flavors, i.e. 1-persistent CSMA, non-persistent CSMA and p-persistent CSMA as depicted in Figure 2.4 which will be discussed next.

**1-Persistent CSMA**   If the channel is busy, 1-persistent CSMA waits until the channel becomes idle. As soon as the channel is found idle a frame is transmitted with a probability of 1, hence 1-persistent CSMA. If the frame collides with another, the node waits for a random backoff time and then the whole process is started all over again.

Despite being a substantial improvement over ALOHA, this protocol has at least two problems [3]:

- Provided propagation delay is zero or negligible, collisions can still occur. Imagine a three-node-scenario with nodes $A$, $B$ and $C$. $A$ is transmitting, while $B$ and $C$ are waiting for their turn. Once $A$ finished transmission $B$ and $C$ will simultaneously start their transmissions leading to collision.

- If propagation delay is not negligible the protocol suffers from an additional problem. In another scenario $A$ has just begun sending. $B$ will assume the
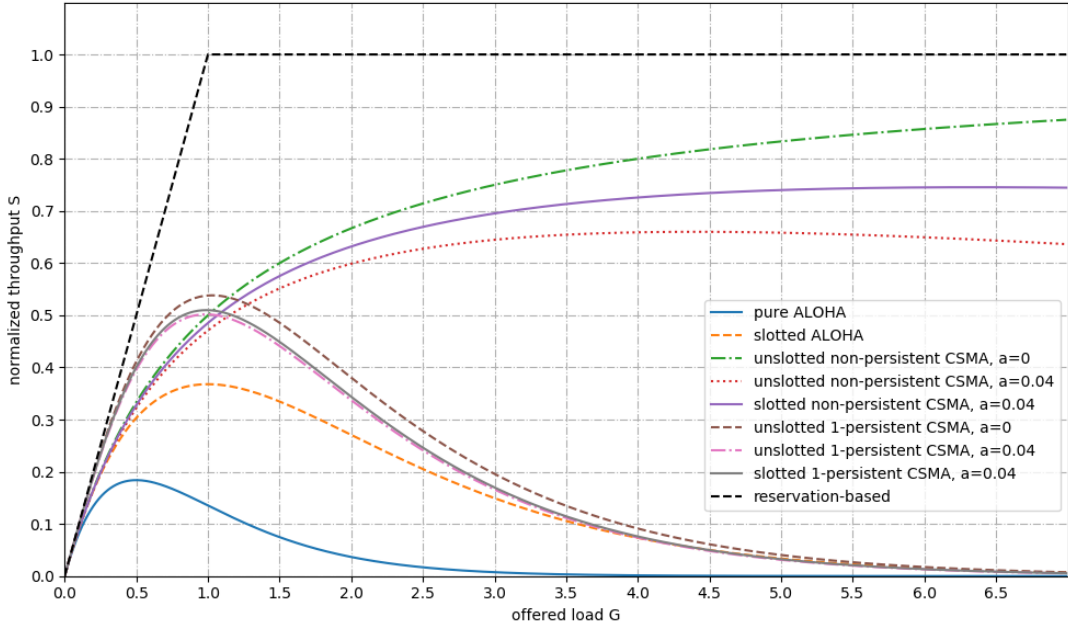
FIGURE 2.3: Normalized throughput over offered load according to formulae in [1], [2], [3], with $a = \tau/T_p$, where $\tau$ is the maximum propagation delay and $T_p$ the packet transmission time and under the assumptions made in Section 2.1.5.1.

channel is idle and send off his frame, since, due to the propagation delay, $B$ has not yet heard of $A$. This is why propagation delay may significantly hamper the performance of this protocol.

**Non-Persistent CSMA** In order to alleviate 1-persistent CSMA's problem with several nodes trying to seize the channel as soon as it becomes idle, a less greedy attempt is made with non-persistent CSMA. Instead of continuously sensing the channel until it becomes idle, the nodes wait a random backoff time until they listen again. As a result, this protocol leads to better channel utilization with the downside of higher delays.

**P-Persistent CSMA** P-persitent CSMA is a protocol for slotted channels. Whenever a node $A$ wishes to send a packet, the channel is sensed. If the channel is found idle the node transmits its packet with a probability of $p$. With a probability $1 - p$ the node defers its transmission to the next slot. This process is repeated until either the packet is sent or the channel is found busy again. In the latter case $A$ acts as though a collision had taken place and waits a random time until starting again [3].

This flavor of CSMA can be regarded as a compromise between 1-persistent CSMA and non-persistent CSMA, where the choice of $p$ determines the greediness. The smaller $p$, the less greedy and thus the closer p-persistent CSMA approximates non-persistent behavior. An appropriate choice of $p$ can get the best out of both mecha-

(a) 1-persitent CSMA        (b) non-persistent CSMA        (c) p-persistent CSMA
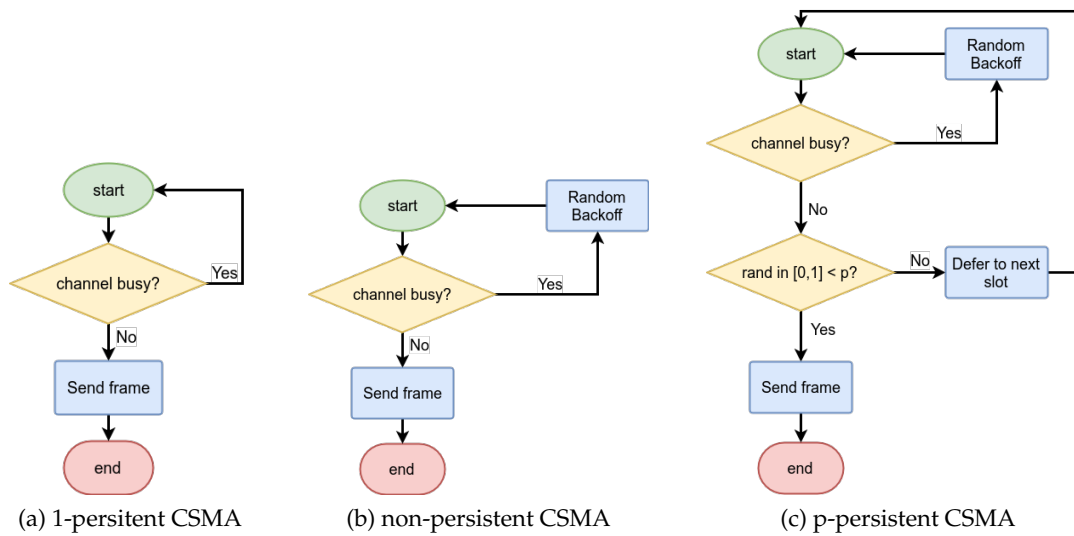
FIGURE 2.4: The three basic flavors of CSMA

nisms: minimal delays as in 1-persistent CSMA, as well as high channel efficiency as in non-persistent CSMA.

### 2.1.5.3 CSMA with Collision Detection

A way to further improve the CSMA protocols is to immediately cancel transmissions once a collision is detected. There is no point in continuing these transmissions, as the transmitted data is lost in any case and aborting the transmission saves bandwidth, time and energy.

CSMA with Collision Detection (CSMA/CD) is used on wired LANs and serves as basis of the wide-spread Ethernet. However, this mechanism is not extensively made use of in wireless networks. Concerning the reason, it is cardinal to understand that collision detection is an analog process. A collision is detected by comparing the received and transmitted energy or pulse width of the signal, which premises transmission and reception taking place simultaneously. This condition is seldom met for wireless nodes, which are mostly half-duplex. The reason for this lies in the conservation of energy, since wireless signals spread in all directions around their origin and thus degrade exponentially with the distance. Furthermore, wireless channels are typically much more noisy than their wired counterparts and suffer from multipath fading. To make up for the loss in signal strength we would have to employ expensive signal processing in order to recover fainter signals. Alternatively, we could increase the transmit power, but this increases interference with other nodes, as well as energy consumption.

### 2.1.5.4 CSMA with Collision Avoidance

IEEE 802.11 is a set of physical layer (PHY) and MAC specifications for wireless local area networks (WLANs). When the dominant mode of operation, the so-called
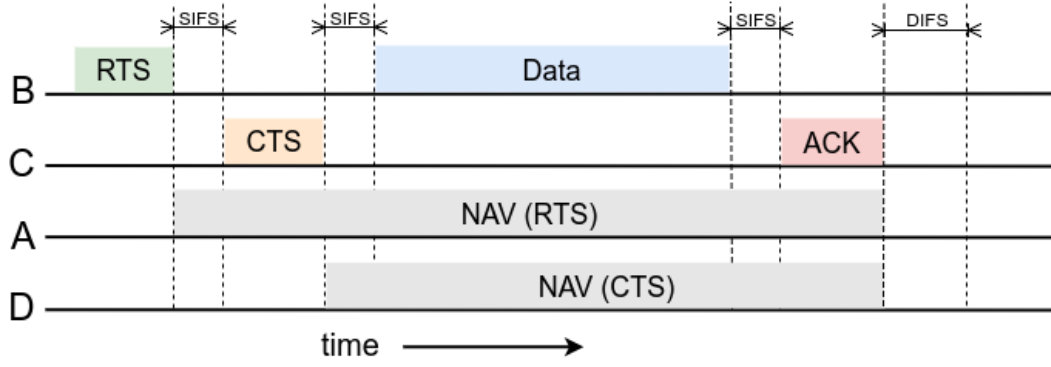
FIGURE 2.5: Virtual carrier sensing in CSMA/CA, as described in [3] and [5]

distributed coordination function (DCF) is employed CSMA/CA is used in the MAC layer, which we will discuss next.

As depicted in Figure 2.5 there are specific intervals of given length between each of the frames. Varying lengths of these interval types serve the purpose of prioritizing certain frames over others.

The short interframe spacing (SIFS) is the interval until the next control frame or next fragment (of a fragmented data frame) may be sent. SIFS is designed to allow one node out of the two nodes in dialog to have a higher priority to access the channel than uninvolved nodes. The longer interval DCF interframe spacing (DIFS) is the interval after which any station may try to seize the channel for their transmission.

For the sake of completeness, we briefly mention two further intervals used in IEEE 802.11, namely point coordination function interframe spacing (PIFS) and extended interframe spacing (EIFS). If IEEE 802.11 is operates in an alternative mode of operation, where a node acts as point coordinator of traffic the standard prescribes an interval of length PIFS to allow the controlling node to send certain control (beacon and poll) frames. EIFS is used to report the reception of a bad or unknown frame and due to the low priority of this action is the longest interval among the mentioned four.

Physical carrier sensing takes place in these intervals. If a node wants to transmit a packet and the channel is sensed busy in one of these intervals then the node defers its transmission and launches the binary exponential backoff (BEB) procedure [5]. With BEB a node picks a slot in the so-called contention window (CW). This slot is just a random integer and the contention window is a range lower-bounded by zero and upper-bounded by $2^{n+m} - 1$, where $m$ is a fixed integer, $2^m$ called minimum CW ($CW_{\min}$) and $n = 0$ for the moment. After picking the slot the node waits for $t_w =$ #slot $\cdot t_s + t_i$, where #slot is the number of the slot, $t_s$ a constant called backoff slot duration or simply backoff slot and $t_i$ the appropriate of the four intervals SIFS, PIFS, DIFS and EIFS. After $t_w$ has elapsed the channel is sensed again. In the case it is sensed busy again the whole BEB procedure is repeated with $n$ incremented, thus the CW doubled, hence **binary** exponential backoff. The motivation for $CW_{\min}$ is to reduce the chance that two contending nodes pick the same slot in the first round of BEB.

Beside physical carrier sensing, another mechanism, namely virtual carrier sensing using RTS/CTS exchange is optionally employed to mitigate the problems caused by

hidden nodes. In order to explain these mechanisms we refer to the setup of Figure 2.1. Figure 2.5 visualizes the chain of events whose explanation follows.

$B$ wants to send to $C$, hence issues a request to send (RTS). Every node receiving the RTS remains silent, except for $C$ that in response to the RTS creates a clear to send (CTS) frame. Not only $B$ receives this CTS frame, but also $D$, a hidden node from $B$'s point of view. Upon reception of CTS $D$ is silenced as well. Therefore, RTS/CTS is addressing the hidden node problem. RTS/CTS are frames of 30 bytes length containing the length of the frame that, in this case, $B$ wants to transmit. Based on this length, $A$ and $D$ setup the so-called network allocation vector (NAV), which are node-internal timers reminding $A$ and $D$ that the channel is still in use. This mechanism is called virtual carrier sensing due to the fact that the nodes defer their transmission based on the information received through other frames.

### 2.1.5.5   LAA

One principal approaches to ensure harmonious coexistence of LTE and WiFi in the unlicensed band is LAA, relying on LBT. Since the LBT mechanism of LAA largely resembles CSMA/CA it seems quite natural to assume it will coexist better with WiFi [8]. The other one is LTE-U which uses DCs and is discussed in Section 2.1.7.

### 2.1.6   Duty-Cycle MAC Protocols

In duty-cycle MAC schemes nodes repeatedly alternate between active and inactive phases. In some protocols, especially in those designed for WSNs, nodes may sleep when inactive to reduce idle listening and thus energy consumption. Due to increased contention during active phases these protocols are mostly designed for limited contention traffic situations as in WSNs. The fraction of an active period in a cycle is called duty factor. Sources to this Section were [2] and [6].

### 2.1.7   LTE-U

LTE-U uses Carrier Sense Adaptive Transmission (CSAT), which tries to avoid primary channels of WiFi transmissions and other LTE-U operators. If that is not possible, duty-cycles are dynamically adapted depending on WiFi medium utilization (MU). If MU is below a certain threshold the DC is increased. If it is between that threshold and a higher one, the DC is kept constant, otherwise it is decreased [9].

### 2.1.7.1   Sensor MAC

In SMAC the active period is divided into to a synchronization and a data transmission phase. During sync phase nodes transmit SYNC packets. Nodes receiving SYNC packets adopt the schedule carried by the packet and broadcast into their neighborhood. Nodes that follow the same schedule form a virtual cluster. Borderline nodes between virtual clusters adopt multiple schedules and thus have an increased duty factor. During contention period SMAC features the RTS/CTS exchange and fragments data frames, which are transmitted in a burst to reduce collision likelihood. The duty factor per schedule is predetermined on the basis of expected load as the result of an optimization problem on the competing goals of reducing idle listening and

contention. The higher the duty factor the more idle-listening and the less contention occurs.

### 2.1.7.2 Timeout MAC

While TMAC shares the same principle of schedule establishment with SMAC nodes adaptively vary duty factors depending on expected traffic. Furthermore, TMAC shifts all communication to the beginning of the active period. This allows nodes to sleep earlier should no traffic be detected during a certain time period. In variable load situations TMAC saves as much as five times more energy compared to SMAC at the cost of increased latency.

### 2.1.7.3 Berekeley MAC

Still, TMAC maintains common active phases at high energy expenses. BMAC drops the requirement of maintaining common active phases. Instead payload is preceded by extended preambles such that every receiver is able to reliably detect packets. This has the effect of shifting energy expenses from the receiving to the sending side, which saves energy in low load applications such as surveillance. In BMAC CCA is based on outlier detection, instead of thresholding like in CSMA further reducing energy use [7].

## 2.2 SOFTWARE-DEFINED RADIO

### 2.2.1 Purpose of Software-Defined Radio

Traditional radio equipment is "hardware-defined", i.e. that the signal processing runs on a specialized electrical circuit. This has the potential advantages of efficient energy use and cheap production at the cost of limited flexibility in operation.

In SDR signal processing components such as filters, amplifiers, modulators, detectors and many more are implemented in software and mostly run on general-purpose processors, sometimes in combination with digital speech processors (DSPs) and field programmable gate arrays (FPGAs).

While the limitations of hardware-defined radios are acceptable for a number of applications, such as e.g. self-made radio receivers as shown in Figure 2.6, it is very desirable to get rid of these limitations for rapid prototyping of new technologies including but not limited to cognitive radio, software-defined antennas and wireless mesh networks. In the case of this thesis SDR simplifies studying the influence of different MAC mechanisms.

### 2.2.2 What is GNU Radio?

The GNU Radio (GR) project is dedicated to the evolution of a free and open-source software development kit (SDK) enabling both the creation of actual software-defined radio, as well as simulated signal processing. Written in C++ and Python, GNU Radio also comes with the intuitive graphical software GNU Radio Companion (GRC) that allows creating block diagrams called flowgraphs simply by connecting signal
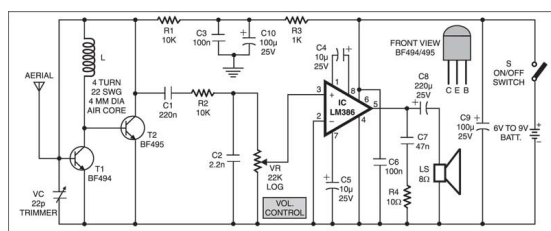
(a) FM Receiver
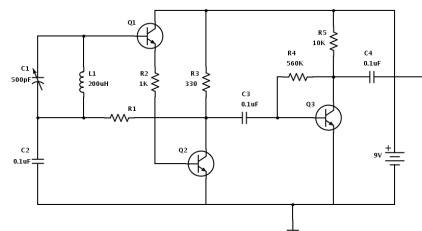
(b) AM Receiver

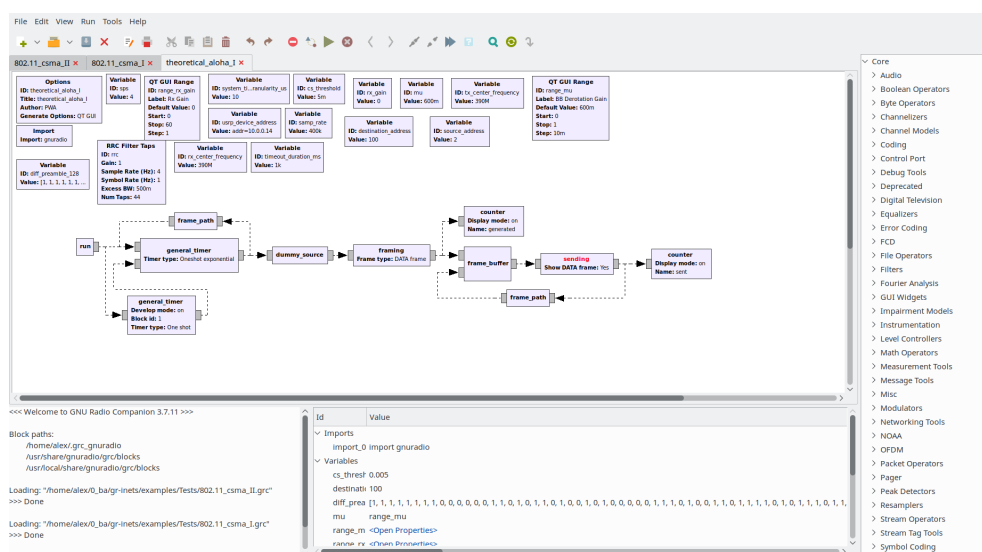FIGURE 2.6: Simple do-it-yourself (DIY) radio receiver circuit diagrams



FIGURE 2.7: GNU Radio Companion GUI

processing blocks into a directed graph. Its target user market is not merely limited to research and industry, but also encompasses academia, government and private users.

A proprietary, well-documented alternative to GNU Radio is LabVIEW developed by National Instruments. LabVIEW takes a purely graphical approach similar to GRC relying on block diagrams, but lacks the freedom of user-defined block creation with a programming language such as C++ or Python.

Mathworks MATLAB/Simulink also provides a communication systems toolbox. However, the devices we used are not on the list of officially supported devices [10].

### 2.2.3   Core Concepts of GNU Radio

#### 2.2.3.1   Flowcharts and Blocks

The two most basic concepts of GNU Radio are flowgraphs and blocks. As mentioned in 2.2.2 flowgraphs are directed graphs, whose nodes are functional blocks and whose vertices determine the direction of data flow [11].

The behavior of these blocks is programmed in either Python or C++, where the latter is recommended for performance-critical applications, which is also why the blocks in our flowgraphs are all written in C++. If performance is less critical Python is a superior choice since it is more concise and allows faster prototyping as there is no need for compilation. Each block generally serves exactly one purpose for the sake of modularity. Blocks in turn can be composed of an arbitrary number of inner blocks, making extensive use of the modularity and hiding implementation complexity from the user, much like a blackbox in electrical circuits. These composed blocks are called hierarchical blocks. In our case the complete PHY layer is hidden in hierarchical blocks called "sending" and "receiving".

Blocks are connected through ports, which can either be input or output ports. Depending on which types of ports a block has, it can either be a source, sink or neither of the former. Each input port only consumes data of a specific data type. Similarly, each output port only produces data of a specific data type. The set of types ranges from integers, floating point and complex numbers to messages and a bunch of others. Since each block implements a certain function these ports can be regarded as input parameters and return values of a function, respectively.

#### 2.2.3.2   Message Passing and Stream Tags

When designing packet-based protocols, such as MAC protocols it is of tremendous importance to be able to detect packet data unit (PDU) boundaries. For this purpose GR provides an asynchronous message passing system. A synchronous alternative is to attach so-called stream tags to the "infinite" stream of data. The former method is the right choice when designing MAC protocols due to the asynchronous nature of packet delivery [11] [12].

#### 2.2.3.3   Polymorphic Types and SWIG

Polymorphic types (PMT) are opaque data types that enable safe information exchange across blocks by serving as generic containers of data. Self-evidently, the original data type must be retained as a PMT class member. For thread-safety reasons PMT are immutable. We make extensive use of PMTs when passing messages. As an aside, note that the python PMT class has some powerful tools unavailable its C++ counterpart, making use of Python's weak typing [12].

Simplified wrapper and interface generator (SWIG) is a software that helps to connect code written in C or C++ to a variety of scripting languages, such as in our case Python. This is achieved by generating a Python module from the C/C++ code with the help of an interface file. This "compatibility layer" is necessary, because blocks can be written in either Python or C++ as mentioned earlier.

# 3

# RELATED WORK

## 3.1 COEXISTENCE STUDY BY GOMEZ-MIGUELEZ ET AL.

Gomez-Miguelez et al. propose srsLTE, an open-source SDR library for the PHY layer of LTE release 8 [13]. In contrast to many earlier simulation-based studies they have actually set up physical devices, better reflecting system level details of both technologies and providing insight for real-world deployments [14] [15] [16] [17] . Their testbed comprises of several WiFi and LTE links, for which they used Ettus USRP B210 boards (LTE) and low-power single-board computers from Soekris (WiFi). In order to detect vendor-specific performance issues they decided to use two different sets of wireless NICs from Atheros and Broadcomm.

In their study the influence of the following parameters was examined: LTE-U duty cycle, WiFi and LTE TX power, LTE bandwidth, LTE central frequency (i.e. LTE and WiFi spectrum overlap).

Their main results can be summarized as follows:

- WiFi throughput is inversely proportional to LTE duty cycle.

- WiFi TX power has little impact on WiFi throughput.

- The influence of LTE bandwidth and central frequency on WiFi throughput depends very much on the vendor of the NIC card. As a result, more experimental research with physical devices from different vendors is strongly recommended.

## 3.2 COEXISTENCE STUDY BY CAPRETTI ET AL.

Another empirical study [18] conducted by Capretti et al. also evaluates LTE Unlicensed/WiFi coexistence based on LTE-U. Their testbed consists of one eNB and one UE, one WiFi access point and five WiFi nodes. Their WiFi network was based on embedded PCs equipped with commodity wireless adapters. The LTE nodes were based on desktop computers with Ettus USRP B210 RF front ends running the open-source driver UHD. The software used includes srsLTE to build up a LTE release 8 compliant LTE stack, as well as GNU Radio.

The following parameters were subject of interest: duty cycle, WiFi power settings WiFi MCS (modulation and coding scheme) and packet size. The metrics measured were satisfied load in percent, total WiFi throughput, WiFi jitter and LTE packet loss.

Their main findings can be summarized as follows:

- The duty cycle patterns are a main influence on achievable WiFi throughput. Particularly, shorter duty cycles decrease jitter, which is important for real-time

applications. On the other hand longer duty cycles offer superior throughput due to reduced overhead.

- LTE suppresses WiFi transmissions if the TX power levels are comparable and no duty cycling is employed.

- If WiFi TX power is increased, WiFi load negatively impacts LTE throughput.

- There is no panacea strategy ensuring maximum WiFi throughput operating under different MCSs and packet sizes.

- LTE performance is unaffected by WiFi contention levels.

## 3.3   CONNECTION TO OUR WORK

Both studies aim at understanding under which circumstances duty-cycle-based LTE-U can coexist with WiFi in the unlicensed band by conducting experimental research with SDR (USRP) LTE and commodity WiFi devices.

We, too, carry out experimental research and use USRPs to understand the influence of parameters used in CSMA/CA in a setup with two links each either employing ALOHA or a CSMA/CA on the overall performance. While the studies focus on the variation of power and bandwidth parameters of the transmission, we put emphasis on timing aspects.

# 4

# MEASUREMENT METHODOLOGY

This chapter is dedicated to answering the questions of what was measured and how results were obtained. Firstly, the measurement setup is discussed. Secondly, the GNU Radio flowgraphs are explained. Subsequently, with reference to the flowgraphs measurement metrics are formally defined in view of the necessity to verify the recorded data. Lastly, an overview of the semi-automatic measurement script system designed to automate, therefore accelerate the process of file system management, data processing and result plotting is given.

## 4.1 MEASUREMENT SETUP

The setup consists of two USRP2s from Ettus Research and two USRP 2920s from National Instruments. The former pair is programmed as receiver and sniffer, whereas the latter as senders as depicted in 4.1. Each USRP was connected to a gigabit switch through a LAN cabel. The scripts running on the devices were launched from the institute's computer with the IP 134.130.223.151, which was remote controlled from my private laptop. Hereafter, we will call the node pair 10.0.0.9-10.0.0.6 link 1 and 10.0.0.3-10.0.0.6 link 2. Table 4.1 contains other necessary information to reproduce the measurement results.
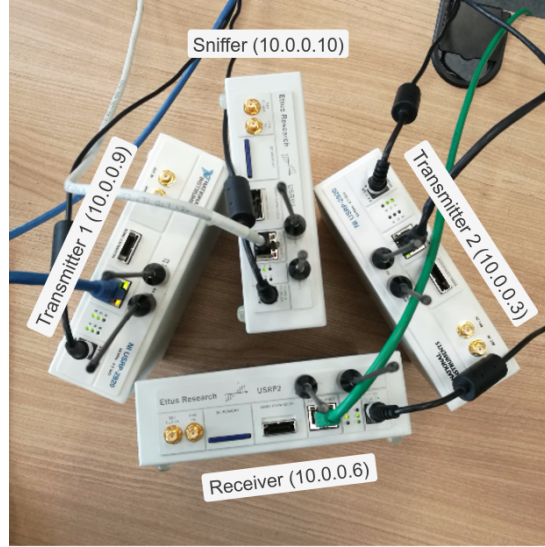


FIGURE 4.1: Photo of the measurement setup.

| Function | TX Gain | RX Gain | Source Address | Dest. Address | IP Address |
|----------|---------|---------|----------------|---------------|------------|
| Receiver | 4dB | 10dB | X | any | 10.0.0.6 |
| Sniffer | 0 | 0 | any | any | 10.0.0.10 |
| Transmitter 1 | 5dB | 0 | Y | X | 10.0.0.9 |
| Transmitter 2 | 9dB | 0 | Z | X | 10.0.0.3 |

TABLE 4.1: Setup parameters

## 4.2 GNU Radio Flowgraphs

### 4.2.1 Receiver and Sniffer

Figure 4.2.1 shows the two-way handshake receiving logic. After frame integrity is checked and type is confirmed to be data frame an acknowledgment is generated. The `frame_probe` blocks record the times when the frames reach certain positions in the flowgraph representing the occurrence of events such as frame reception, passed or failed frame integrity check and more. Note that the address check is disabled so that the receiver may receive frames from any sender.

The sniffer consists only of a single `frame_probe` block, which records detected power above noise level during the whole measurement. The sniffer provides valuable insight of what is actually going on in the channel from a "neutral" point of view. Neutral in the sense of:

- A clear distinction between the senders can be made according to the energy levels, since the sniffer is located between the senders and transmission gains were chosen accordingly.

- Sensing the channel is possible during the whole measurement time, because the sniffer is never sending.

In a nutshell, the sniffer is a valuable debugging and verification tool as described in more detail in section 4.3.

### 4.2.2 Pure ALOHA Transmitter

The `run` block enables us to start several senders exactly at the same time, which is useful if we execute the flowgraphs manually without the automated measurement scripts. Payload is generated in the `dummy_source` block, packed into a frame in the `framing` block and buffered in the `frame_buffer` block. The interval between generated frames is determined a `general_timer` block, which we trigger either in constant or exponentially distributed intervals. Self-reception is prevented by shutting down the receiver when about to send a frame through the sending block. As soon as the data packet is sent off the `timeout` block receives a copy of the data frame. If the timeout timer is reset by a recevied ACK before it runs out the next frame in the buffer is dequeued, otherwise the data is forwarded to the `resend_check`

block. If the maximum number of retransmissions, in our case 6 has not been reached a retransmission is issued, otherwise the frame is dropped without substitution.

### 4.2.3 CSMA Transmitter

The CSMA transmitter is based on the ALOHA transmitter, but features extra mechanisms as described in section 2.1.5.2, which will now be discussed. The flowgraph aims at resembling IEEE 802.11 DCF and features CCA through thresholding in the `carrier_sensing` block. Despite the fact that this block has the feature of adaptively determining an appropriate carrier sensing threshold we chose a fixed value of 0.002 power units (PU) [1]. This choice was made to make sure that ALOHA transmission power levels were not confused with noise during the adaptive CSMA noise floor detection period.

DIFS and SIFS are realized through `general_timer` blocks with the respective values. The design, as depicted, does not feature the RTS/CTS exhange.

---

[1]Power unit is a linear-scale unit read out via the UHD driver.

(a) Receiver

(b) Sniffer
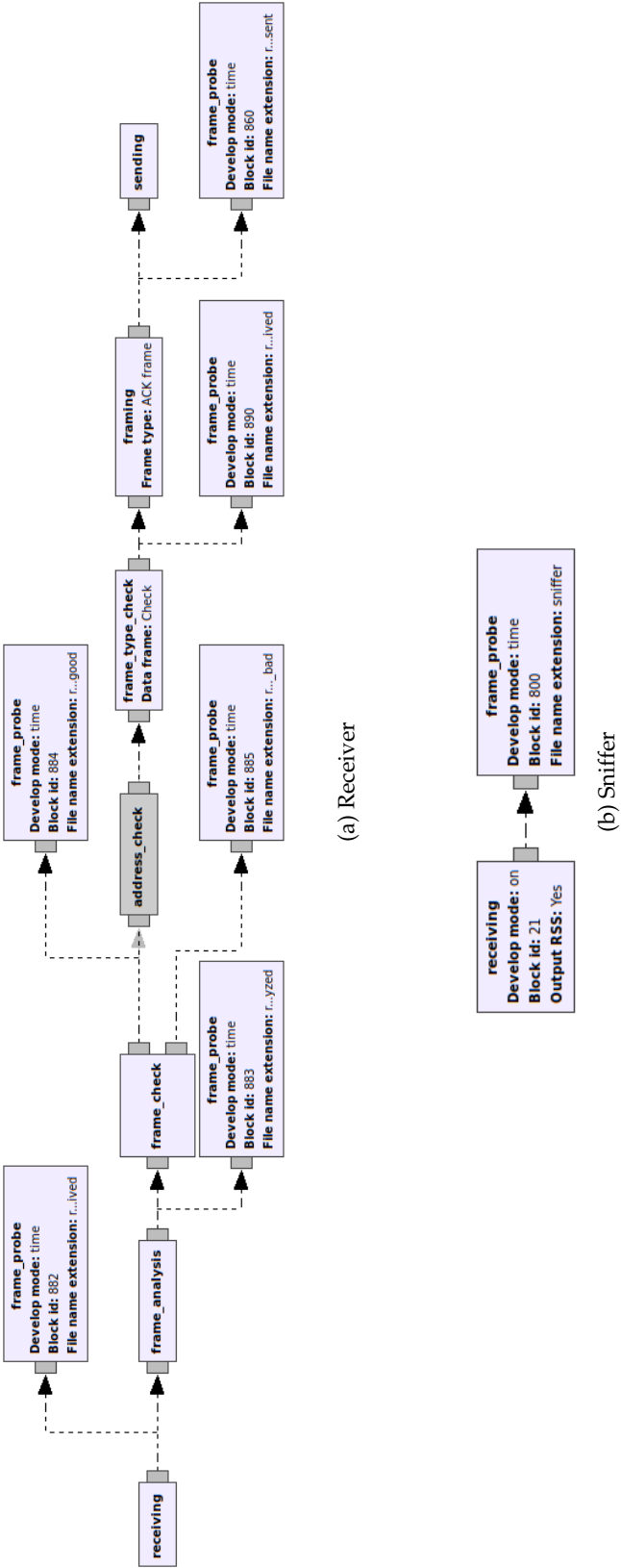
Figure 4.2: GRC Receiver Flowgraphs
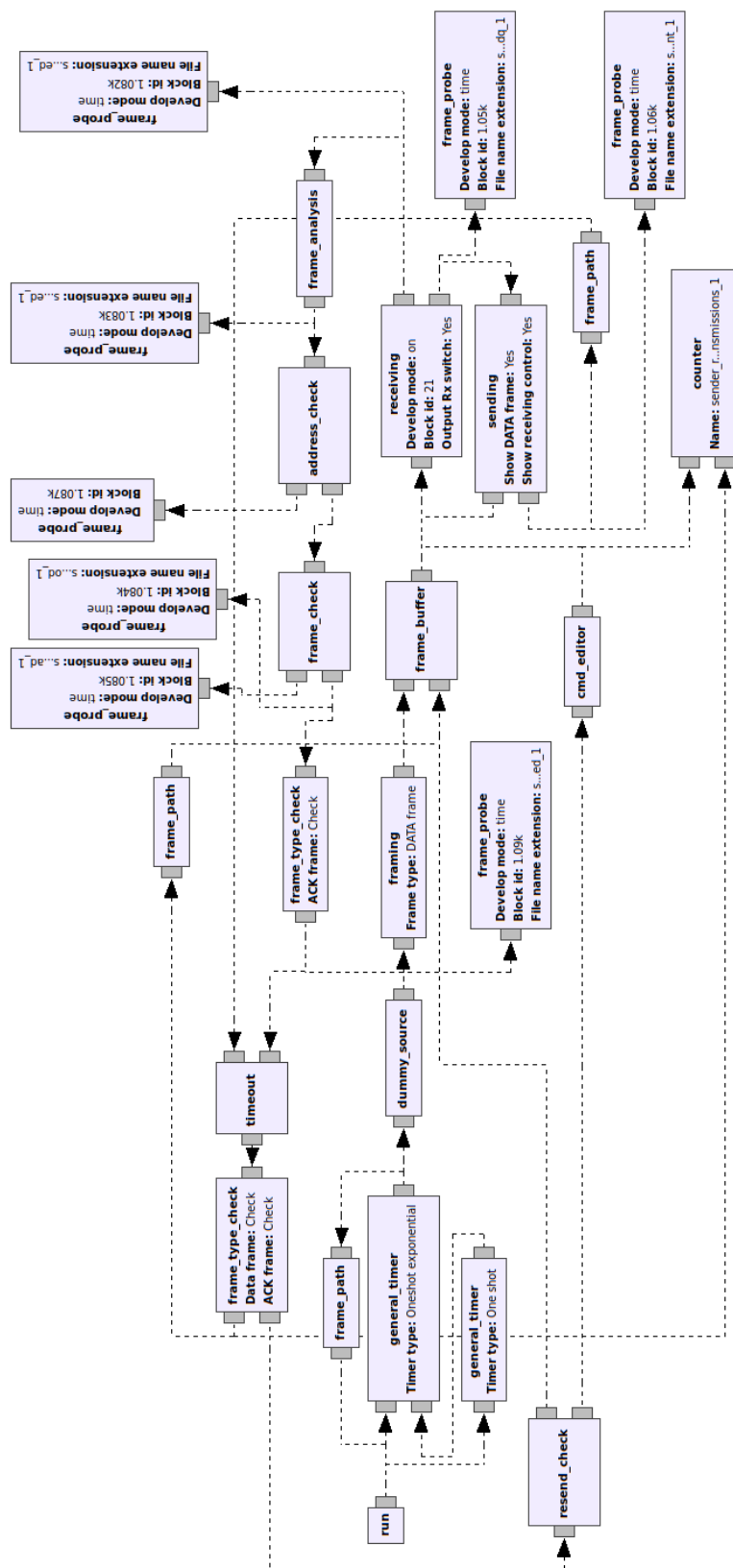
Figure 4.3: GRC Pure ALOHA Transmitter Flowgraph
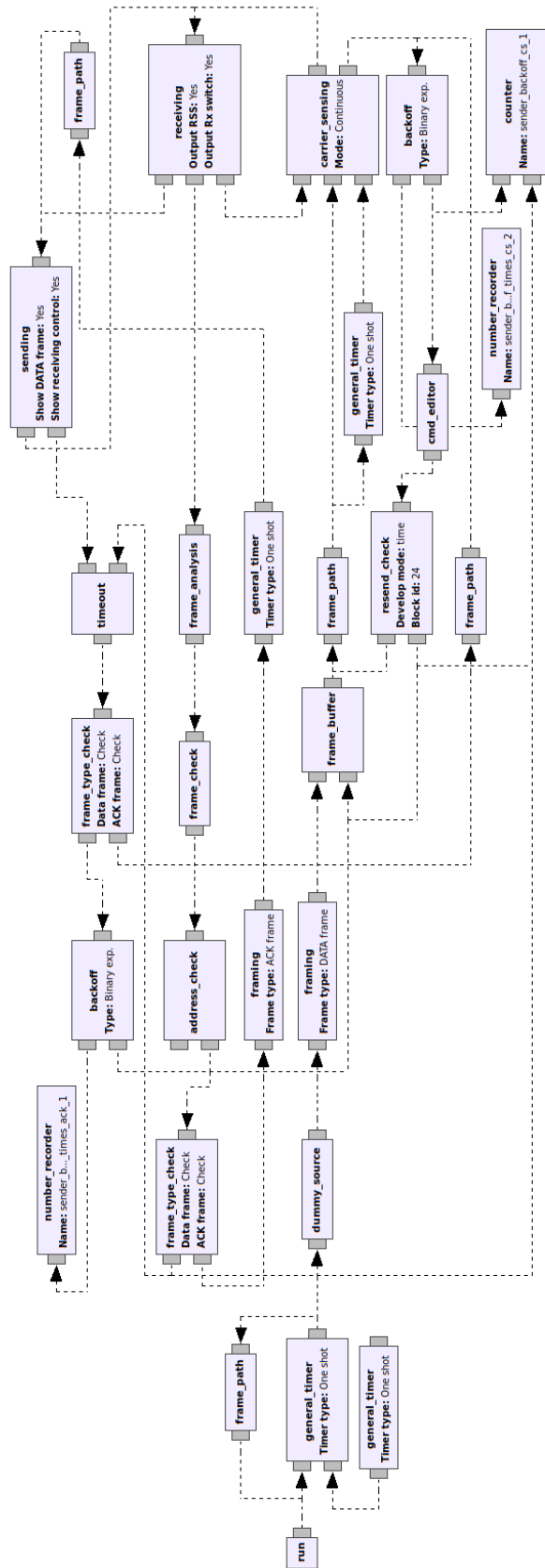
FIGURE 4.4: GRC CSMA Transmitter Flowgraph

## 4.3  MEASUREMENT METRICS

All recorded metrics will be defined in this section. Furthermore, we will describe the way how they were obtained and how we verified them. All metrics were originally captured with at least one of the following blocks: `frame_probe`, `counter`, `number_recorder` and `time_probe` as depicted in figures 4.2.1, 4.2.2 and 4.2.3.

### 4.3.1  Throughput

We define throughput as the mean useful data [2] transmission rate in the unit kbit/s. We obtain this metric simply by counting the number of ACKs received at the sender, multiply it with the frame length of 8 kbits and divide it by the measurement duration. The calculations are done in `throughput.py` making use of the CLI tool `wc` to count lines. Joint and single throughputs are our main metrics to judge a protocol's efficiency or how well a certain combination of protocols can coexist under different conditions, respectively.

### 4.3.2  Round-Trip Time

We define round-trip time (RTT) as the mean time from the buffer dequeuing a data frame until ACK reception. If the variable `rtt_mode` is set to `rtt` then this calculation excludes retransmitted frames. If `rtt_mode` is set to `frame_delay` instead then retransmitted frames are taken into account. How we obtain these metrics is best explained with the code in Listing 4.1, where `ack_received_times` and `data_sent_times` contain the timestamps of the frames.

```
1  # pointer onto data frame which we use for frame delay calculation
2  data_pos = 0
3  for k,ack in enumerate(ack_received_times):
4      for l,data in enumerate(data_sent_times):
5          # go to 1st data frame that is sent after the respective ack
6          if data > ack:
7              if self.rtt_mode == "rtt":
8                  # the data frame before current position l
9                  # must be the frame the ack corresponds to
10                 rtt_single_measurement += [round(ack -
    data_sent_times[l-1],5)]
11             if self.rtt_mode == "frame_delay":
12                 # the pointer onto our frame delay reference
13                 # is used to calculate frame delay
14                 rtt_single_measurement += [round(ack -
    data_sent_times[data_pos], 5)]
15             # set new reference point for frame delay calculation
16             data_pos = l
17             # break loop to look at next ack frame!
```

---

[2]payload and headers disregarding retransmissions

```
18              break
```

LISTING 4.1: The method used in `rtt_alternative.py` to calculate rtt and frame_delay

Another way to calculate the RTT is by recording the number of retransmissions of each data frame and subtracting the element with the correct offset in `data_sent_times` from each ACK reception time. We will not show any code (which can be found in `rtt.py` ) here, because this has not been used to create any of the plots, although it has been verified to return the same results as the first method.

### 4.3.3    Packet Loss and Retransmissions per Frame

Obtaining both metrics involves data processed in `rtt.py` , which is why they are calculated there as well. Specifically, we make use of the lists containing the timestamps of ACKs and data frames as well as the number of retransmissions per frame. We define packet loss as $1 - \frac{n_{\text{ACKs}}}{n_{\text{data}}}$, where $n_{\text{ACKs}}$ and $n_{\text{data}}$ are the number of ACK packets received and data packets sent by the transmitter. Retransmissions per frame are obtained simply by recording them with a `counter` block, which is incremented whenever the `timeout` runs out and reset when an ACK is received.

### 4.3.4    Backoff Times

The script `backoff.py` sums up three different backoff times: Firstly, the backoff due to failed [3] carrier sensing. Secondly, we capture the backoff times due to successful transmission to give other nodes a chance to seize the channel. Lastly, we sum up the two to obtain the total backoff. The total backoff duration in our view reflects the efficiency of the CSMA protocols in dependency on the parameters DIFS, SIFS and backoff slot length [4]. We chose a minimum contention window of $2^5 = 32$ backoff slots with binary exponential increase.

### 4.3.5    Packet Durations & Channel Occupation

The channel occupation chart as in figure **??** provides an approximated logical view on the channel in the fashion of a Gantt chart. Blue patches represent data frames, red patches ACKs and black patches the reception of ACKs. The chart is only a (good) approximation of the channel because the width of the patches are fixed and defined in `channel_occupation.py` . The duration of DATA and ACK frames was previously recorded with the `time_probe` blocks as the difference between the times when the frame was dequeued from the buffer and when it was received by the receiver. As expected, the frame durations were very stable. A data frame took 40ms to transmit and an ACK frame took 7ms. The variation of frame length was in the range of 1-2 milliseconds for data frames and in the sub-millisecond range for ACK frames. Depending on the time-limits chosen for the plot this may be well below the

---

[3]by failed we mean a negative CCA, i.e. a busy channel.

[4]E.g. for two CSMA transmitter it would be ideal to have both transmitters back off for around 50% of the transmission time to give each other a chance to transmit.

plot's resolution, which is why the time axis of such plot will be limited to a range of a few seconds at most.

### 4.3.6 *Channel Energy Level*

The energy levels (denoted in a linear-scale, non-negative power unit) in the channel observed by the sniffer (and processed in `sniffer.py`) help us to verify a multitude of metrics. We can verify frame durations, round-trip time, backoff time (for saturated traffic) and logical channel occupation. Even collisions are clearly visible and which sender caused them. Throughput ratio among senders can easily be verified by opting in data representation as CDF, e.g. if two identical MAC protocols run under identical circumstances then we expect a CDF with a step roughly at $y = 0.5$.

## 4.4 MEASUREMENT SCRIPT SYSTEM

The elaborate script-system was an integral part of the work and enables future users to much more quickly gain results based on automation, since it is no longer necessary to manually execute flowgraphs, manage captured files, run data processing scripts, sync files with github ...Instead everything is automatically done for them. Literally the transmission of every frame and data processing step can be traced back with the log files. Furthermore, to accommodate the need for comparison a retrospective evaluation of any set of measurements `belated_evaluation.py` was created. The user only needs to add a few lines to the script as shown in listing 4.2.

```
1  measurement      = [714,715,728,646]
2  links            = [1,2,1,2]
3  boxplot_xticks   = [
4      "CSMA\nDIFS=15ms\nSIFS=0ms\nBO=0ms\nLink 1 @ 450MHz",
5      r"unsaturated ALOHA ~ Poisson($1/\lambda=200ms$), Link 2 @
       450MHz",
6      "CSMA\nDIFS=15ms\nSIFS=0ms\nBO=0ms\nLink 1 @ 450MHz\n Baseline",
7      "unsaturated ALOHA\nLink 2 @ 450MHz\n Baseline",
8  ]
```

LISTING 4.2: Evaluation of measurements with `belated_evaluation.py`. In `links` we denote the link we used in the corresponding measurement (compare figure 4.1)
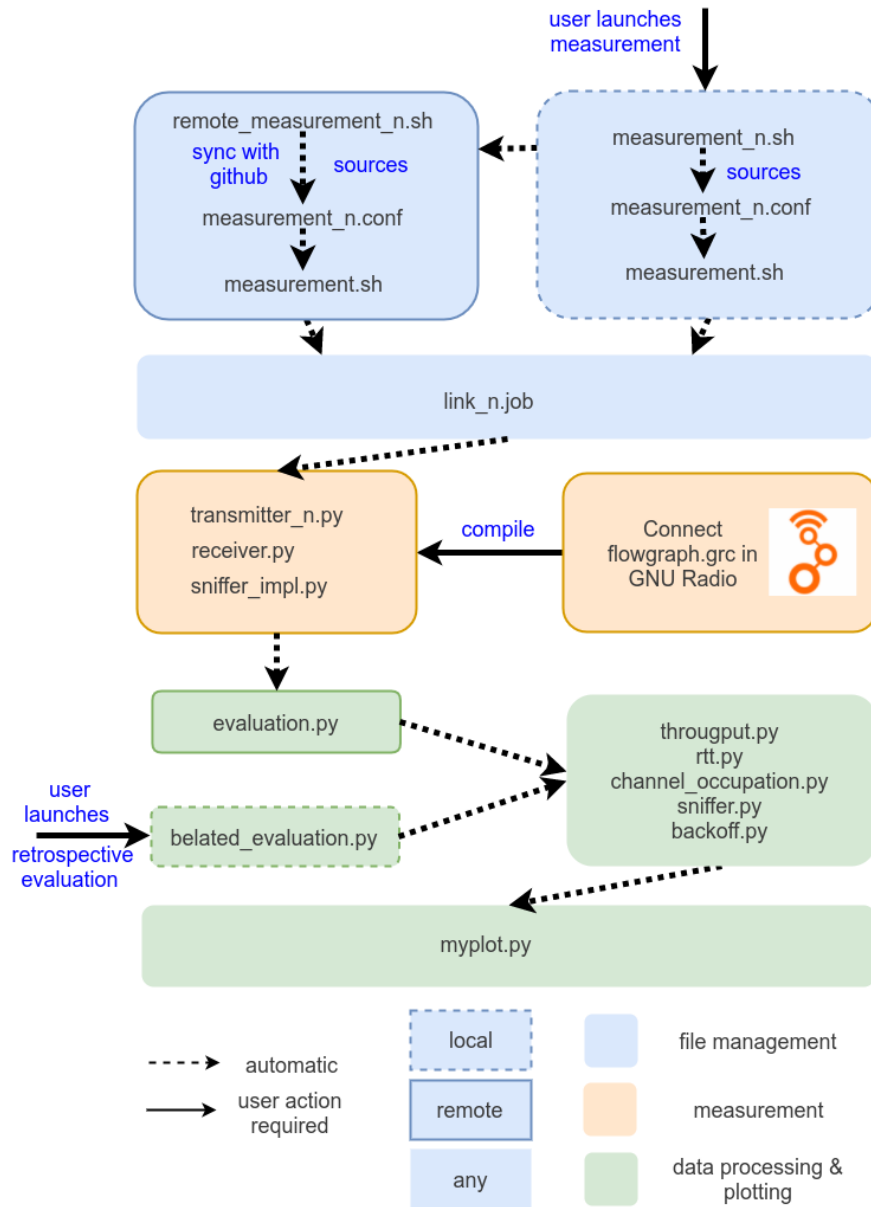
FIGURE 4.5: The three-phase measurement script system. Starting with the user calling `measurement_n.sh`, where n is the ID of the link, general settings are "imported" from `measurement_n.conf`. If the user sets `remote_measurement` to 1 in the conf file then `remote_measurement_n.sh` synchronizes the files on the remote machine with the github repository, then executes `measurement_n.sh` remotely. Subsequently, `measurement.sh` for link n works on open "jobs" from the `jobs_open_n` directories and optionally puts them into the `jobs_done_n` directory after completion. In the job files important variables such as duration, repetitions and flowgraph scripts of the measurement are defined. Any variable set in the conf file can be overwritten in the job file since they both are just exporting variables and were separated for semantic reasons only. After the measurement concluded `evaluation.py` coordinates data processing which eventually leads to plotting based on Matplotlib as defined in `myplot.py`.

# 5

# MEASUREMENT RESULTS

For this chapter different combinations of two links employing pure ALOHA, non-persistent CSMA and 1-persitent-CSMA-like MAC protocols were run on the same channel. In-depth analysis of different metrics and a consecutive protocol assessment are provided.

**As a reminder:** If not specified otherwise all transmitters are backlogged. CSMA/CA throughout this thesis is not featuring the optional RTS/CTS exchange.

## 5.1 SAME PROTOCOL COMBINATIONS

Throughout this section both transmitters are executing identical flowgraphs. Generally, when both links use the same MAC protocol we expect to see comparable results for any over a sufficiently longer period of time, although small variations are also expected due to statistical and hardware-related effects and inaccuracies.

### 5.1.1 Pure ALOHA

For two links with saturated ALOHA traffic we have zero throughput, since each and every package collides.

(a) throughput

(b) packet loss CDF

(c) channel energy

(d) channel energy CDF
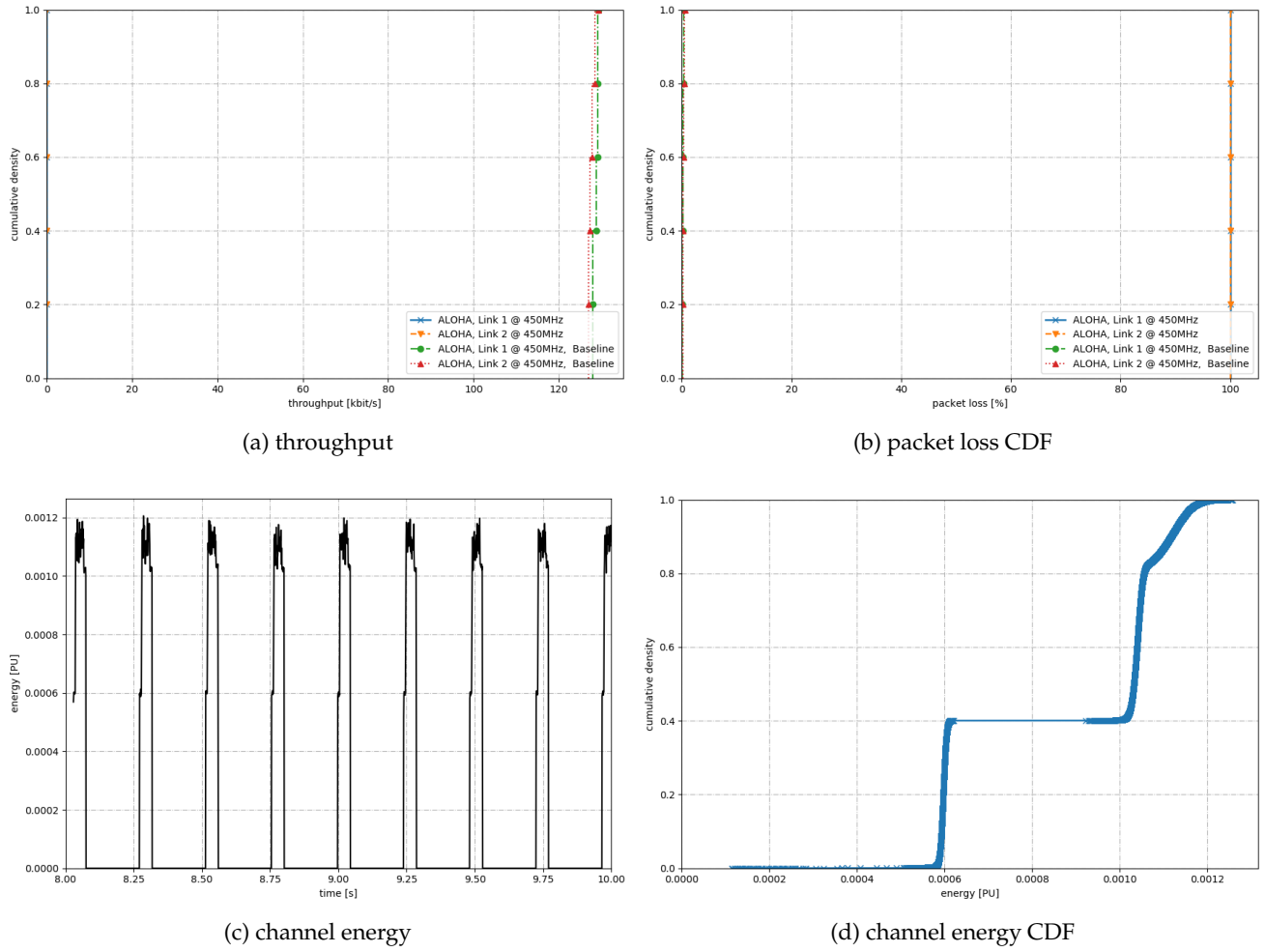
FIGURE 5.1: Measurement results for the CSMA/CA with large parameter set

*5.1.2 CSMA/CA With High Parameter Set*
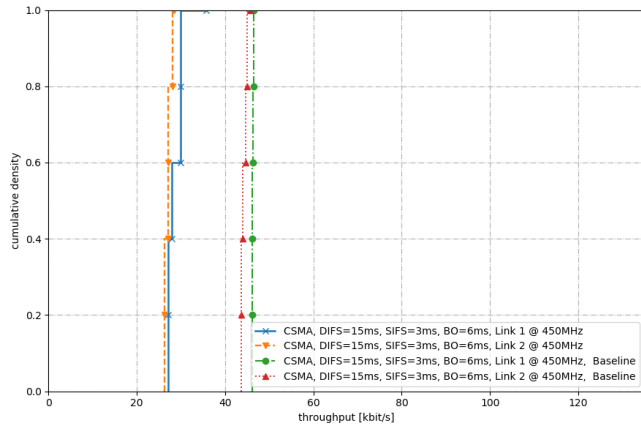
(a) throughput
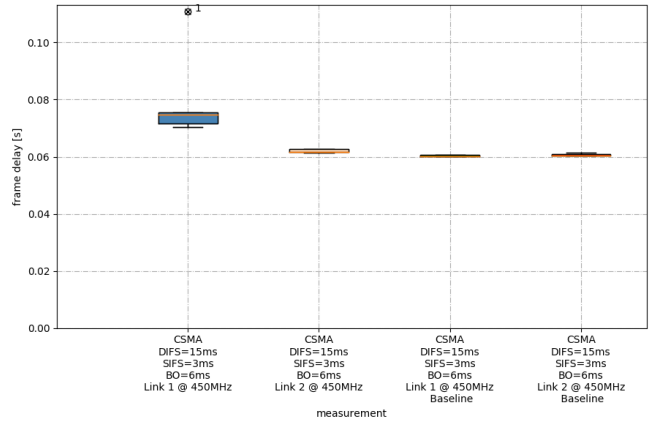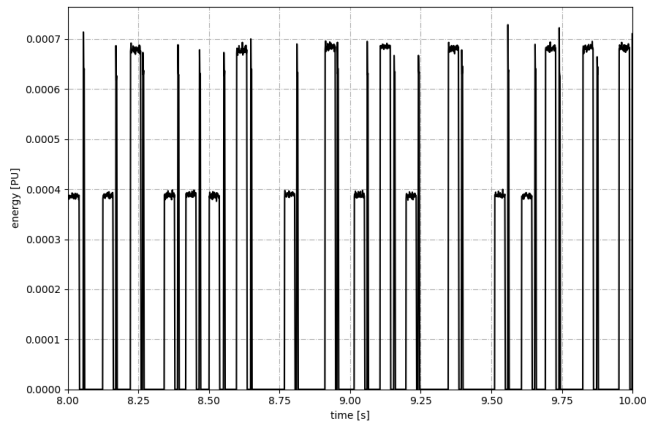

(b) frame delay
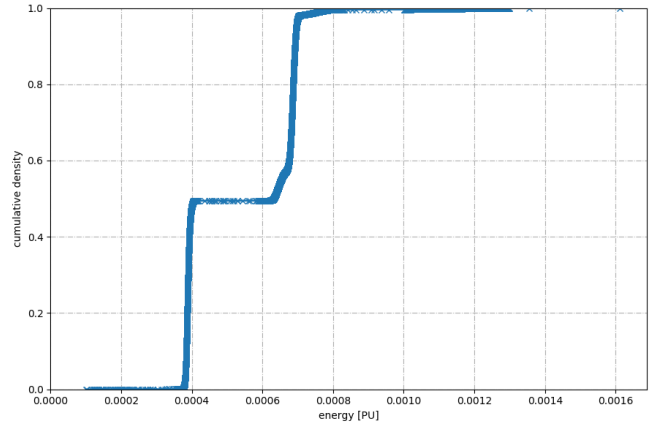

(c) channel energy


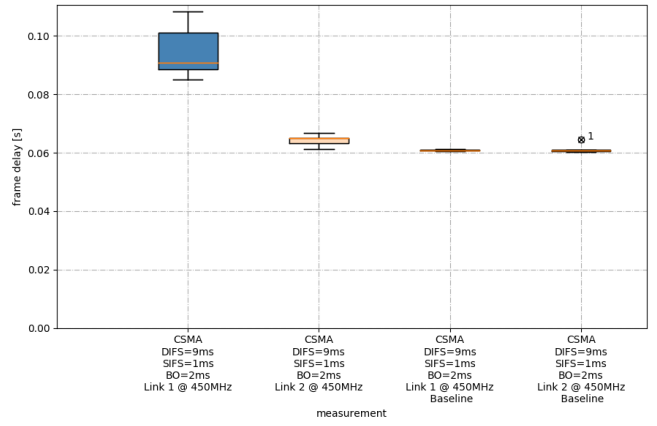(d) channel energy CDF
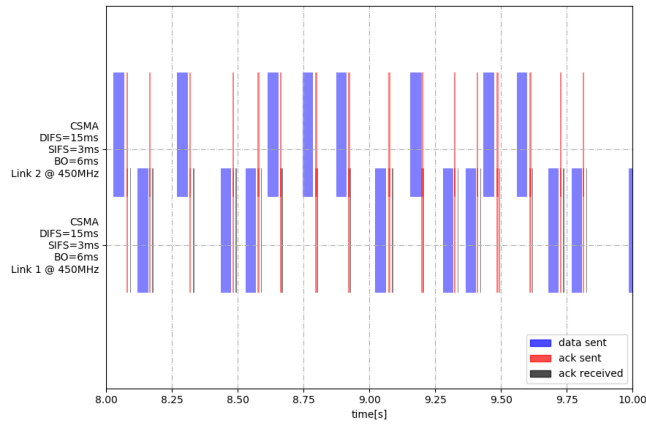

(e) logical channel occupation
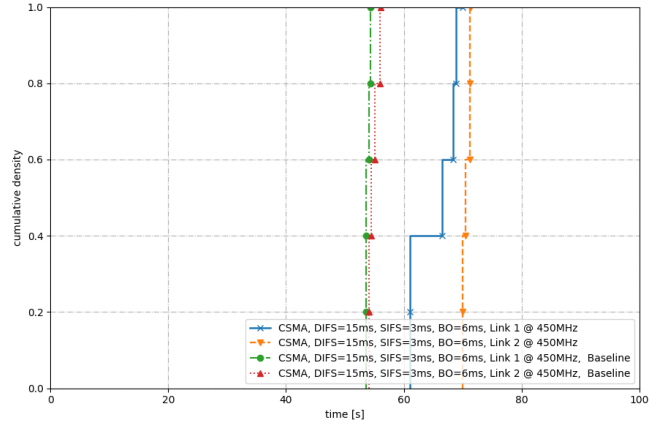

(f) total backoff

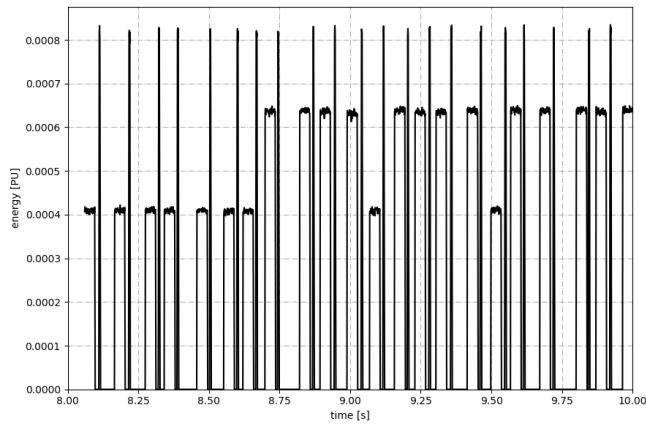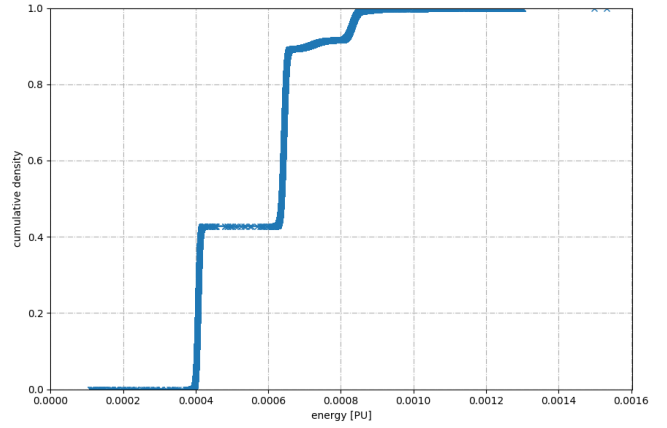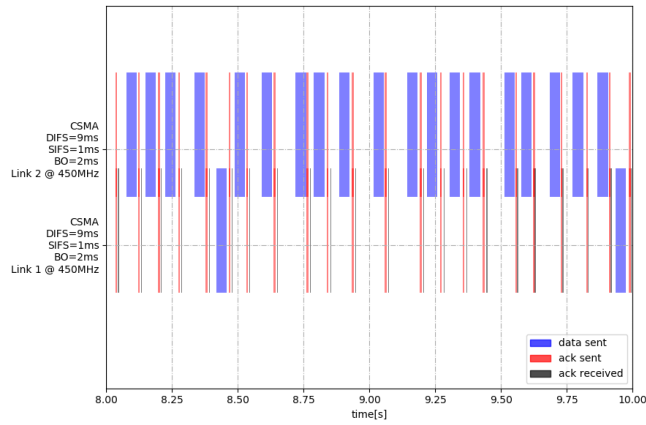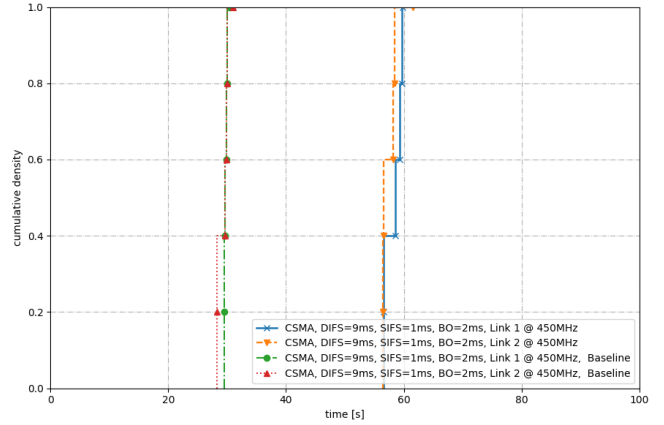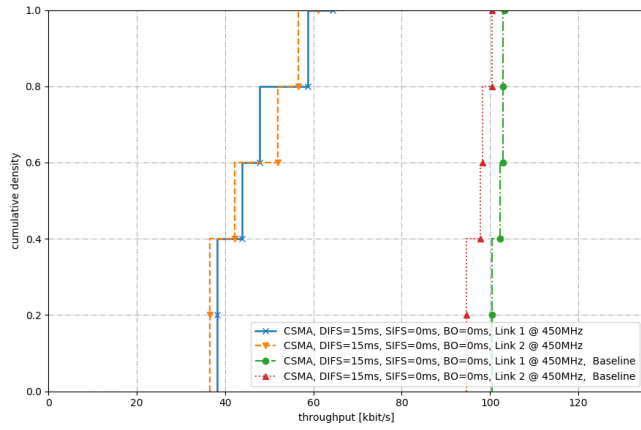FIGURE 5.2: Measurement results for the CSMA/CA with high parameter set

*5.1.3 CSMA/CA With Low Parameter Set*
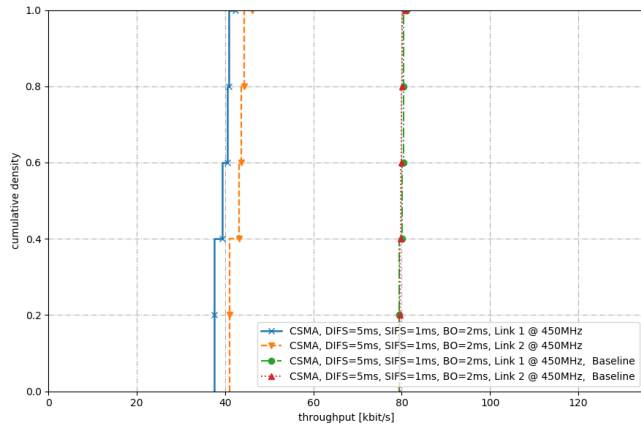
(a) throughput
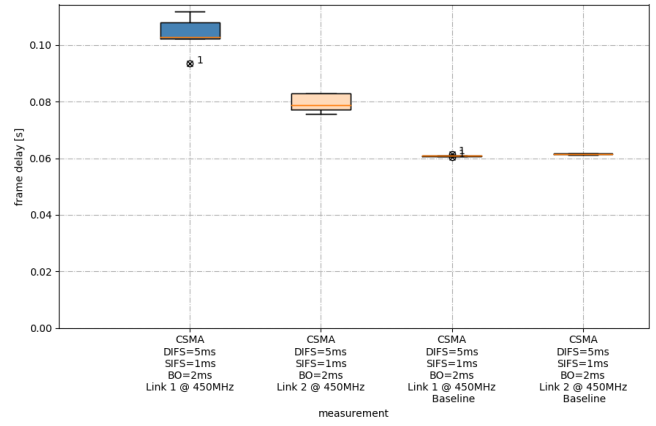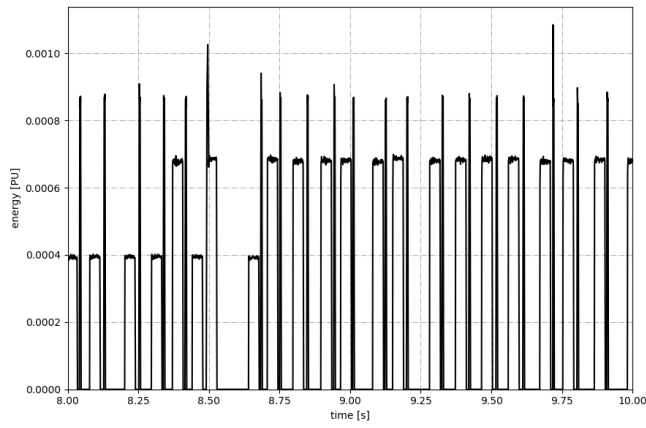
(b) frame delay
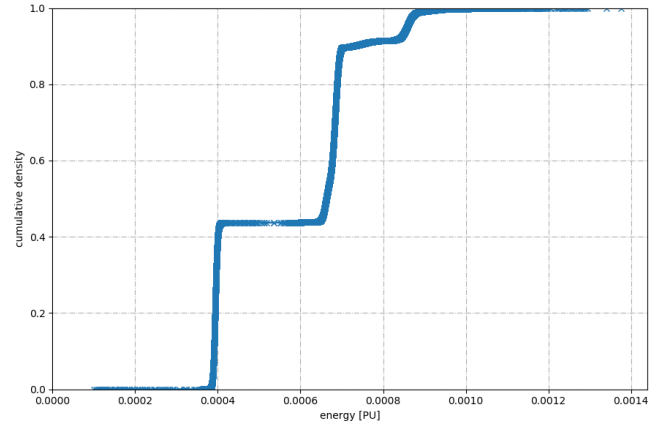
(c) channel energy

(d) channel energy CDF
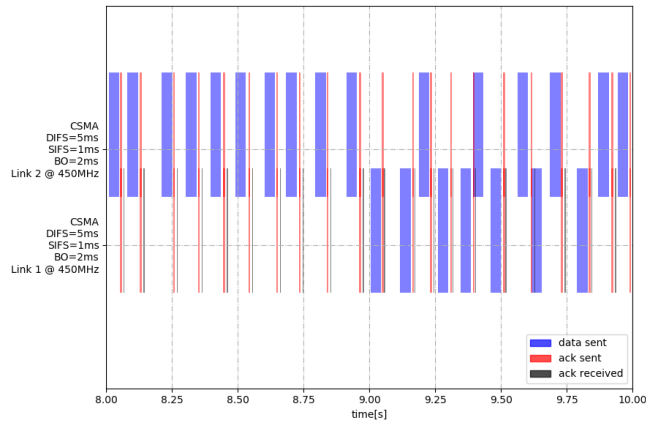
(e) logical channel occupation
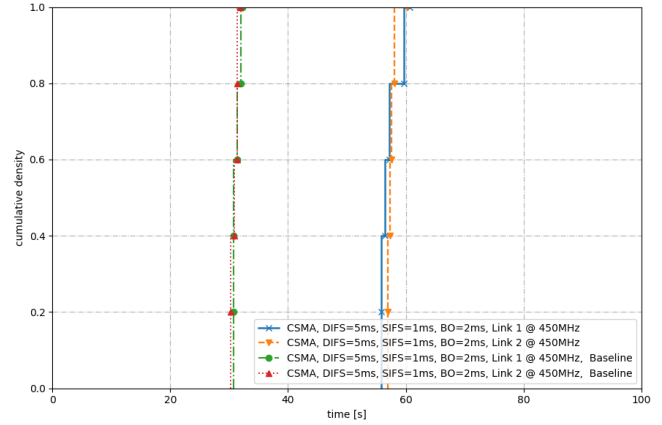
(f) total backoff

FIGURE 5.3: Measurement results for the CSMA/CA with low parameter set

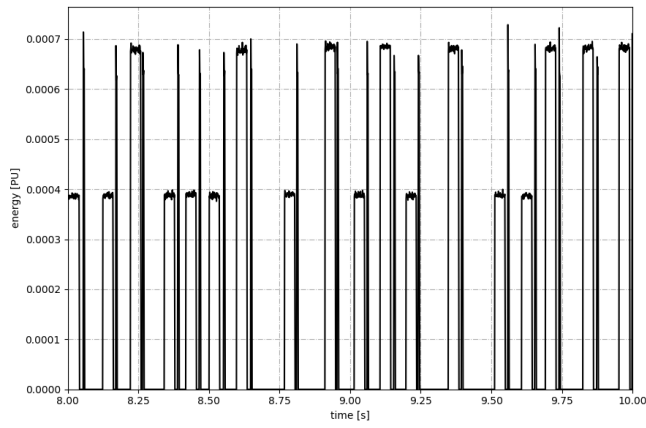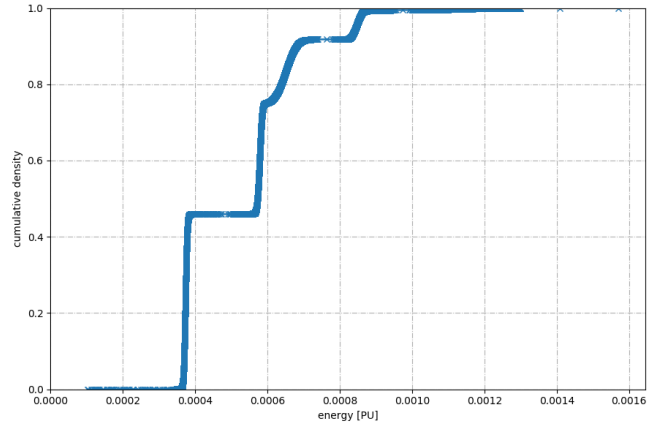*5.1.4 CSMA/CA With Medium Parameter Set*
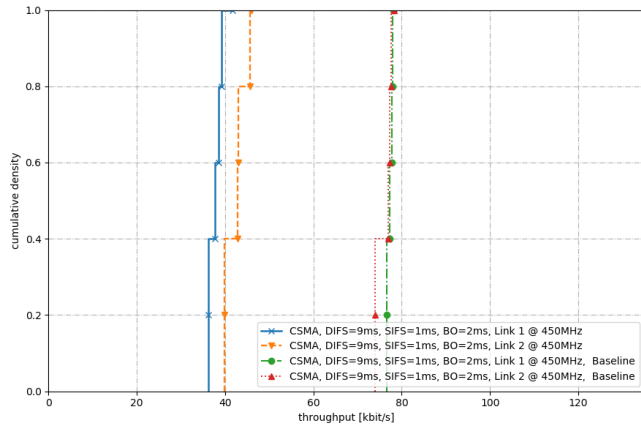
(a) throughput

(b) frame delay

(c) channel energy

(d) channel energy CDF

(e) logical channel occupation

(f) total backoff

FIGURE 5.4: Measurement results for the CSMA/CA with medium parameter set

### 5.1.5   1-persistent CSMA
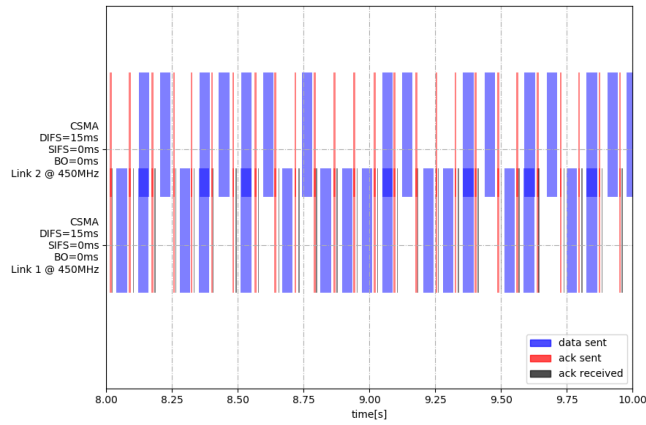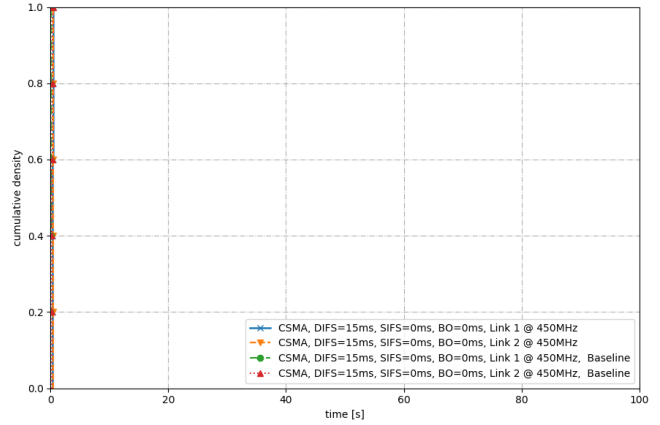
(a) throughput
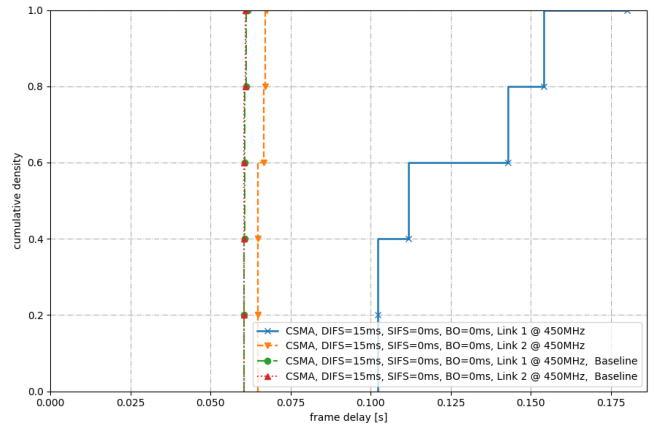


(b) frame delay



(c) Channel Energy



(d) Channel Energy CDF



(e) Logical Channel Occupation



(f) Total Backoff

FIGURE 5.5: Measurement results for 1-persistent CSMA/CA

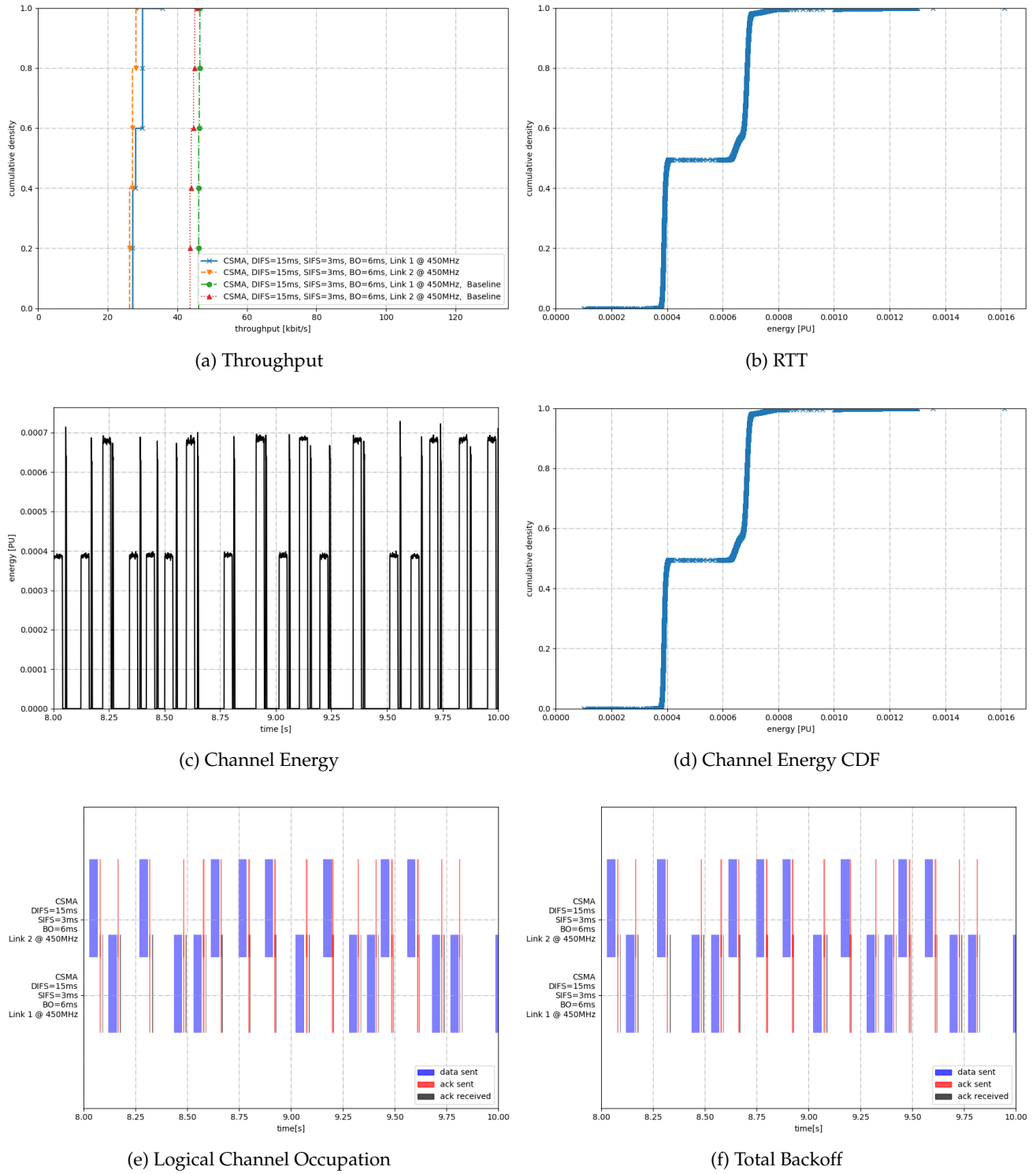## 5.2 DIFFERENT PROTOCOL COMBINATIONS

### 5.2.1 ALOHA and CSMA/CA
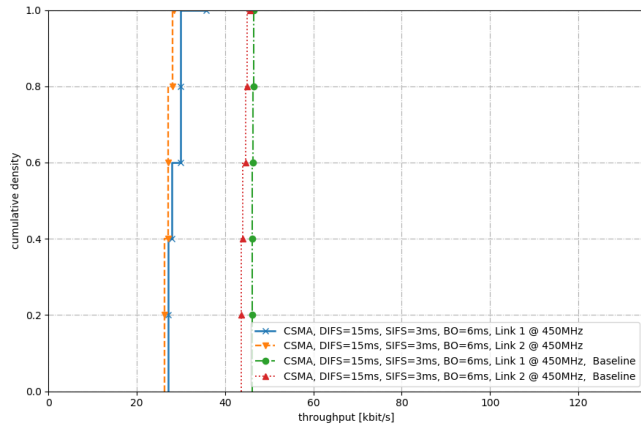
(a) Throughput

(b) RTT

(c) Channel Energy

(d) Channel Energy CDF

(e) Logical Channel Occupation
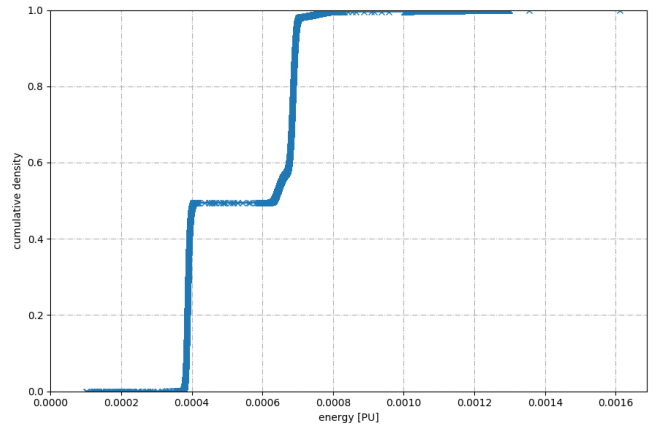
(f) Total Backoff

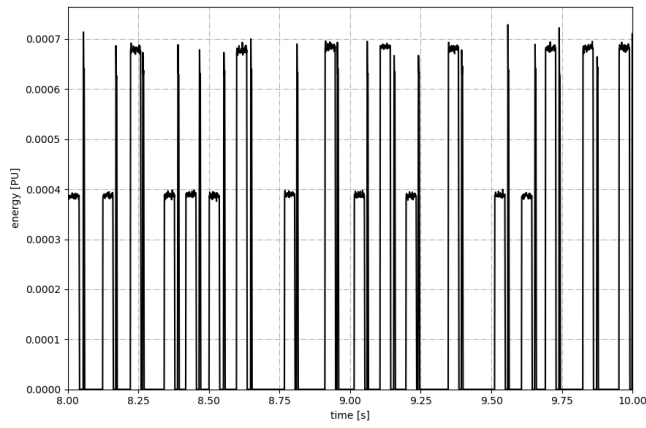FIGURE 5.6: Measurement results for the CSMA/CA with large parameter set

*5.2.2   Unsaturated ALOHA and CSMA/CA*

(a) Throughput

(b) RTT

(c) Channel Energy

(d) Channel Energy CDF

(e) Logical Channel Occupation

(f) Total Backoff

FIGURE 5.7: Measurement results for the CSMA/CA with large parameter set

*5.2.3 Inhomogeneous CSMA/CA*

*5.2.4 1-persistent CSMA and ALOHA*

(a) Throughput

(b) RTT

(c) Channel Energy

(d) Channel Energy CDF

(e) Logical Channel Occupation

(f) Total Backoff
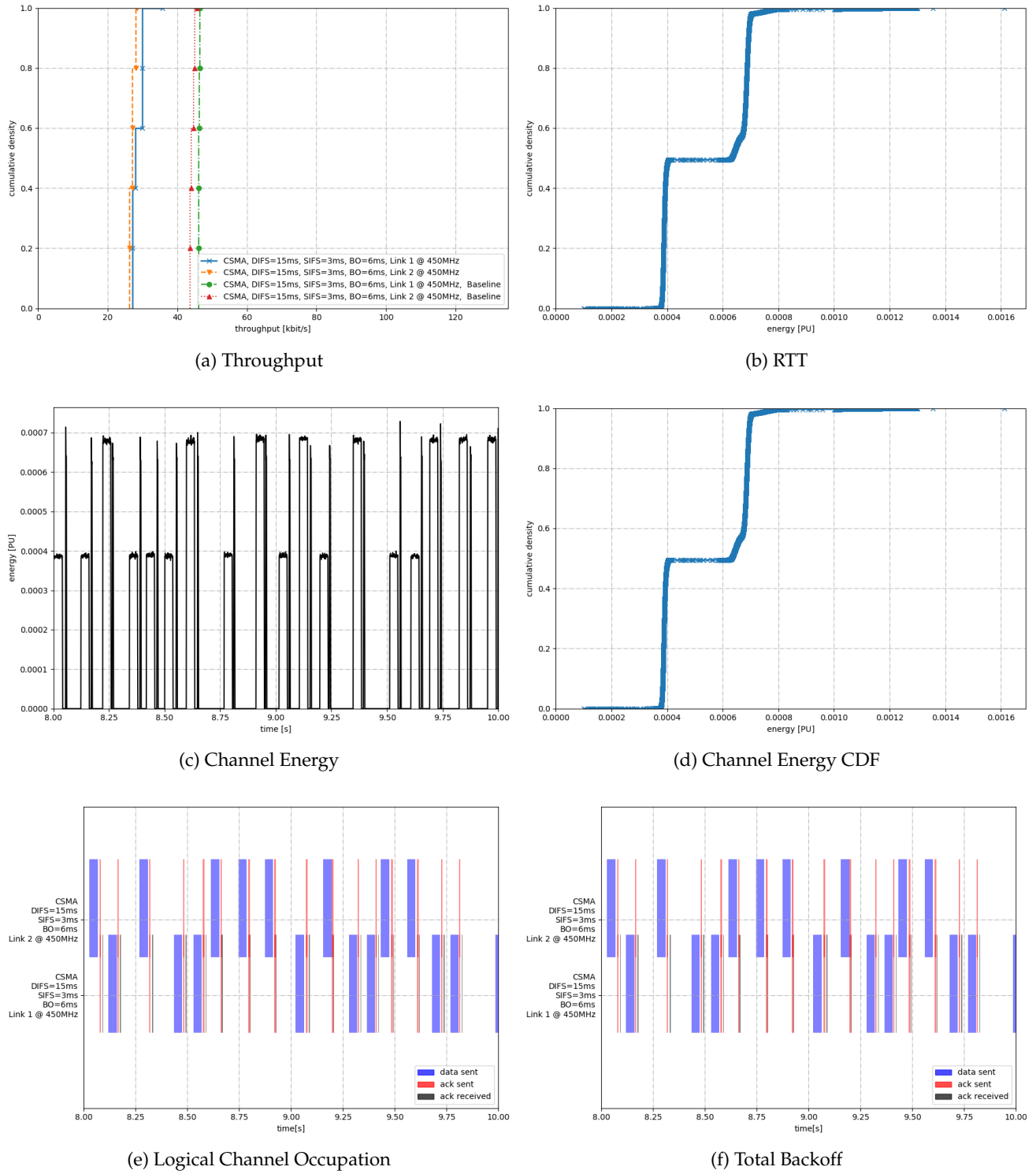
FIGURE 5.8: Measurement results for the CSMA/CA with large parameter set

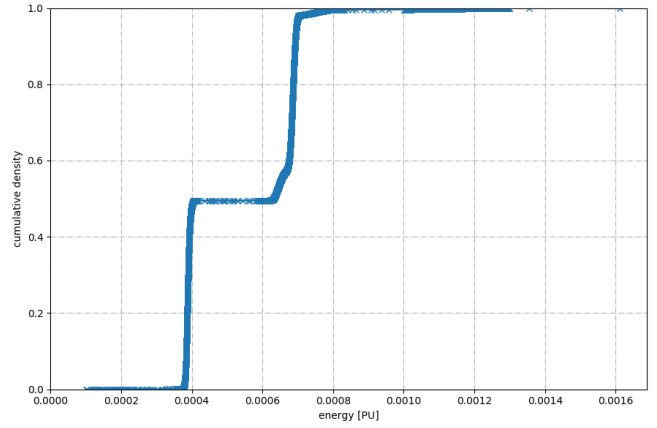### 5.2.5 *1-persistent CSMA and CSMA/CA*
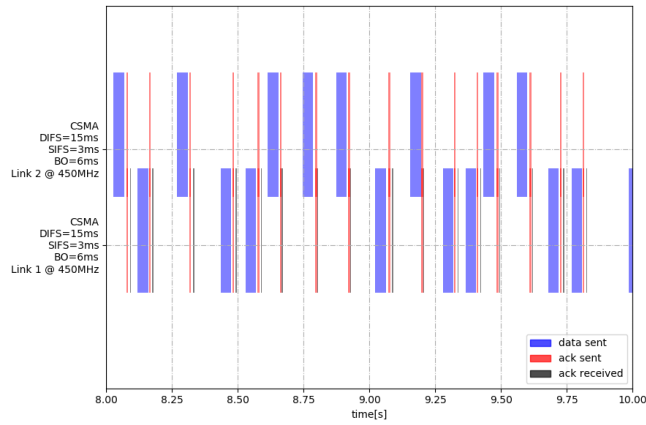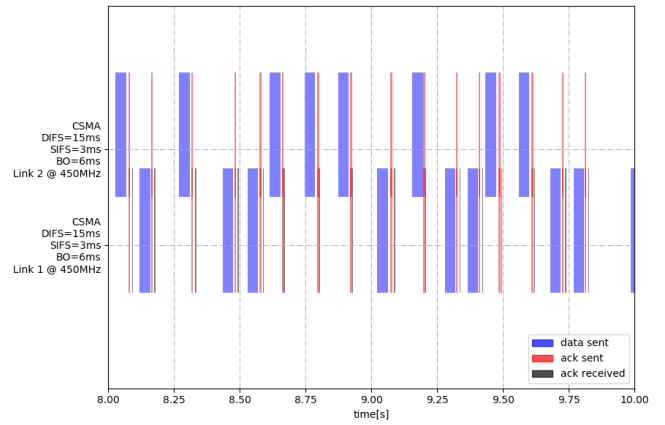
(a) Throughput

(b) RTT

(c) Channel Energy

(d) Channel Energy CDF

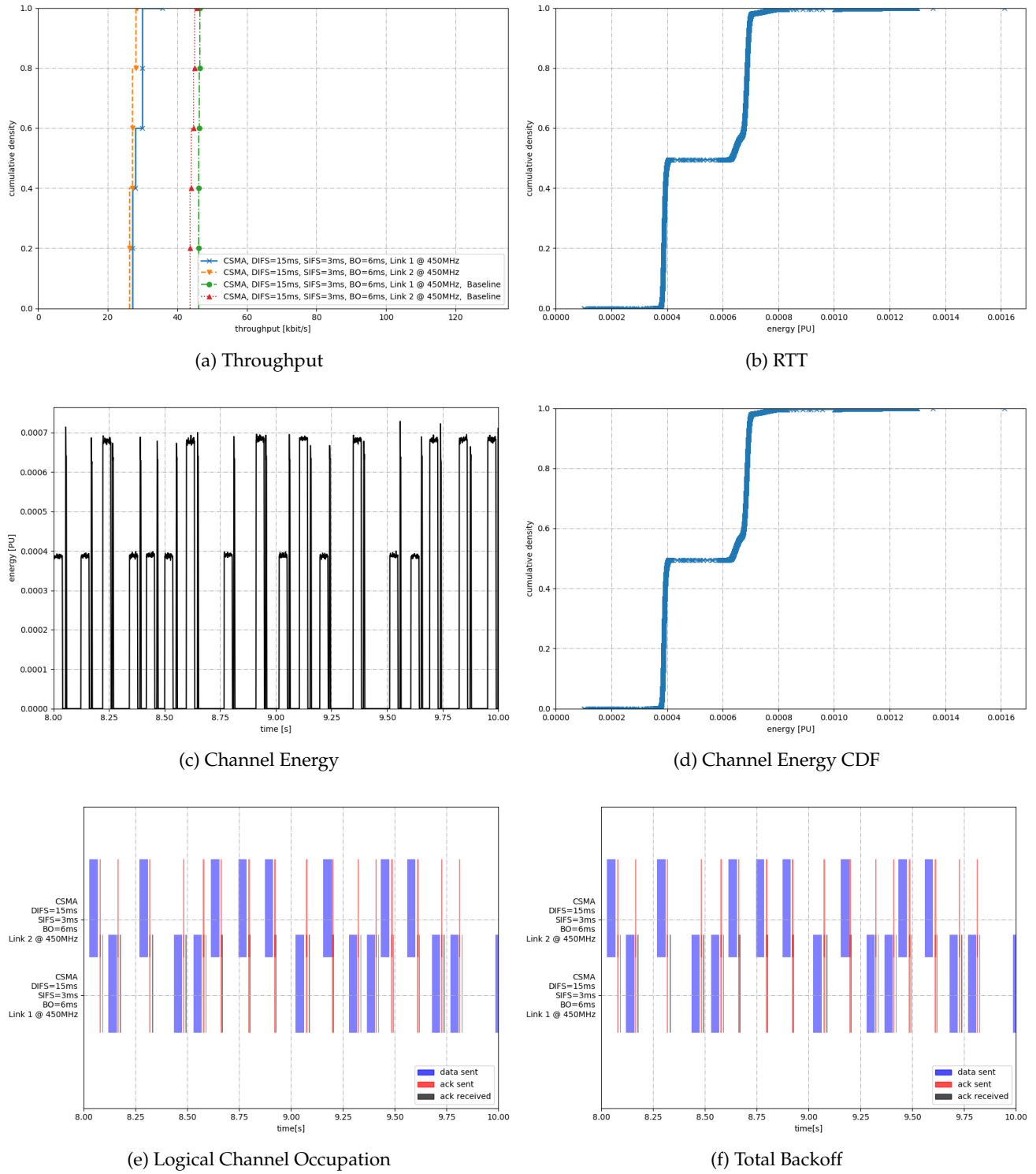(e) Logical Channel Occupation

(f) Total Backoff

FIGURE 5.9: Measurement results for the CSMA/CA with large parameter set

# 6

## CONCLUSIONS AND FUTURE WORK

Conclusions and Future Work here.

# A

## BASH AND PYTHON SCRIPTS

This appendix aims at giving in-depth insight in the scripts used in the three phases of the measuring, data processing and plotting process. The basic principle, however, is depicted in section 4.4. Minor edits were made for format and aesthetic reasons.

```bash
echo "remote_measurement is set to "$remote_measurement"."

function setup_remote_connection
{
  reset
  sshpass -p "inets" ssh -$remote_flags $remote_user@$remote_ip
    "bash -s" < remote_measurement_$link.sh
}

function prepare_measurement
{
    reset
    measurement_counter=0
    ## let's make sure all the directories exist
    printf "\nchecking if paths exists...\n"

    #let's first make absolutely sure the raw data source path
    exists
    if [ ! -d $raw_data_source_path ];
      then
        mkdir -p $raw_data_source_path
        echo $raw_data_source_path" created."
      else
        rm -r $raw_data_source_path/*
    fi

    if [ -d $plot_directory_path ];
      then
        echo $plot_directory_path" already existed!"
        cd $plot_directory_path
        # create measurement directory
        while [ -d $measurement_counter ]; do
            measurement_counter=$(($measurement_counter+1))
        done
        export measurement_counter;
    fi

    if [ -d $log_path ];
```

45

```
37         then
38           echo $log_path" already existed!"
39         else
40           mkdir -p $log_path
41           echo $log_path" directory created."
42      fi
43
44      mkdir -p $plot_directory_path/$measurement_counter
45      echo $plot_directory_path/$measurement_counter" directory
     created."
46
47      mkdir -p $data_source_path/$measurement_counter
48      echo $data_source_path/$measurement_counter" directory created."
49
50      mkdir -p $jobs_open_path
51      mkdir -p $jobs_done_path
52
53      ## let's check if measurement script is defined
54      # if $measurement_scripts undefined:
55      # go through directory and list all python files
56      if [ -z ${measurement_scripts+x} ];
57        then
58          echo  "no measurement scripts set,
59              going through files inside of $locate_base_path."
60          echo "please add a the full path of one of the files to
     \$scritps."
61          #locate -r "$locate_base_path" | grep "\.py$"
62          echo "terminated. ding dong"
63          exit -1
64      fi
65
66      printf "\n"
67 }
68
69 function measure
70 {
71   local prematurely_aborted=0
72
73   for ((x = 1 ; x <= $measurement_repetitions ; x += 1)); do
74
75     # get pid to later kill it
76     for i in "${measurement_scripts[@]}"
77     do
78       python $measurement_script_path/$i &
79     done
80
81     for ((y = $timer ; y > 0 ; y -= 1)); do
82       echo "measurement $x/$measurement_repetitions complete in $y
     second(s)."
83       if [ $check_if_prematurely_aborted -eq 1 ];
84         then
85           if $(ps -p ${measurement_scripts_pid[*]}) | grep
     ${measurement_scripts_pid[*]};
```

```
86            then
87              :
88            else
89               prematurely_aborted=1
90               echo  "Scripts were killed prematurely. Measurement
     may be incomplete."
91               break
92           fi
93       fi
94       sleep 1
95     done
96
97     kill $(jobs -p)
98
99     # save this measurement's data to special folder
100    mkdir -p $data_source_path/$measurement_counter/$x
101    echo  "measurement $x raw data directory created
     $data_source_path/$measurement_counter/$x/."
102
103    echo $raw_data_source_path
104    echo $(ls $raw_data_source_path | egrep "*_$link.txt")
105
106    cd $raw_data_source_path
107    mv -v $(ls | egrep "*_$link.txt")
     $data_source_path/$measurement_counter/$x/
108    cp -v $(ls | egrep "sniffer")
     $data_source_path/$measurement_counter/$x/
109    if [ "$receiver_mode" == "single" ];
110      then
111        cp -v $(ls | egrep "receiver")
     $data_source_path/$measurement_counter/$x/
112    fi
113    echo  "measurement $x raw data moved to
     $data_source_path/$measurement_counter/$x/."
114    printf "\n"
115    if [ $prematurely_aborted -eq 1 ];
116      then
117        if [ $plot_if_prematurely_aborted -eq 0 ];
118          then
119            echo "plotting if measurement prematurely aborted set
     to false."
120            echo "terminated."
121            exit -1
122        fi
123    fi
124
125  done
126
127  #exit remote connection
128  if [ $remote_measurement -eq 1 ]; then
129    echo "remote_measurement is set to "$remote_measurement"."
130    exit
131  fi
```

```
132 | }
133 |
134 | function plot
135 | {
136 |   ## plot the results
137 |   echo "now processing results..."
138 |
139 |   # call the plotting scripts as data
140 |   #echo "starting to generate plots..."
141 |   echo "plotting python should be: "$plot_py" ("$os")."
142 |
143 |   for i in ${plot_scripts[@]}; do
144 |     bash -c "$plot_py $plot_py_path/$i"
145 |   done
146 |
147 |   echo "+-----------------+"
148 |   echo "|plotting completed|"
149 |   echo "+-----------------+"
150 | }
151 |
152 | function cleanup
153 | {
154 |     ##cleaning up the mess you created!
155 |     #kill all child proceesses
156 |     echo "staring cleanup..."
157 |     echo "killing all lingering child processes..."
158 |     killall -9 -g $0
159 |     cd $this_path
160 |     exit
161 | }
162 | trap cleanup sighup sigint sigkill;
163 | trap "cd $this_path" exit;
164 |
165 | function main
166 | {
167 |   # clear up console
168 |   #reset
169 |   # check if jobs_open directory is empty
170 |   if [ ! "$(ls -a $jobs_open_path)" ]; then
171 |     echo "there seem to be no open jobs. measuring with default
172 |      parameters."
172 |     prepare_measurement
173 |     #take measurements
174 |     measure | tee -a $log_path/default_$measurement_counter.log
175 |     # create plot if desired
176 |     if [ $plot_enabled -eq 1 ]; then
177 |       plot | tee -a $log_path/default_$measurement_counter.log; fi
178 |   else
179 |     prepare_measurement
180 |     echo "open jobs detected! let's get to work..."
181 |     jobs=$jobs_open_path/*
182 |     for job in $jobs; do
183 |       source $job;
```

```
184        job_name=$(echo $job | rev | cut -d"/" -f1 | rev )
185        log=$log_path/$job_name"_"$measurement_counter.log
186        #echo $job_name
187        cat $job | tee -a $log
188        cat measurement_$link.conf | tee -a $log
189        measure | tee -a $log
190        if [ $plot_enabled -eq 1 ]; then
191          plot | tee -a $log
192        fi
193        if [ $move_after_job_done -eq 1 ]; then
194          cp $job $plot_directory_path/$measurement_counter/
195          mv $job $jobs_done_path/
196        fi
197        export measurement_counter=$((measurement_counter++))
198      done
199    fi
200 }
201
202 if [ $debug_mode -eq 1 ]; then
203   echo "+----------------+"
204   echo "|debug mode active|"
205   echo "+----------------+"
206 fi
207
208 if [ $remote_measurement -eq 1 ]; then
209   # call to main included here
210     setup_remote_connection
211   else
212     main
213 fi
```

LISTING A.1: measure.sh

```
1 import numpy as np
2 import myplot
3 import os
4
5 import rtt
6 import throughput as tp
7 import channel_occupation
8 import backoff
9 import sniffer
10
11 # From Bash
12 measurement = [int(os.environ["measurement_counter"])]
13 links = [int(os.environ["link"])]
14 repetitions = int(os.environ["measurement_repetitions"])
15 data_source_path = os.environ["data_source_path"]
16 plot_path =
       os.environ["plot_directory_path"]+"/"+os.environ["measurement_counter"]+"/"
17 plot_type = ["cdf", "boxplot"]
```

```python
18  throughput_data_files =
        os.environ["throughput_data_files"].split(",")
19  rtt_data_files = os.environ["rtt_data_files"].split(",")
20  co_data_files = os.environ["co_data_files"].split(",")
21  sniffer_data_files = os.environ["sniffer_data_files"].split(",")
22  retxs_data_files = os.environ["retxs_data_files"].split(",")
23  show_plot = int(os.environ["show_plot_after_measurement"])
24  rtt_mode = os.environ["rtt_mode"]
25  max_retxs = 6
26  eval_mode = "live"
27  timer = int(os.environ["timer"])
28  receiver_mode = os.environ["receiver_mode"]
29
30  #From Python
31  plot_pdf = False
32  boxplot_xticks = [ "measurement "+str(index) for index in
        measurement ]
33  legend_labels = [ tick.replace("\n", ", ") for tick in
        boxplot_xticks ]
34
35  custom_legend_coordinates = {
36      "rtt":                  [0.24,0.85,"upper left"],
37      "packet_loss":          [1,0,"lower right"],
38      "retxs":                [1,0,"lower right"],
39      "throughput":           [1,0,"lower right"],
40      "diagnosis_sender":     [1,0,"lower right"],
41      "diagnosis_receiver":   [1,0,"lower right"],
42      "backoff":              [1,0,"lower right"],
43      "channel_occupation":   [1,0,"lower right"],
44      "sniffer":              [1,0,"lower right"]
45  }
46
47  create_plots = {
48      "rtt":                  False,
49      "packet_loss":          False,
50      "retxs":                False,
51      "throughput":           True,
52      "diagnostic":           True,
53      "backoff":              True,
54      "channel_occupation":   True,
55      "sniffer":              True
56  }
57
58  channel_occupation_mode = {
59      "occupation_mode":  ["overview", "zoom"],
60      "zoom":             [5,7],
61      "zoom_mode":        "interval",
62      "zoom_interval":    2
63  }
64
65  sniffer_settings =  {
66      "sniffer_mode":             ["physical", "smoothed"],
67      "link":                     1,
```

```python
68         "zoom":                     [0.0,timer*repetitions],
69         "zoom_mode":                "interval",
70         "zoom_interval":            2,
71         "smoothing_difference":     0.0001,
72         "smoothing_derivative":     0.01,
73         "smoothing_range":          [0.0010,0.0013]
74  }
75
76  #Unimplemented, use later
77  annotations_below   = []
78  annotations_other   = []
79
80  eval_dict = {
81      "measurement":              measurement,
82      "repetitions":              repetitions,
83      "data_source_path":         data_source_path,
84      "xticks":                   boxplot_xticks,
85      "legend":                   legend_labels,
86      "annotations_below":        annotations_below,
87      "annotations_other":        annotations_other,
88      "throughput_data_files":    throughput_data_files,
89      "retxs_data_files":         retxs_data_files,
90      "rtt_data_files":           rtt_data_files,
91      "show_plot":                show_plot,
92      "legend_coordinates":       custom_legend_coordinates,
93      "create_plots":             create_plots,
94      "links":                    links,
95      "rtt_mode":                 rtt_mode,
96      "channel_occupation_mode":  channel_occupation_mode,
97      "co_data_files":            co_data_files,
98      "sniffer_data_files":       sniffer_data_files,
99      "sniffer_settings":         sniffer_settings,
100     "timer":                    timer,
101     "plot_pdf":                 plot_pdf
102 }
103
104 for index,a_plot_type in enumerate(plot_type):
105     if plot_type[index] == "cdf":
106         grid                = True
107     else:
108         grid                = True
109
110     eval_dict["plot_type"]  = [plot_type[index]]
111     eval_dict["plot_path"]  = plot_path
112     eval_dict["grid"]       = grid
113
114     if create_plots["backoff"] == True:
115         print("Creating backoff plot!")
116         backoff.backoff(**eval_dict).plot()
117     if create_plots["rtt"] == True:
118         print("Creating rtt plot!")
119         rtt.rtt(**eval_dict).plot()
120     if create_plots["throughput"] == True:
```

```
121          print("Creating throughput plot!")
122          tp.tp(**eval_dict).plot()
123
124 # The plots with only one plot type!
125 if create_plots["channel_occupation"] == True:
126     print("Creating channel occupation plot!")
127     channel_occupation.channel_occupation(**eval_dict)
128 if create_plots["sniffer"] == True:
129     print("Creating sniffer energy plot!")
130     sniffer.sniffer(**eval_dict)
131
132 print("Done.")
```

LISTING A.2: evaluation.py

# B

## ABBREVIATIONS

**AM** amplitude modulation

**BEB** binary exponential backoff

**BMAC** Berkeley MAC

**CA** carrier aggregation

**CCA** clear channel assessment

**CDMA** code division multiple access

**CDF** cumulative distribution function

**CLI** command line interface

**CSMA** carrier sense multiple access

**CSMA/CA** CSMA with collision avoidance

**CSMA/CD** CSMA with collision detection

**CSAT** carrier sense adaptive transmission

**CTS** clear to send

**CW** contention window

**DC** duty cycle

**DCF** distributed coordination function

**DIFS** DCF interframe spacing

**DIY** do it yourself

**DLL** Data Link Layer

**DOS** denial of service

**DSP** digitial speech processor

**EIFS** extended interframe spacing

**FDMA** Frequency Division Multiple Access

**FM** frequency modulation

**FPGA** field programmable gate array

**GNU** GNU is not Unix

**GR** GNU Radio

**GRC** GNU Radio Companion

**GUI** graphical user interface

**IEEE** Institute for Electrical and Electronics Engineers

**LAA** Licensed Assisted Access

**LabVIEW** Laboratory Virtual Instrumentation Engineering Workbench

**LAN** local area network

**LLC** logical link control

**LBT** listen before talk

**LTE** Long Term Evolution

**MAC** medium access control

**MATLAB** Matrix Laboratory

**MCS** modulation and coding scheme

**MU** medium utilization

**NAV** network allocation vector

**NIC** network interface card

**OFDMA** orthogonal FDMA

**OSI** Open Systems Interconnection

**PCF** point coordination function

**PDU** packet data unit

**PHY** physical (layer)

**PIFS** PCF interframe spacing

**PU** power units

**PMT** polymorphic type

**QOS** quality of service

**QPSK** quadrature phase-shift keying

**RF** radio frequency

**RTS** request to send

**RTT** round-trip time

**RX** receiving/reception

**SDK** software development kit

**SMAC** Sensor MAC

**SDL** supplemental downlink

**SDR** software defined radio

**SDU** service data unit

**SIFS** short interframe spacing

**SWIG** simplified wrapper and interface generator

**TDD** time division duplex

**TDMA** time division multiple access

**TMAC** Timeout MAC

**TX** transmitting/transmission

**UE** user equipment

**UHD** USRP hardware driver

**USRP** universal software radio peripheral

**WLAN** wireless LAN

**WSN** wireless sensor networks

# LIST OF FIGURES

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