System level simulation of passive and active backscatter devices

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Abstract

Ambient Backscatter is a communications method for batteryless, carrier-powered radio devices which harvest the needed energy from ambient sources and send their information by backscattering the ambient radio signals. An ambient backscatter device sends data bit by bit by either backscattering or not backscattering the received carrier wave. This work studies the operation of an ambient backscatter communication system consisting of a transmitter, a number of ambient backscatter devices and a receiver by simulating it in MATLAB. This thesis aims to answer the research questions: when it is better to use either passive or active ambient backscatter devices and what factors primarily affect the maximum data rate, communication range and susceptibility to interference of the devices. A definite answer to the research questions could not be given, but the thesis results show that active aBS-devices have potential of reaching the same performance figures as passive ones in terms of achievable range.

Keywords Backscatter, wireless, network, simulation

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Ambient Backscatter on käsite, joka kuvaa teholähteettömien, ympäristön radiolähetteistä käyttövoimansa haalivien, takaisinsirontaa hyödyntävien radiolaitteiden toimintaa. Laite lähettää oman datansa bitti kerrallaan joko sirottamalla tai olemalla sirottamatta vastaanottamansa radiolähetteen. Tässä työssä tarkastellaan backscatter-laitteiden joukon, yhden lähettimen ja yhden vastaanottimen muodostaman järjestelmän ominaisuuksia MATLAB-simulaation avulla. Simulaation avulla etsitään vastausta tutkimusongelmaan: missä tilanteissa kannattaa käyttää passiivisia ja missä aktiivisia backscatter-laitteita ja mikä tai mitkä ovat rajoittavia tekijöitä tiedonsiirtonopeuden, kantaman tai häiriöalttiuden kannalta. Johtopäätökset työssä saaduista tuloksista eivät yksiselitteisesti tue kumpaakaan laitetyyppiä, mutta osoittavat aktiivisilla aBS-laitteilla olevan kehityspotentiaalia kantaman osalta.

Avainsanat takaisinsironta, langattomuus, verkko, simulaatio

Preface

Wireless, intelligent devices used for short-range communication are shrinking in size as the packaging density of electronics increases. The concept of Internet of Things is largely dependent on ubiquitous independent sensors and other devices providing information about their surroundings to be later processed and analyzed in larger systems. Such small devices, while getting smaller, may soon reach a size limit under which it is difficult to go due to energy requirements. The size of the battery may often dictate the minimum size of a device, and batteries bring about the practical maintenance problem of battery replacement or recharging. Optimally, the operating power should be extracted from the environment somehow. Radio frequency identification devices are powered by the dedicated reader device which simultaneously provides a carrier wave to be modulated by the data that the device wants to send back.

Pioneering researchers in the area of this kind of radio-powered devices have gone even further and introduced the concept of Ambient Backscatter communications by passively modulating the received radio waves from an existing ambient source such as a television transmitter. During the last few years, research has been ongoing and yielded results in areas like detector design and power consumption optimization. To this date, there is little written about the system level behavior of the Ambient Backscatter devices.

This thesis contributes to the simulation of Ambient Backscatter systems where one or more devices are distributed over an area illuminated by the carrier of a transmitter with sufficient power. A receiver is placed in the test bed, accordingly. The devices transmit data independently by backscatter, and might or might not interfere with each other. By running a sufficient number of simulations where a portion of the installed devices transmit, I study the effects on range, interference and throughput of the devices depending on the device type.

Advances in semiconductor technology, miniaturization, the ever-growing data processing capabilities of small devices and the availability of powerful yet affordable software defined radio receivers have enabled research and experimentation in this area that continuously seem to push the limits of radio communication downwards in terms of signal levels that can be distinguished above the noise floor, provided that suitable encoding and modulation schemes and low enough bit rates are used. Simulation can be a tool that enables tighter development cycles, cost reduction and increased reliability of these new wireless devices.

I want to thank Professor Riku Jäntti and my instructor M.Sc. Jari Lietzén for their guidance and patience, and for providing me laboratory measurement data to work on. I also thank Luis de Jussilainen Costa for his invaluable help with the thesis structure.

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Symbols and abbreviations

Symbols

aBS_k	Ambient Backscatter device k (of N), the interesting one
aBS_i	Ambient Backscatter device i (of N), interfering with aBS_k
d_{TR}	Distance between transmitter and receiver
d_{TBk}	Distance between transmitter and aBS-device k
d_{RBk}	Distance between receiver and aBS-device k
E_g	Energy of signal $g(t)$
G	Gain of an antenna or a function block
$g(t)$	Signal as a function of time (t), also $s(t)$, $x(t)$ etc.
k	Boltzmann's constant, $1.38 \cdot 10^{-23} J/K$
kbits/s	Kilobits per second (respectively Mbits for megabits)
N	Total number of aBS-devices (in a simulation)
n	Number of transmitting aBS-devices

Operators

$\sum_i$	sum over index i

Abbreviations

aBS	Ambient Backscatter
ADC	Analog to Digital Converter
AP	Access Point (of a wireless network)
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase-Shift Keying
COTS	Commercial Off-The-Shelf
CSI	Channel State Information
DC	Direct Current
dB	Decibel
dBm	Decibel milliwatt (power respective to one mW)
EIRP	Effective Isotropic Radiated Power
ERP	Effective Radiated Power
FET	Field-Effect Transistor
FPGA	Field-Programmable Gate Array
HF	High Frequency
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
LED	Light Emitting Diode
LF	Low Frequency
MAP	Maximum A Posteriori
ML	Maximum Likelihood
NF	Noise Figure
NFC	Near Field Communication
OFDM	Orthogonal Frequency-Division Multiplex
OOK	On-Off Keying
PDF	Probability Density Function
QR	Quick Response (code)
RF	Radio Frequency
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
RX	Receiver
SDR	Software Defined Radio
SINR	Signal to Interference and Noise Ratio
SIFS	Short Inter-Frame Space
SNR	Signal to Noise Ratio
TX	Transmitter
UHF	Ultra High Frequency
UWB	Ultra Wideband
VHF	Very High Frequency
VNA	Vector Network Analyzer
Wi-Fi	Wireless Fidelity
WISP	Wireless Integrated Sensor Platform

1 Introduction

Radio communication has traditionally consisted of a transmitter and a receiver, or multiple receivers in case of broadcast. Transmitting radio signals is a low efficiency, energy-consuming process, considering the amount of transmitted energy actually conveying information compared to the energy input to the transmitter. Miniature, battery-powered electronic devices containing a transmitter suffer from this inefficiency. As the size of electronic devices gets smaller and their number increases and wireless networking of devices becomes almost always the only feasible alternative, providing energy for the devices becomes a problem. Replacing or recharging batteries to hundreds of small devices, for example in a sensor network can be very tedious, if not impossible. Wireless power transfer can be an alternative way of supplying energy to the devices. Near-field communications (NFC) is a method where either the electric field or the magnetic field of a high-frequency signal is used for data transmission between devices that are considerably closer to each other than the wavelength of the frequency that is being used. The radio frequency (RF) signal is provided by a specific reader device that emits a signal which is sufficiently strong to the small devices nearby. An RF-powered device can also be made to work in far-field of the electromagnetic signal where neither the electric field nor the magnetic field alone dominates. Regardless whether the device operates in the near- or far-field, the received RF signal is rectified in the tag and the rectified DC collected to a large capacitor or a similar storage which can hold enough charge to power the tag for the time it takes to read data from it. Thus, the high frequency field has the dual purpose of both providing energy and enabling communication between the device and the reader. In this way many kinds of small devices can be powered sufficiently to transfer small amounts of data back and forth.

Radio Frequency Identification (RFID) became the first widespread application of small, RF-powered devices. RFID devices are ubiquitous low-power, low data rate transceivers used for transmitting identification information or sensor data, or for indicating when objects which they are attached to pass some control point. Typical uses include product identification, stock monitoring, theft prevention and data acquisition. An important goal is to make RFID devices as simple and inexpensive as possible, as they are often disposable like theft prevention tags. An RFID system has a reader, sometimes called an interrogator and one or more RFID tags located in places or attached to objects of interest (Figure 1).

RFID tags just passively wait to be activated and read by the reader which, as said, also provides the power to them. A tag is not aware of other tags since every tag serves its own purpose, and is unable to initiate any communication by itself, or without the reader which is often human-operated. *Ambient Backscatter* (aBS) is a new communications technology where the devices communicate by scattering radio waves from an ambient source such as a TV station, modulated by the information to be sent. The transmitter carrier may be modulated by any payload signal, analog or digital, voice or data, but that has no significance in aBS, and therefore it is removed at the receiver. Only the backscattered signal from the aBS devices conveys data to be recovered in the receiving end. The broadcast, cellular, Wi-Fi or other

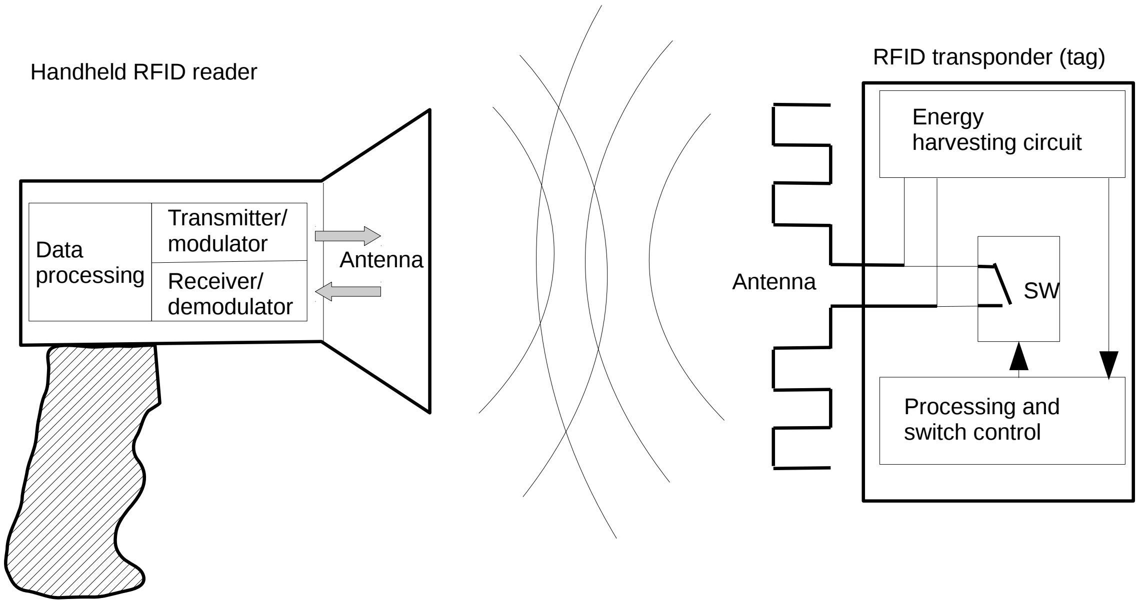

Figure 1: An RFID reader and tag block diagram.

radio service is oblivious to the backscatter communications that are "piggybacking" for a short distance on top of the original transmission. Far-field operation is required for aBS operation as the load modulation method used by NFC employs wavelengths considerably longer than the tag antenna size. Also, the modulation in NFC applications is detected at the reader, whereas in aBS a separate receiver is used. The frequencies used for aBS communications are therefore on UHF or higher frequency bands. Because the power levels are very low and no new radio signals are generated in the process, aBS communications do not violate laws or the licensed service provider's rights [1, p. 3]. The amount of energy drained from the ambient transmission is insignificant, causing practically no loss for the service provider [1, p. 2],[2, p. 13]. A major difference between RFID and aBS communication is that an RFID reader emits an RF signal solely for tag powering and communications purposes and only when needed. In aBS, the transmitter's signal has the purpose of providing its own service and can be considered to be always present.

An overall view of aBS communications is shown in Figure 2. Here, a TV transmitter provides the carrier power for the aBS device. Besides TV, FM broadcast transmitters, cellular phone base stations and Wi-Fi access points (APs) are also suitable for powering aBS-devices. Using the Wi-Fi bands also gives the benefit of powering aBS communications with own equipment. Namely, a drawback in relying on ambient signals from broadcast transmitters or mobile phone base stations is the possibility of service breaks. A broadcast or third-party signal cannot be replaced legally with an own carrier source even if service breaks were of short length. Wi-Fi on the other hand is freely deployable. Nevertheless, broadcast signals can be considered free from interference as the frequencies and channels are allocated solely for that purpose.

Typically, the distance from the transmitter to the aBS devices can be long

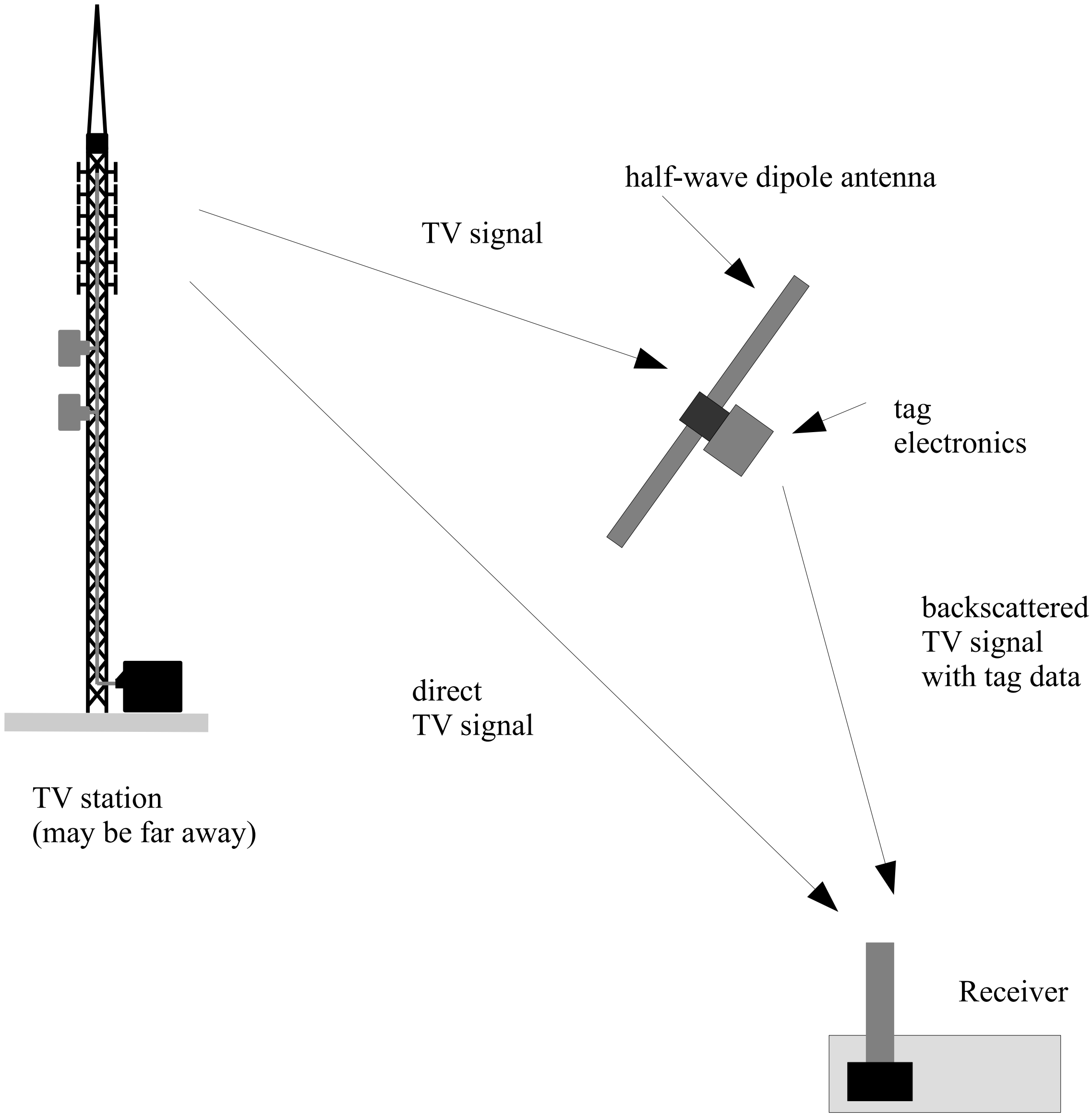

Figure 2: A TV station can provide the carrier for aBS communication.

compared to the distance between the aBS devices, and between an aBS device and the receiver. An aBS sensor bed can employ more than just one receiver and it could also utilize more than one transmitter.

The behavior of aBS devices can be studied by building prototypes for measurement. Simulation is another research tool, as the radio theory of backscatter communications is well understood. The two may complement each other, thus shortening the development cycle and reducing cost. In this thesis a simulator written in MATLAB/GNU Octave for Ambient Backscatter system level simulation is presented. Simulations are run for setups where there are 1 to N aBS-devices of the same type, of which n can be transmitting simultaneously. One aBS-device of interest is placed in the test bed and its position changed during the simulation run. One transmitter is sending a continuous signal on either a fixed or a varying power level. A receiver with a predefined sensitivity and noise figure receives the aBS-device transmissions from which the signal to noise -ratio (SNR) and the signal to noise and interference ratio (SINR) can be calculated.

The goal of this thesis is finding out the performance differences of active and passive aBS-device types with simulation. Three areas of interest are: (i) range, the maximum distance from the receiver where aBS-devices can send data to the receiver with a tolerable bit error rate (BER), (ii) the bit rate that can be achieved and (iii) the tolerance against interference.

Structure of this thesis

From here on the structure of this thesis is as follows: Section 2 discusses the historical background of backscatter communications, the terminology used with backscatter devices, the similarities and differences between RFID and aBS, radio theory that applies to backscatter communications and analyzes the backscatter communications channel in the scope of this thesis. It also presents the prior art in Ambient Backscatter communications and some related work in the RFID area that are important from the viewpoint of this thesis. Section 3 gives the methods and data used in this thesis. Section 4 gives the results of the simulations, verifies them and discusses the validity of assumptions and error margins. Section 5 summarizes the thesis work and discusses the reliability of the results and possibilities of further development.

2 Theoretical background and prior art

This section discusses first the history of backscatter radio communication and RFID, then the development from RFID to Ambient Backscatter. RFID and aBS research work coexist which means that recent research results in RFID can be seen as interesting from the aBS viewpoint. The radio theory behind backscatter communications is explained next. The central RFID and aBS prior art works that give important research results for reaching the thesis goals are presented. Definitions for “active” and “passive” backscatter devices for the scope of this work are made. The section conclusion summarizes the researched backscatter radio prior art from the viewpoint of the thesis goals. Sources of data for the thesis research are identified.

The research work done in Aalto University Comnet laboratory forms another important prior art area. The aBS-device prototypes they have developed give actual data to work on when constructing a computer simulation. These prototypes are all passive aBS devices, and at the time when the measurements were made they were all externally powered instead of being powered by a carrier source. Some of the prototypes were selected for further development and others possibly abandoned, but as the data are available, simulations using even the less successful prototypes can be interesting. The Aalto prototype properties will be discussed in detail in Section 3.

Historical background and RFID

Radio communication using backscattered signals dates back to Harry Stockman’s work from 1948 [3], just after the World War II during which radar development had advanced significantly. He showed that it is possible to detect rotation of an object by directing microwave radiation onto it and receiving the backscattered waves. Earlier, in 1945 an espionage case employing backscattered radio waves had taken place when the U.S. Moscow embassy was eavesdropped. The Soviet Union had given an emblem carved in wood as a gift to the embassy where it was hung on the wall. Containing a resonance cavity responding to speech frequencies, unknown to the embassy personnel, it could be remotely illuminated by microwaves and the backscattered speech-modulated signal received and demodulated [4].

The above two cases are considered to be the first applications of backscattered radio waves to other than object detection purposes. It was not until the era of semiconductors when backscatter communications was possible in a commercially viable scale. Anti-theft devices using resonant metal strips were developed in the 1960s. They operate by draining energy from the reader via inductive coupling and can be deactivated by magnetizing another adjacent metal strip which detunes the resonator strip [5, p. 12]. One early and major RFID application was railroad car monitoring when passing a reader point in the early 1970s [5, p. 16]. Since the 1970s, the market of RFID devices have replaced optically read bar codes especially in environments where bar code markings cannot last for long or have to be read from a longer distance. The benefits of RFID compared to optically read codes such as the bar code or a Quick Response (QR) -code, lies in not needing to be in visual contact with the tagged object. The RFID market is expected to be growing in the coming years especially in the retail area [6]. The RFID devices may utilize different technologies to achieve wanted goals in the most economical way. Anti-theft tags are typically disposable, contactless smart-cards come in both reusable and disposable varieties, and sensors and wireless instrumentation related devices may even be serviceable.

Today, regulations and standards are in place to govern the frequencies, transmitting powers and protocols used by RFID worldwide. RFID frequency bands have been allocated from LF around 135 kHz to UHF and microwave frequencies [7, pp.157–161]. Frequency band allocations for industrial, scientific and medical devices (ISM) exist also from upper HF and lower VHF bands, at around 27 MHz and 40 MHz, respectively. However, the VHF frequencies are somewhat unsuitable for RFID use because the wavelength is too long to be practical in terms of antenna size for far-field operation, and on the other hand the frequency is too high for an NFC magnetic loop to be efficient [7, p.160].

RFID tag and reader types

Considering their energy source, there are three main types of RFID devices (tags). A *passive* RFID tag gets all its energy from the RFID reader signal: it does not have any battery or other power supply. The simplest type of a passive RFID tag is the resonating metal strip used as an anti-theft device. A *semipassive* RFID tag has a battery because its electronics consume significantly more energy due to processing than what would be possible to harvest from the reader's signal. Its radio part, receiver and transmitter, are powered from the reader signal, however. It is also called a "battery-assisted tag". An *active* RFID tag contains a battery that provides energy for all circuitry in the tag. [5, pp. 34–40] There are three main topologies in RFID reader/tag systems. The carrier source and receiver of an RFID reader are typically combined into a single device, a *monostatic* reader. A *bistatic* RFID system uses separate antennas for transmitting and receiving. A *collocated bistatic* system has separate antennas for transmitting and receiving, but they are still in the same place. In a *dislocated bistatic* system the transmitter (TX) and receiver (RX) are separate devices and placed irrespective of each other (Figure 3). With aBS, the receiver and

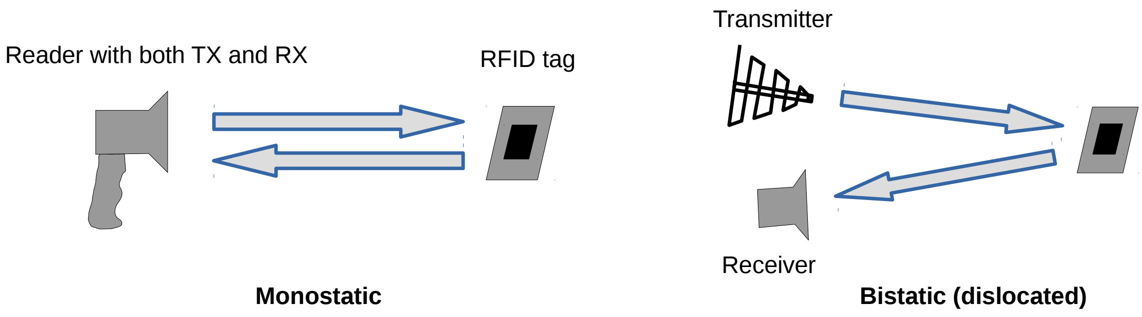

Figure 3: Monostatic RFID reader/interrogator (left) and a bistatic dislocated reading setup (right)

transmitter are typically dislocated and the distance between the receiver and the

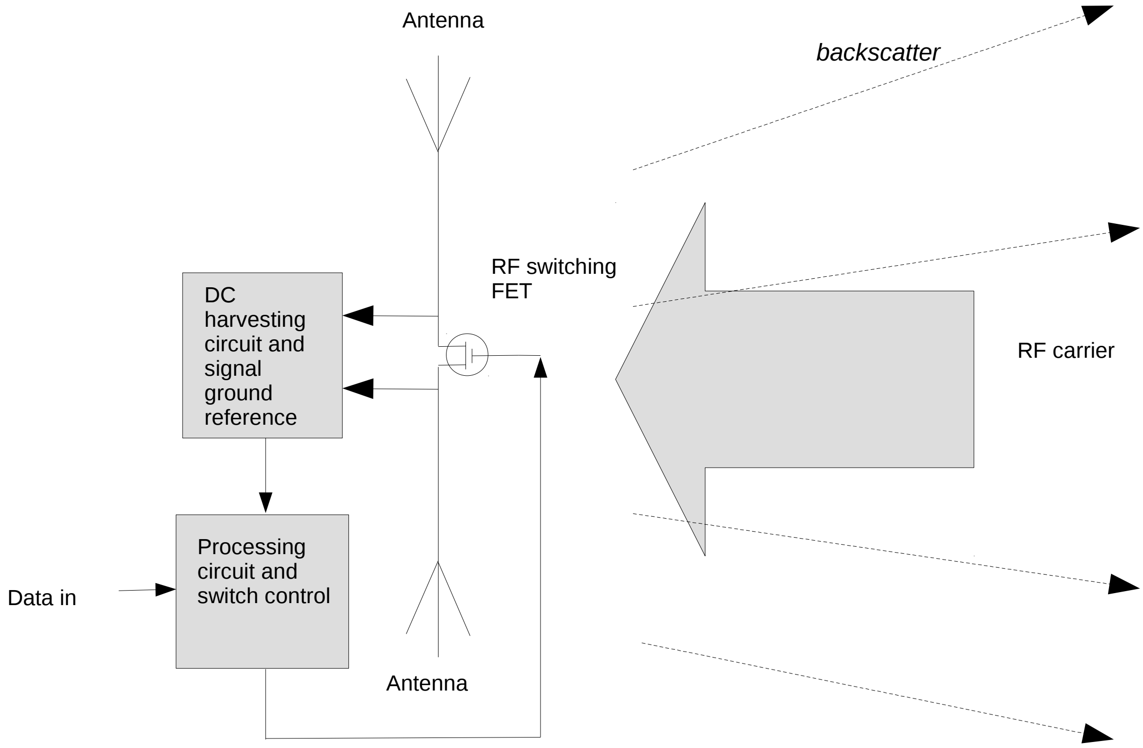

Figure 4: An RF-powered passive backscatter tag in operation.

transmitter (nearest one in case of several transmitters) is considerably greater than the distance from the aBS-devices to the receiver. This means that there are two distinctive radio paths: one from the transmitter to the tag (the power-up link) and another from the tag to the receiver (the backscatter link).[8] Figure 4 shows a block diagram of an RF-powered backscatter device. Signal from the antenna is rectified and the energy is collected to a storage capacitor from which the rest of the circuit will take its operating energy. Tag electronics process the information to be sent, e.g. sensor data, and transmit it by on-off -keying of a semiconductor RF switch, often an FET or a switching diode.

Backscatter radio theory

Radio waves propagate from a transmitter's antenna to a receiver's antenna across a distance and through some medium, in practice either air or the near-vacuum in space. A basic radio communications system such as in Figure 5 contains gains and losses along the path from the transmitter output to the receiver input. Important factors considering wireless power and backscatter communications are the distance between the transmitter antenna and the receiver (an aBS tag or the system receiver), transmitter antenna radiation pattern and receiver antenna pattern. Because the transmitter is operated by an external party, transmitter's output power and transmission line losses at the transmitter end are probably unknown to the aBS system operator. The effective radiated power (ERP) or effective isotropic radiated power (EIRP) of the transmitter's antenna are more important figures than the transmitter's output power when designing an aBS communications system [1, p. 2].

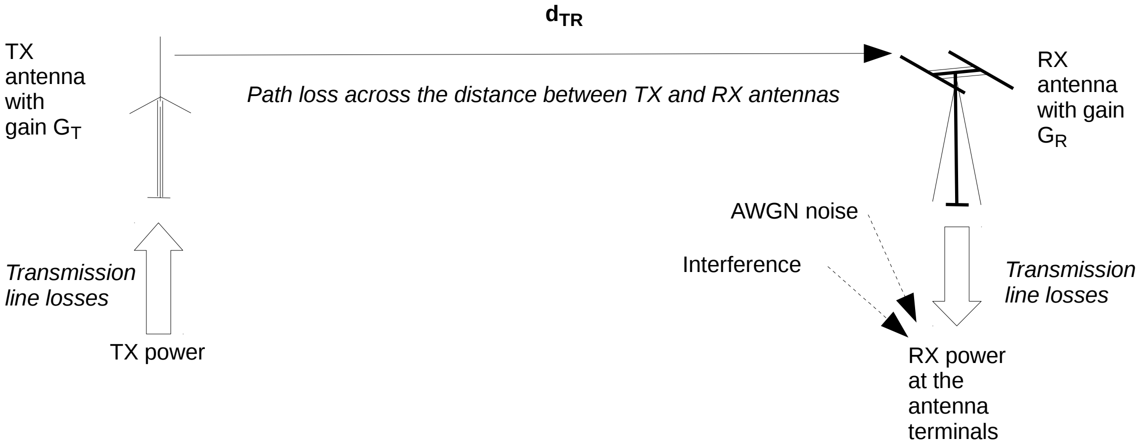

Figure 5: Gains and losses in a radio communications system.

The Friis formula for calculating path loss over a radio link, yielding received power P_R is given in Equation 1 as

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 \tag{1}$$

where P_T is the transmitter power, d is the distance between stations, G_T is the transmitter antenna gain and G_R is the receiver antenna gain [5, p. 87]. The Friis formula can be written in a form that shows the *effective apertures* of the transmitter and receiver antennas. The effective aperture, A_e is the measure of the area that radiates or captures the electromagnetic field efficiently, considering radiation resistance, on its operational wavelength

$$A_{eT} = G_T \left(\frac{\lambda^2}{4\pi}\right) \quad \text{and} \quad A_{eR} = G_R \left(\frac{\lambda^2}{4\pi}\right) \tag{2}$$

where A_{eT} and A_{eR} are antenna apertures of the transmitter and receiver antennas and G_T,G_R are the antenna gains relative to the gain of an isotropic antenna as a dimensionless absolute figure. [9, p. 33-37],[5, p. 87]

In the real world, radio devices are often surrounded by objects that reflect radio waves. At least the ground cannot be disregarded as a reflector. Path models that take ground reflections (or tabletop, roof of a building etc.) into consideration, also include wavefront polarization and ground properties [10, p. 3]. Transmitter signal reflection from the environment forms a major spectral component around the carrier frequency, surrounded by considerably weaker components from backscatter devices as shown in [11]. The direct signal from a transmitter attenuates as the receiver is moved away from it and the signal attenuates according to the inverse of squared distance. A wave reflected from an object or from the ground arrives to the receiver with a phase shift that may differ arbitrarily from the phase of the direct signal and, when summed up in the receiver with the direct signal, might either enhance or attenuate it. Therefore, depending on location, the signal strength may vary considerably. Multipath propagation is a phenomenon that causes difficulties in digital radio communications especially at UHF and higher frequencies, affecting for example UHF RFID [5, p. 94]. In an Ambient Backscatter communications system where all stations (transmitter, aBS-devices and the receiver) are at fixed locations, the multipath propagation from surroundings cause a constant attenuation or emphasis on a locally received signal. In essence, the transmissions of aBS devices are themselves a form of multipath propagation: when the interfering aBS devices are scattering back the transmitter's carrier, the situation is similar to multipath propagation, with the exception that the backscatter is modulated with slow bit rate data by the aBS-device. Therefore, the system receiver must be able to distinguish a particular aBS-device among many others possibly transmitting simultaneously. This is akin to the ability of a person standing in front of a large audience where everyone is waving a hand, to spot one particular person's hand-waving amongst all of them. In both of these cases, perception and processing capability of the received signal, RF or visual, is instrumental.

A radio channel can convey only a limited amount of information. The channel is affected by thermal noise proportional to the channel bandwidth and the receiver antenna temperature. Noise causes bit errors to digital signals using the communications channel. An additive white Gaussian noise (AWGN) channel is a channel model where this thermal noise with Gaussian distribution limits the information throughput. The SNR is a very often used signal quality indicator. It is defined as the ratio of received power and received noise and expressed in decibels as a power ratio as in Equation 3

$$\mathrm{SNR} = 10 \cdot \log_{10} \left(P_{signal} / P_{noise} \right) \tag{3}$$

where P_{signal} is the received signal power and P_{noise} is the channel noise power. The channel noise power is defined as

$$P_{noise} = k \cdot T \cdot B \tag{4}$$

where k is Boltzmann's constant, T the absolute temperature and B the bandwidth in hertz [12, p. 31]. In digital communications it has become common to give the "energy of a bit per hertz of bandwidth" to express the ratio between the energy used for transmitting one bit and the channel noise bandwidth of one hertz. It is denoted usually "EbNo" and calculated by Equation 5 as

$$\mathrm{EbNo} = E_b / N_0 \tag{5}$$

As the energy of an electric signal is its power integrated over a period of time, term Eb in 5 is the energy from the duration of one bit. However, several bits can be encoded in a symbol. In case of OOK or ASK keying, the number of bits and the number of bits per symbol are the same. With a digital signal where bits are coded into symbols, the distance between the symbols is the determining factor for error probability. Noise impulses or signal jitter cause bit inversions. If the distance between two symbols containing multiple bits is small, it likewise requires only a small amount of noise or interference to cause several bit errors. The bit error probability P_b of an OOK signal can be calculated according to [13, p. 519] by

$$P_b = Q\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{6}$$

where Q is the error function. Interference must be taken into account when analyzing the properties of a radio link. SINR contains interference power added to the noise

$$\text{SINR} = P_s/(P_i + P_{noise}) \tag{7}$$

where P_s is the signal power, P_i is the total power of interference and P_{noise} is the noise power at the receiver input. In the case of an aBS device bed where the signal from only one device, aBS_k, is of interest, the remaining aBS devices add to the SINR denominator in Equation 7

$$\text{SINR} = P_k/(P_{noise} + P_{i0} + \sum_i P_i), i \neq k \tag{8}$$

where P_{i0} is the power of interference from other sources. From these equations it can be seen that signal quality improves as its power increases and that increasing the temperature or the bandwidth increase the channel noise and therefore the expected bit error rate is increased.

Interference from other, identical aBS devices to the reception of one particular aBS device's signal depends on several factors. Equation 8 does not take into account reflections or rescattering of the already scattered signal. To keep the interference analysis on a level that fits in this thesis, the rescattering and possibly shadowing by objects or other aBS-devices is ignored. Interference is considered independently distributed and random, although all the aBS devices have the transmitter carrier as a common factor, i.e. they are subjected to power level changes and modulation peaks or valleys. Radio waves travel at a constant speed, nearly that of light, c. The receiver gets a signal from each aBS_n device which

- is delayed by $\tau_n = \frac{(d_{TBn}+d_{BRn})}{c}$ (ignoring any internal delay in the device)
- has an amplitude which depends on the distances d_{TBn} and d_{BRn} (according to equation 1) and the reflection coefficient magnitude $|\text{s}_{11}|$ of the device
- is phase-shifted depending on $d_{TBn} + d_{BRn}$ and the phase angle of the reflection coefficient $\angle s_{11}$ of the device

A radio device in a communications system shares the same medium, the radio channel, with other devices in the network. Devices that operate independently may transmit simultaneously unless a communication protocol is used to prevent such collisions. With RFID, when several RFID-tagged objects are in the read range of the interrogator, several responses may result as well. RFID-equipped goods are often on the move: they could be handled manually or transported on a conveyor belt. In such cases, distinguishing between the tagged items is relatively simple. But with aBS, a large number of sensor tags could be permanently installed in an inaccessible location. Relocating the receiver or directing its antenna could be the only way to pinpoint a particular tag to get its signal. Some sensor tags could be in the fringe area of usable transmitter field strength. If in such case the power that the tag receives fluctuates because of the transmitter's power changes or of because of external factors, for example passing vehicles, communication breaks may occur. Likewise, aBS-devices can interfere with each other causing transmission errors depending on tag-to-receiver distance, antenna radiation patterns and the ratio between harvested and backscattered energies.

To summarize the effect of radio channel conditions to RF-powered small devices on ultrahigh frequencies where wavelengths are measured in centimeters and devices located far away from an energizing radio source, impairments are plenty and conditions challenging. Analyzing the behavior of a network of independent aBS-devices can therefore be complicated. However, the radio theory applicable for e.g. UHF RFID tags applies to UHF aBS devices as well since the underlying radio theory governing wave propagation will be the same.

Active and passive aBS-types

As the driving force in Ambient Backscatter communications is powering by a transmitter carrier, all the aBS-device types are batteryless and hence the definitions of "active" and "passive" aBS-device types have to differ from those in the RFID context. Before going into the prior art of aBS-communications, the following definitions will be made for the purposes of this thesis. Backscatter prior art, both RFID and aBS, supports these definitions although the following terminology is not used there explicitly:

A *passive aBS-device* is powered solely by the transmitter carrier. It does not contain any kind of amplifier, neither does it have an oscillator for transmitting purposes. It passively backscatters its data by keying a semiconductor component on and off, shorting or opening some specific part of the device's antenna circuit. In its simplest form, a passive aBS-device has a semiconductor switch directly connected to its antenna for OOK-modulation. A more complex variant of an aBS-device capable of BPSK or QAM uses transmission line stubs of certain length which are short-circuited, left open or terminated by a resistance with semiconductor switches according to the symbol to be sent.

An *active aBS-device* has for example a *reflection amplifier* which uses a negative-resistance semiconductor device such as the tunnel diode [14], [15]. Tunnel diodes are often associated with oscillators, but in this case it will amplify the impinging signal. The tunnel diode exhibits a negative resistance on a certain forward bias voltage range. Because of this amplification, the tag's reflection coefficient will be above unity in magnitude, but negative i.e. in the opposite phase, for a part of the RF cycle. An active aBS-device could be alternatively designed to use the energy it harvests to power an oscillator. Thus it would be possible to transmit on a completely different (yet legal) frequency than the impinging carrier. An example of a device that is capable of relatively large frequency shifts is introduced in [16]. According to the definition, this kind of aBS-device can be categorized as an active device because it contains an oscillator. However, modeling of this kind of device and network were considered too complex in the simulation framework of this thesis.

Finally, an aBS device can be designed to harvest transmitter carrier energy from multiple sources. One type is the ultra wideband (UWB) backscatter tag that has a broadband antenna capable of gathering signal energy on a wider frequency band, for example from the higher VHF frequencies to the top of the UHF band. A UWB signal occupies a large bandwidth, 20% or more of the center frequency or an absolute bandwidth of 500 MHz or more [17]. From radio theory it is known that narrowband antennas radiate more efficiently than wideband antennas and that an antenna has *reciprocity*: it works equally well for transmitting and receiving [18]. A narrowband antenna could gather sufficient energy for an RFID or aBS tag on a few percent of its dimensioned frequency, but because of it being narrowband, scatter back only a little on frequencies that are far off the center frequency. Thus it follows that a backscatter device either will have to work at (or near) one carrier frequency, or that some of its backscatter capability will be traded for bandwidth. UWB for aBS use could prove to be fruitful as carrier sources are abundant and increasing in numbers as wireless networks on different frequency bands proliferate, but due to its complexity it is out of the scope of this thesis.

Ambient Backscatter prior art

The Ambient Backscatter communications model is introduced in [1] which contributes wireless prototype devices powered only by TV transmissions, capable of communicating also with each other instead of only backscattering their signal to a dedicated receiver. One of their motivations is the energy-efficiency of backscatter radio communications. They also give two applications for aBS communications with their prototypes: a grocery store item misplacement indicator where an LED blinks if an item is put on the wrong shelf, and a bus card application where funds can be transfered from one card to another with ambient backscatter communications activated with finger swiping. Their aBS-devices are built using analog commercial off-the-shelf (COTS) components instead of a dedicated integrated circuit such as a field-programmable gate array (FPGA) or a microcontroller. A UHF TV transmitter's signal was used as the carrier in the 539 MHz DTV band, with 50 MHz bandwidth. Tags have dipole antennas dimensioned to about half of the wavelength. The aBS-devices communicate on a rate of 1 kbit/s over a distance of 0.45 m indoors and 0.75 m outdoors. No interference was caused to TV reception in the tests as long as an aBS-device was not closer than 18 cm from the TV receiver's indoor antenna. Their results confirmed that the aBS communication is possible with the amount of harvested energy, as was shown earlier in [19] and [20]. Their measurements show that their aBS-device requires 0.25μW power for the receiver and 0.54 μW for the transmitter. They also comment on the legality of backscatter communications and note that the distinction is drawn between backscattering existing RF signals and generating RF energy on a band reserved for licensed services. In this prior art work, the principle of aBS-communications with an OOK-device is presented formally. A TV station transmits a fluctuating carrier $x(t)$ is sampled in the system receiver at its Nyquist rate, yielding a discrete-time signal vector $x[n]$. The aBS-device signal consists of this TV signal multiplied by the device's data bits, either 0 or 1, for the respective samples, $B[n]$. They show that the total signal at the receiver's antenna input is therefore

$$y\,[n] = x\,[n] + \alpha B\,[n]\,x\,[n] + w[n], \tag{9}$$

where α is the complex attenuation of the radio path and $w[n]$ is the noise. The adjacent TV signal samples in $x[n]$ are uncorrelated because of sampling at the Nyquist rate which is considerably higher than the transmitting bit rate of the aBS-device. If at some instant, i, N samples are averaged over $1...N$, the bit transmitted by the aBS-device, the receiver can detect this single bit, even in the middle of its state transition, as a change in this average [1, p. 4]. The receiver in the aBS-device consists of an envelope detector with a diode and an RF filtering capacitor, an RC lowpass circuit and a comparator [1, Fig. 6]. The time constant of the RC lowpass circuit is dimensioned according to the bit rate used in the aBS signal to be detected. The comparator output changes state as the detected and filtered average signal changes. This analog solution enables aBS signal reception without resorting to a power-hungry digital signal processor.

The Wi-Fi Backscatter system introduced in [21] has a single carrier source, single backscatter device and a single receiver. The carrier is provided by a Wi-Fi enabled mobile device. The existing Wi-Fi -infrastructure is utilized for aBS-communications. Subsequently, the solution is generalized to work with multiple Wi-Fi base stations as energizers [21, p. 6]. Their Wi-Fi Backscatter aBS-device's transmitter part ASK-modulates and scatters the impinging signal back to the mobile device which can detect it from the changes in received signal strength indicator (RSSI). The distance with RSSI detection was reported to be 30 cm, and 60 cm using channel state information (CSI) with the Intel CSI Toolkit [21, p. 2]. The Wi-Fi Backscatter setup achieved an uplink range is 2.1 m with a bit rate of 1 kbit/s. The duration of a Wi-Fi packet is considerably shorter than the length of a one-bit transmission so RSSI changes within Wi-Fi packets are less probable. In Wi-Fi Backscatter there is no need for a dedicated reader. The power requirement of the aBS-device's RF switch is claimed to be less than 1μW, but the source of this information remained unclear. The receiver adapts to variations due to mobility-induced fading by computing a moving average for 0/1 detection of the RSSI levels. The detector in their aBS-device is similar to that in [1] but with the difference that a peak detector is added between the envelope detector and the RC lowpass circuit. The purpose of the peak detector is to catch the peak values in an OFDM modulated Wi-Fi -signal that has occasionally high peaks but a relatively low average energy [21, p. 6].

Considerable energy savings in aBS communications is achieved in prior art work [22] by performing the computations in the analog domain instead of using an ADC and a microcontroller. The work introduces RFID communication enhancement by using multiple antennas for interference cancelling and a range-extending encoding which also enables duplex communication. The prototype in this paper uses energy harvested from TV transmissions. Until this work, RF-powered devices that make use of ambient RF signals from e.g. TV stations have not been able to distinguish the modulation in the TV signal from noise. Previous multi-antenna designs required amplitude and phase information and the channel estimation has been processing-intensive due to this, and not feasible for battery-less RF-powered devices. Their backscatter "μmo" receiver and "μcode" protocol are firsts in backscatter communications. The receiver uses dual antennas and it is made entirely with analog electronics, thus keeping the required power on a very low level compared to existing multi-antenna receivers with digital processing. This paper does not discuss the technology on the transmitting side of a backscatter device, which interpretation as defined in this thesis may as well be an active device as a passive one, as long as it is capable of OOK modulation.

The "BackFi" backscatter communications system is introduced in [2]. It is a batteryless aBS communication device with a method for transmitting sensor data via backscattering Wi-Fi AP signals for short distances, modulating the sensor data into Wi-Fi packets so that normal Wi-Fi -devices can receive it within a range of 1–5 meters. The throughput in the order of tens of kbit/s to one Mbit/s. The backscatter modulator in this work uses switched RF transmission line stubs which are shorted according to the required phase, thus reflecting RF power back to the antenna port at the desired phase per symbol. The concept of self-interference becomes clear when comparing an RFID system and an ambient backscatter system: The receiver receives both the transmission from the carrier transmitter and the tag signal. In RFID's case, that transmission may be a simple tone, or otherwise known beforehand, but in aBS's case, and BackFi's in particular, the transmission comes from a Wi-Fi AP as a complex signal which cannot be easily modeled with just attenuation and phase shift and therefore difficult to cancel at the receiver.

It is possible to make a Bluetooth device to transmit a single tone by undoing the Bluetooth data whitening [23]. Normally, sending a long sequence of zeros or ones would not result in a single tone transmission due to the data whitening. In this work solution, the whitening sequence is reversed in order to get a single tone. The aBS-device, in this case a body implant, scatters this carrier back as a Wi-Fi packet. Passive, phase-shifting modulation is used to SSB-modulate the carrier. Their modulation method limits the SSB bandwidth so that the modulated signal will fall within the boundaries of the Wi-Fi ISM band.

The frequency-shifted backscatter (FS-Backscatter) communications method presented in [16] enables Wi-Fi and Bluetooth compatible ultra low power backscatter communication. The fundamental idea is to shift the backscattered signal to an adjacent frequency which is still within the licensed band. The design of their FS-Backscatter device achieves a relatively high throughput with low power consumption, by making use of a ring oscillator that also can tolerate the frequency changes in the signal from a moving Wi-Fi device. This work presents Wi-Fi backscatter throughput as a function of distance with two kinds of antenna. The adverse effect of the strong ambient carrier is pointed out which is difficult to separate from the backscattered signal. This issue is addressed by translating the signal to a clean adjacent band. This method makes the FS-Backscatter device an active one as it has an oscillator for transmitting purposes.

A backscatter communications system is presented in [24] where the backscatter device is equipped with an FPGA. It utilizes solely a Wi-Fi infrastructure which means that it can be powered with the user's own equipment. From the viewpoint of this thesis, this device and communications can be seen as aBS because off-the-shelf Wi-Fi devices can enable backscatter communication with the Passive Wi-Fi -device without modifications. A Wi-Fi "Plugged-In Device", an externally powered conventional Wi-Fi client device, serves as one processing node in the system. Another key infrastructural node is a Wi-Fi router which receives the signals. Wi-Fi association is done with that the tag [24, p. 5] The FPGA keys the switching FET on and off short-circuiting the antenna which makes this tag a passive one by the thesis aBS type definition. However, the FET is keyed at a considerably high rate because it is desired to produce Wi-Fi packets. The spectrum of the resulting transmission and the use of an oscillator puts this device into the active category as an aBS device. They analyze the Passive Wi-Fi range by the signal level at the receiver with a modified Friis formula where the reflection coefficient difference $|\Delta\Gamma|^2$ is a variable. They also analyze the Passive Wi-Fi's signal strength, resulting in a "bathtub curve" where the RSSI is lowest when the backscattering device is located halfway between the plugged-in device and the Wi-Fi router. They also describe how it is possible to avoid collisions even when the backscattering device does not actively participate in the channel access procedure. The plugged-in device's carrier sense takes care of free channel monitoring and the backscatter device makes its transmission during the Short Interframe Space (SIFS) so as to keep the channel reserved and other Wi-Fi clients silent. [24, p.6]. A rate of 160 kbits/s is reached and a range in excess of 20 feet (6 m).

An RFID-type device with a tunneling amplifier is presented in [15]. In their experiments the amplifier was externally biased. It is nevertheless possible to construct an energy harvesting circuit in conjunction with the tunneling amplifier, using the same antenna. According to a real tunnel diode's $V - I$ -diagram [15, fig.5], it becomes conducting when forward-biased by even a small voltage, smaller than the threshold voltage of a rectifier diode in the harvesting circuit. Therefore a DC blocking capacitor must be used between the tunnel diode and the antenna. Tunnel diodes may have a significant role in the future in long-range RFID according to [25], hence it is possible that the component will be useful in Ambient Backscatter communications also. In [26] and [27], FM broadcast signals are used for powering backscatter communications. FM frequencies are in the VHF band, which is the lowest Ambient Backscatter frequency in the prior art that was researched for this thesis.

Modulation, receivers and demodulation

Modulation is the method with which one signal is made to carry another signal. There are two distinct places where modulation has a role in an Ambient Backscatter communications chain. The first one, transmitter's own payload modulation is discussed first, then the modulation by the aBS tag itself.

In Ambient Backscatter communications the third party carrier sources are uncontrollable by the aBS-application and use modulations of many different types from analog AM and FM to digital many QAM and PSK variants. The power fluctuations of the transmitter(s) affect the amount of energy that can be harvested and scattered back. [1] shows how an RF-powered aBS tag can recover the backscattered signal from another aBS tag by averaging with a time constant that is considerably longer than the rate of amplitude variations in the transmitter carrier. The digital TV carrier has a complex modulation but averaging removes its effect in the aBS-device.

The aBS-device types described in prior art are capable of OOK modulation. Pure OOK is difficult to achieve with real world components because of the switching devices are not ideal. When ASK modulation is used, the aBS devices scatter back a small amount of signal also in their absorbing state. The difference in backscattered signal strength between the two states is a measure of the power in the modulating baseband ASK signal that is received. Also, it can be seen from prior art results where the s_{11} parameter is measured that on-off -keying the switch also affects the phase of the backscattered wave, modulating the carrier's phase as well. The power put into phase-shifting is wasted in case of OOK/ASK modulation. [28, p.4]

A modulation method ensuring constant power delivery from the reader to the tag is necessary for RFID use. In aBS applications, the transmitter's carrier power might fluctuate so that aBS devices on the fringe area can transmit only intermittently because the power received by the device does not charge its storage capacitor sufficiently. Bandwidth is dependent on the used bit or symbol rate. A trade-off between bit rate and achievable range will have to be made. Selecting a tolerable BER is necessary to be able to compare the different aBS types. Mapping of bits to symbols and using spreading codes can result in an increase in robustness towards bit errors and lower bit error rate. In [29], coding schemes where multiple bits per symbol are shown to possibly increase the data rate that can be reached in aBS communications. The paper shows that long chip sequences yield better SNR and thus improve BER, but lower the data rate. Channel state allowing, lowering the bits per symbol count will increase the data rate with a slight penalty in robustness. In general, robustness of the encoding can increase the range of aBS-devices [p. 1][29].

The weak signals from backscatter devices, either RFID or aBS, place high performance requirements on a receiver. The development of the software defined radio (SDR) has practically been the enabler of aBS communications. With an SDR much weaker signals can be detected among interference and channel noise than what was possible with traditional receiver design. After the introduction of Ambient Backscatter, research has been ongoing for finding reception methods capable of low BER in demodulation. In [30], a maximum likelihood (ML) detector and multiple antennas in the receiver are shown by simulation to increase the probability of detecting the sent bits correctly. In [24], a statistical covariance-based detection method of backscatter signals is proposed, and proved to perform better than an energy detector, yielding an improved BER corresponding to a 1.5 dB increase in SNR [p. 5][24].

Range of backscatter devices

The range of communicating parties is defined as the maximum distance at which communication is still possible, because the received signal is above the noise floor. The noise factor, or more often the noise figure (NF) indicates the noise power added by the receiver to the channel noise. Since the aBS communication is digital, the bit error rate plays a major role. When the received signal gets weaker, the receiver's detector makes wrong decisions when it tries to determine the received bit value, causing bit errors. Regarding equation 1 and 3 and taking into account the energy requirements by the devices it can be concluded that when the bit errors exceed some limit defined for the application in question, the communication channel becomes useless in practice. With backscatter devices that are fully carrier-powered, the farthest distance where a device can work is where it can harvest enough energy to operate. This has to be taken into calculations of link budgets, by including a *fade margin*, a window of available power that will guarantee the operation of the backscatter device with some chosen outage probability [p. 7][8]. In [8] there are small-scale fade margins calculated for RFID tags. Of those, the bistatic dislocated fade margin F_β can be used to give a rough estimate of the fade margin required of an aBS-device sensor application. For example, choosing an outage probability of 5%, fade margins between 6 dB to 19 dB are required per the table in [p. 8][8] in order to reliably power a tag. At the receiver side, it can be concluded that using either passive or active aBS-devices, transmitter power fluctuations are carried over to the signal in the same proportion. As long as the tag stays operative it will scatter back signals but according to the aBS-type definitions of this thesis the backscattered signals should fade accordingly, provided the devices are linear in their function.

Interference susceptibility

Interference is an unwanted radio signal that impairs the reception of a wanted signal. It can originate from the outside of a radio communication network due to external electromagnetic noise sources, from other transmitters, or from other transmitting devices of the network. In backscatter communications, all transmitting aBS-devices in an application operating in the same frequency range cause interference to each other to some degree. One of the goals of this work is finding the difference between active and passive aBS-devices concerning interference. This discussion concentrates on the interference from aBS-devices to each other.

The aBS-devices in e.g. a sensor bed backscattering or absorbing the carrier resemble multipath propagation from objects in the environment. When the scattered waves from unwanted aBS-devices are received (either by the system receiver or an aBS-device), the superimposed signals may either sum up constructively or destructively. With aBS, how device-to-device interference occurs depends on the device type. A passive aBS effectively sends its data by baseband modulation of the impinging RF carrier. An active aBS can either amplify the carrier signal, or convert it to another frequency or band. OOK and ASK are prone to interference like impulse noise because the information being transferred is coded into amplitude variations of OOK to which the noise impulses are added [13, p. 339]. An aBS-device containing an oscillator for frequency translation may seem to be an optimal solution from the interference viewpoint. But as the target band is limited in width due to radio regulations and laws of physics, collisions will occur eventually. For example, if an active aBS backscatters Bluetooth signals to Wi-Fi channels, interference on a particular channel probably results.

Also, in an aBS system the receiver will have to suppress the direct ray signal from the system transmitter(s) and also reflected rays from the ground and surrounding objects. This is also the case with an RFID reader as its transmission can equally well reflect from the ground and objects. What makes the zeroing out more complicated for an aBS system receiver is the payload modulation of the TV transmission of which the receiver has no prior knowledge. While this is feasible for an SDR receiver, for aBS devices receiving each other's transmissions it is a demanding task. The signal processing capability that is required implies larger complexity and especially larger energy consumption. In some cases the task can be accomplished with the help of analog electronics. In [22] the aBS receiver uses analog circuitry for averaging the impinging signal and subtracting signals by analog computations: subtracting the logarithms of two signals before detection with COTS analog components like operational amplifiers, diodes, capacitor and resistors.

The continuous transmitter carrier presence in an aBS system has a twofold effect on the system. Firstly, power is available continuously to the aBS devices and secondly, the carrier is interfering with aBS reception at the receiver. It can be several orders of magnitude greater than the signal received from the aBS-devices. The first point is a necessity for enabling tag-to-tag communications, should the usage case be such, and the second one places high performance requirements to the system receiver. In RFID the carrier comes from the reader and the communication is coordinated, which means that the receiver part of the RFID reader is able to cancel the effect of its own signal. Moreover, the own signal is exactly known at the RFID reader: its magnitude, phase and modulation.

Therefore, the direct transmitter signal itself is a major interferer in an aBS system. With RFID, the tag interrogation protocol takes this into account, but with aBS, the system transmitter is always on and sending its complex digitally modulated signal. The processing capability of an SDR makes it possible to cancel out the direct transmitter signal so that the scattered signals from the aBS-devices can be detected.

Throughput in aBS communications

Throughput is the amount of bits transferred in a time unit. It is expressed as the bit rate, R_b, bits per second. Throughput in backscatter communications is affected by the same factors as other radio communications: signal strength and quality, fading, interference, receiver sensitivity and internal noise, and the overall efficiency of all communicating devices. aBS or RFID backscattering devices transmit on a short energy budget with extremely low power levels, which limits the bit rate. In communications theory it is well known that higher rates of transmitting information require more power in addition to low channel noise and interference compared to the signal level. The efficiency of the selected modulation, and an encoding that makes the most use of the modulation are important. It has been shown that choosing the most appropriate encoding of bits into symbols for a particular purpose has a large effect on throughput improvement [31, p. 6]. By designing an FPGA especially for backscatter communications purposes as in [24], a bit rate of 11 Mbits/s can be achieved with a power requirement that is four orders of magnitude below that of commercial Wi-Fi chipsets [p. 1][24]. The Passive Wi-Fi backscatters the Wi-Fi carrier as its own data frames without an own power supply. This prior art work is the first one to demonstrate the feasibility of making 802.11b aBS-transmissions.

In the scope of this thesis, focus is on the difference between active and passive aBS-devices in terms of maximum achievable R_b. The question is, whether higher bit rates are more economical on one type over the other if the energy budget of the both is the same. Referring to the definition of active aBS-device, it may contain an amplifier which is powered by the harvested energy. In most digital communications where networked devices are continuously powered, throughput is not a function of available energy. Backscatter communications powered by radio signals are different in this aspect. The amount of energy that a backscatter device has to collect to be able to transmit data depends on the tag's energy consumption and the number of bits the tag should send while its transmitting.

Devices powered by radio signals typically contain an energy harvesting circuitry, made with capacitors and diodes. These components can be connected as a voltage multiplier in order to raise the operating voltage of the tag components [5, p. 202]. Naturally, the multiplier cannot make energy out of nothing, so the cost of multiplied voltage is a decrease in available current. The impinging radio signal has to be large enough to exceed the threshold voltage of the rectifier diodes. Capacitors used in the circuitry must be low-loss and low-leakage types. Once energy has been accumulated sufficiently, the tag can perform its data processing task and scatter back its information. The harvesting circuitry has an efficiency factor which can be in the order of a few percents. The impinging signal from Equation 1 multiplied by this factor yields the available total power for computing and backscattering in the device. [32, p. 7]

The energy efficiency of a backscatter tag, be it RFID or aBS, affects the achievable throughput because the device has to operate alternating between harvesting and backscattering states. The *duty cycle* of an aBS-device is in this work defined as the ratio between the time when its is harvesting energy and the time when it is transmitting, slightly differing from the active RFID tag duty cycle definition in [5, p.195]. There a backscatter device, e.g. a sensor is seen as a state machine that alternates between sleep, sensing and transmitting. Unlike an externally powered tag, when a backscatter device goes from the harvesting state to the backscattering state, it can remain there only for the while the storage capacitor holds enough charge to power all electronics in the device [33, p. 3]. While the switching device itself, e.g. an FET, does not require much power, it short-circuits the antenna elements when conducting, preventing energy harvesting.

It should be noted that the device duty cycle is a different concept the duty cycle of an OOK signal, although the two are related. It depends on the used communications protocol and tag energy efficiency whether there are harvesting periods within message transmissions or only in between them. For example, the tag circuitry might need a minimum period of time to complete its data processing task during which the tag does not transmit in order to conserve energy, then transmit the processed information and at the end of the cycle harvest energy again to repeat the action. Ideally, the shorter the harvesting time, the more efficient the tag is in terms of throughput as it can transmit data for the most part of the cycle. When the distance between the tag and its carrier source is increased, received power in the tag antenna drops quadratically according to free space radio signal propagation laws (Equation 1). At some point the transmitter carrier level will drop below what is required for energy harvesting and the tag will stop working. When OOK or ASK modulation is used, it is noteworthy that ASK allows for supplying power from the harvesting circuitry in both 0- and 1-states of the modulation unlike OOK [8, p. 6].

Thus it can be concluded that also the duty cycle has an impact on throughput. On one hand, more data can be sent during a long on-period and on the other hand high data rates consume more energy per bit. Whether a fast bit rate in short bursts during the transmit period is better than a slow bit rate in a longer on-period is however a less interesting question in the active-or-passive -comparison.

Section conclusions

This section has discussed the theory behind Ambient Backscatter and how it relates to the RFID world. Radio communications principles have been reviewed for the relevant parts of this work. From the prior art sources, information can be gathered to synthesize a pair of competing aBS-devices, one active and one passive, that can be put to trial with the help of simulation. While passive aBS technology was well covered, and based on the tried and well known art of RFID, active aBS is more lacking in actual implementations. However, deducing from the works covering active aBS and amplifying RFID devices, a model of an active aBS device can be constructed in a similar way as with an amplifying RFID tag.

After this research in the prior art of aBS, the overall benefits of an active aBS over a passive one or vice versa, can be summarized as follows:

– Passive aBS devices which possess limited modulation capabilities of the ASK family could conserve energy by encoding the sent data into an alphabet where zero-bits are predominant. There is little else that can be done to improve their efficiency.

– An amplifying active aBS can be seen as an improved version of the passive aBS since the magnitude of its s_{11} parameter could exceed that of the passive aBS but be otherwise similar in performance. Which is more energy-efficient probably depends on the other circuitry of the device, for example the part supplying bias current to the amplifying component.

– A passive aBS-device where the antenna switching component is controlled by an oscillator which is modulated by the data to be sent spreads its backscattered signal to a wider band than a device operating on baseband modulation. Prior art has examples of devices where this method is used to get higher bit rates, sometimes called *sideband modulation* [p. 2][23]. It is difficult to categorize such a device as either active or passive, because when a transmitter is defined as something "containing an oscillator for transmitting", a carrier oscillator is usually meant. The spectrum of the output signal of a sideband-modulating device might spread outside the legal frequency band. Nevertheless, the technology looks promising. Naturally, an OOK signal in the baseband also creates sidebands but they are just closer to the center frequency than those of the sideband-modulating device.

– An active aBS device of the type that has a carrier oscillator, such as the an oscillating tunnel diode, could send its data in bursts between harvesting periods, using a suitable form of amplitude or angle modulation. Such device would just be an ordinary transmitter, albeit an RF-powered one.

– If an active aBS was designed to convert its output frequency to another band, tag-to-tag -communication would become more complicated as all tags would have to be able to receive both the incoming TX carrier for powering on one band and the converted signal the other.

For an easier comparison between active and passive aBS devices, it is assumed that the active aBS is of the amplifying kind and that both device types use OOK. Prior art work results [15] and [14] provide good material for simulating an active aBS-device of the amplifying variety. The frequency-shifting backscatter device type cannot be considered as a candidate for the comparison because technically it does not scatter back anything, just transmit with harvested energy by using an oscillator for a period of its duty cycle. In the next section, the selected aBS-device types for the simulation will be presented.

3 Research material and methods

In this section the material and methods used for writing this thesis are presented. The structure and flow of the MATLAB scripts are described on a high level. Data from prototype aBS-devices (passive aBS) and from and previous art experiments (active aBS) that are used as the research material are presented.

The selected research method aims for answering the research questions about the range, interference susceptibility and achievable data rate of active and passive aBS-devices. The problem is approached by putting theoretical results to practice in form of MATLAB functions simulating radio devices, using prior art measurement results from actual aBS-devices and related RF-powered backscatter devices. Applying this experimental method is limited by simplifications in the simulation environment. ASK modulation was chosen as the only one, leaving other possible, and possibly more efficient modulations outside the simulation.

During the research on the aBS prior art and RFID technology for this thesis, it became apparent that an amplifier in an aBS-device would make it only insignificantly different from a passive one in other respects than the level of backscattered power. If an aBS-device is thought as a one-port black box which scatters signals back according to its s_{11} parameter, keyed on and off, the internals of the device are of little interest performance-wise (as per thesis goals). Active devices could have other virtues, like overcoming device losses by amplification, providing a subcarrier for modulation or being more capable than a passive device in creating arbitrary phase shifts to the impinging signal. But if the devices were not simulated, there would be no information to base conclusions on. For this reason the active devices will be simulated nevertheless.

The overall work order towards solving the thesis goals is:

1. Design the models of passive and active aBS-devices, using data from Aalto Comnet laboratory passive aBS-device prototypes (later referred to as the "Aalto prototypes" or by their designators p1–p8) and from active backscatter communications prior art data;

2. Simulate the signal level from each aBS-device to the receiver in different positions, one at a time, without interference, on all the frequency ranges in the laboratory data, considering transmitter power fluctuation;

3. Simulate the effect of interference to the received signal from one aBS-device, on a frequency band that is common for all device types

4. Examine the results in order to find the best performing devices (definition will follow);

5. Estimate how much better either type (active or passive) should be in order to reach the same performance figures.

The most interesting location in the signal level simulations is the one (if there is only one) where the backscattered signal level input to the system receiver is at lowest. Concluding from Equation 1, the signal level can be expected to be at its lowest when the distance d is longest from the aBS-device to both the receiver and the transmitter. In addition to considering the received level, the difference between backscattered and not backscattered power is a measure of transmitted baseband ASK signal level, as ASK is the chosen modulation. Deducing from the above, the "best" aBS-device can be identified in terms of signal strength as the one which has both of these qualities. If there is uncertainty, the device which has a smaller change in its $\angle s_{11}$ value is better, because the smaller the angle, the less energy is wasted on a modulation that will not be received by the ASK receiver. The minimum off-state signal strength at the weakest signal position amongst all the simulated devices is selected as the receiver sensitivity level. The bit rate that the aBS-devices can support at a given BER is then calculated by applying Equation 5.

The simulated radio path

The central results in radio theory on which the MATLAB simulation in this thesis is based are Equations 1, 4 and 3. Equation 1 is applied to all hops in the communication chain: from TX to aBS-devices first, then from aBS-devices to the receiver. In order to be able to determine the performance of aBS-devices in the simulated system, the following parameters are needed in addition to the simulated aBS-device models:

– the positions of the transmitter, aBS-devices and the receiver

– transmitter power and frequency

– radiation patterns and gains of all antennas

– bandwidth of the backscattered signal and the temperature

The whole communication chain from the transmitter via an aBS device k to the receiver can be modeled as follows:

$$P_T \xrightarrow{TL} G_{Tk} \xrightarrow{\alpha_{TBk}} G_{TBk} \xrightarrow{TL} s_{11}(\mathrm{aBS_k}) \xrightarrow{TL} G_{RBk} \xrightarrow{\alpha_{RBk}} G_{Rk} \xrightarrow{TL} P_R$$

where α is the path loss across the distance between stations, s_{11} is the aBS device's scattering parameter and TL is a transmission line. The subscript k at an antenna is the gain to the direction of the aBS device k or from/to the direction of the transmitter and receiver, respectively. For clarity, in this work the index is always written last regardless of the to-from -direction.

In the simulator, a carrier of constant frequency is used as the energizing signal. This means that the phase of the backscattered signal from an aBS-device k at the receiver's antenna can be calculated as follows

$$\phi_{RXk} = \left(\phi_0 + 360 \cdot \frac{\mathrm{d_{TB\mathit{k}}}}{\lambda} + \angle s_{11} + 360 \cdot \frac{\mathrm{d_{RB\mathit{k}}}}{\lambda}\right) \bmod 360 \tag{10}$$

where λ is the wavelength, ϕ_0 the transmitter signal's phase angle at the transmitter antenna at some instant (time-frozen wave), d_{TBk} is the distance from the transmitter to aBS_k, d_{RBk} the distance from aBS_k to the receiver, and $\angle s_{11}$ is the phase shift in aBS_k according to its scattering parameter in either off- or on-state. Phase angles are here given in degrees. Equation 10 will yield the phase of the direct ray signal from the transmitter to the receiver by leaving out $\angle s_{11}$ and substituting the transmitter-receiver -distance for d_{TBk} and d_{RBk}. Two parameters are kept constant in all simulations: the absolute temperature of the receiving antenna and the encoding of bits to symbols, the latter being one bit per symbol for OOK/ASK.

The simulated radio devices

The radio devices in the simulated environment are the system transmitter, N aBS-devices and the system receiver. All aBS-devices in one simulation are of the same type. As stated in the research problem, any number $n \leq N$ of the aBS-devices can be set to either transmitting or not, corresponding to backscattering and not backscattering the signal with OOK/ASK modulation. One of the aBS-devices is considered the interesting one, the rest are interfering. In simulations without interference, only one aBS-device is placed in the test bed. The system transmitter is characterized by its frequency, power and antenna pattern. The emitted signal is constant-amplitude, constant frequency which simplifies the simulation. The transmitter's antenna is omnidirectional and is divided into 60 sectors of 6 degrees. In this vector the gain of the antenna can be set as an absolute number. All radio devices in the simulator use this antenna model. There are no transmission lines to consider, all the transmitting power will go to the antenna and radiate in 2-D according to the antenna pattern. Should a more complex antenna radiation pattern be wanted so that the antenna would have directivity, the antenna pattern vector could be set to contain multipliers for each sector (default is 1 for an omnidirectional antenna). Also, rotating the antenna would be very simple by rotating the contents of the vector. This property, although not used in the simulations of this thesis, would be useful for setting random azimuthal angles for the randomly placed aBS-devices in some test bed.

The aBS-devices are treated as "black boxes" which receive the transmitter signal, harvest power from the transmission and scatter back the signal according to the state they are put in. The device amplifies, or attenuates, the impinging transmitter signal by $|s_{11}|$ decibels and causes a phase shift of $\angle s_{11}$ degrees. These device data are an exception in the simulator's input data: decibels are used instead of absolute numbers. This way it is easier to check the device data from prior art in case an error was suspected.

There is sufficient information on passive aBS-devices in prior art for this thesis. For the comparison between an active and a passive aBS stated in the research problem, information about active aBS's is also needed. This thesis uses results from prior art to synthesize two active aBS device models. Although the frequencies used in the research papers were much higher than those used in Aalto prototype evaluation (5.5 GHz instead of 2.4 GHz), a reflection amplifier suitably redimensioned can be expected to work well on a lower frequency band. It is also assumed that the simulated aBS-device models are linear, i.e. that the device's s_{11}-parameter does not depend on the impinging RF power. An active aBS-device has been modeled, according to the definition made in the Prior art section, by using the topology of amplifier-equipped active RFID tags in Table 1 as an example. Note that in table 1

Table 1: Active aBS-device data from [15] and [14], parameters in the 5.5 GHz frequency range (n/a = not available).

Proto/ paper	Bias power μW	P_{in} dBm	Gain dB	$\angle s_{11(OFF)}$ deg	$\angle s_{11(ON)}$ deg
a1/[15]	45	-50	34.4	91	-140
a2/[15]	47	-50	22.1	80	-133
a3/[14]	29	-60	20	n/a	n/a

the device "a3" has no phase information. It is shown for completeness only and not used in simulations. Using these data for simulating aBS-devices on the 2.4 GHz frequency band requires assumptions about the gain and phase. The gain is given in prior art in decibels, but as not on- and off-state values as with the Aalto prototypes. Hence the gain must be converted to on- and off-state values for both the 5.5 GHz and 2.4 GHz bands so that the difference is equal to the gain. In practice, an aBS-device has losses which should be estimated and subtracted from the gain. The gain has been normalized so that the on-state backscattered signal of the active aBS-devices is at the 0 dB level and the off-state is below that by the number given as the gain. This assumption is based on the working signal of the reflection amplifiers measured in prior art, where the impinging power level was in the order of -50 dBm. From this it can be deduced that because the amplifier was observed to work properly at that signal level, it would also work on higher signal input levels. But an aBS-device can accumulate only a limited amount of energy during its harvesting period, so there has to be an upper limit also. It is unlikely that any active aBS-tag using a small-signal tunnel diode could put out a signal stronger than e.g. 20 dBm (0.1 W) due to its power rating, and not for a long period of time. The accumulated charge in the storage capacitor of such an active aBS-device would drain fast.

In the light of passive aBS-device prior art data, 0 dB as the on-state level seemed realistic. This means that the amplifier would cancel out the effect of the device losses. Therefore the gain scaling has been made by setting the on-state gains of the active aBS-devices a1 and a2 at 0 dB and the off-state gain -34.4 dB below it for a1 and 22.1 dB for a2. The 0 dB on-state as an upper limit is safe also from a legality viewpoint with real devices: there hardly is an issue with a device scattering back everything, but not more, of the signal radiated onto it. The phase angles are used unmodified as given in Table 1 in simulations at 5.5 GHz. For operation in the 2.4 GHz band, arbitrary on- and off-state phase angles have been chosen. These, as well as the difference between $\angle s_{11(OFF)}$ and $\angle s_{11(ON)}$, are realistic compared to those of the Aalto prototypes.

The simulator's system receiver is simply a point in the (x, y)-plane where signal measurements are made. A level is chosen at and above which the signal from an aBS-device can detected with a given bit error probability will result in receiving "0" and "1" levels reliably, when both the bits per symbol, M, and bit rate are fixed. The power fluctuation of the transmitter's output may cause an aBS-device's signal to fall below the receiver's sensitivity. This segment in signal levels is highly interesting as there might be performance differences between aBS-devices to be discovered.

MATLAB simulator structure

The simulator consists of a set of MATLAB scripts that are also GNU Octave compatible. All input data is given and output is written as comma-separated files (CSV). The main script has one main function "mainsimulator" which calls other self-written functions stored as separate MATLAB-files to perform file input, calculations and output. Plotting of the results is made with a separate script, so the intermediate results can be reviewed before creating graphs or tables. All functions except generic MATLAB functions are self-written. No communications libraries or similar modules were used.

The simulator reads first all test environment constants from a CSV-file. These are:

- x- and y-coordinates of the transmitter, in meters
- x- and y-coordinates of the receiver, in meters
- starting transmitter power in watts
- receiver antenna input impedance in ohms
- number of 3 dB transmitter power increment/decrement loops
- bit rate in bits/s
- absolute temperature in degrees Kelvin.

Next, the CSV-files given by the user in the function call are read. There are three files: the first one specifies the positions of the aBS-devices in the simulation test bed in (x, y) -coordinates and whether the device is transmitting or not, and whether it is "interesting" or not. An interesting device is the aBS_k which is being observed and the rest are interfering aBS_i devices. The interfering devices stay put in their given locations but the interesting device is moved so that its positions walk through the list of coordinates from the beginning of the file to the end. The positions can be specified in any order in the position-file. The interfering aBS_i-devices that are present scatter back the transmitter signal also in their off-state so if an interfering device must be muted, it must be removed from the position-file altogether. The second input file is the s_{11}-model of the devices which all are of the same type in one simulation run. This file specifies $|s_{11}|$ and $\angle s_{11}$ for off- and on-states in decibels and degrees. The last file in the function call is the output file, to which results are written. The simulator also copies all input data and test constants to the output file as columns. This way the contents of a simulation run can be kept in one place and configuration files regenerated as needed. The data written to output has at least 19 columns of which columns 1–7 are the test constants, 8 is the calculated absolute receiver AWGN channel noise power, 9–12 the transmitter and receiver coordinates, 13 the direct signal power from transmitter to receiver, 14-17 the position data of aBS-devices. Columns 18 and 19 are the results of the observed aBS_k-device's performance: its power at the receiver and the SINR of its signal. In case the transmitter power is incremented or decremented for power fluctuation simulation, there will be one column for each iteration, containing the received aBS_k signal power as an absolute number. All three file specifications have default values so that a basic test can be run for verifying the proper operation of the simulator with always the same files. There is no interactivity in the simulator. The function "mainsimulator" returns the same data array as is written into the output file. A sample file can be found in Appendix C. Simulating transmitter power fluctuation is achieved by incrementing or decrementing the given starting power by 3 dB. The parameter for this purpose is an integer in the testconstants.csv -file. If the parameter is zero, a single simulation will be run. With a positive value, the power is incremented on each round, i.e. +3 dB added, with a negative value −3 dB is added (the round counter is the absolute value of this integer). The total number of simulation rounds includes the one with the starting power.

Figure 6 shows the simulator's function blocks with one aBS-device, one transmitter and one receiver. The radio signal goes through the antenna pattern to and from

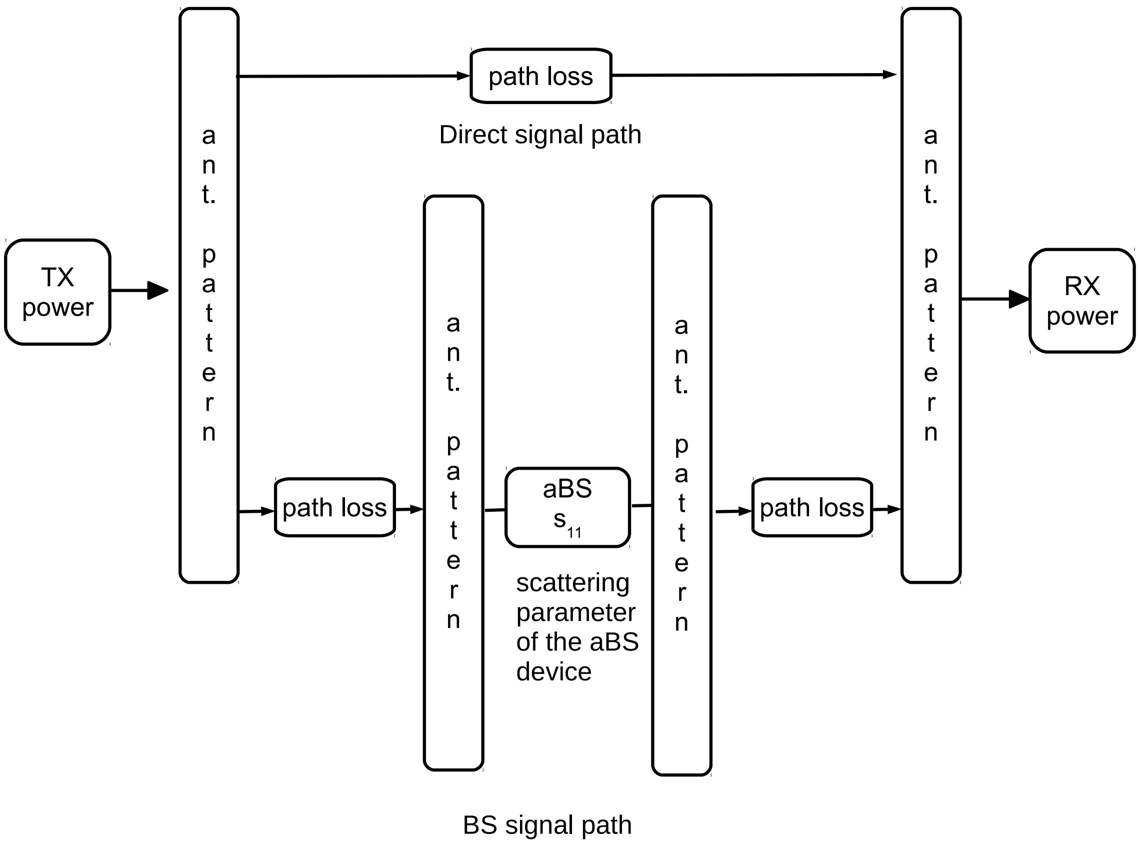

Figure 6: Function blocks in the simulation.

devices. In MATLAB code this is a 60-element numerical vector of absolute gain numbers. Every sector "points" towards other stations that also have an identical vector but with their own gain data. This is illustrated more clearly in Figure 7. Figure 8 is a schematic representation of some simulated radio devices. An aBS-device

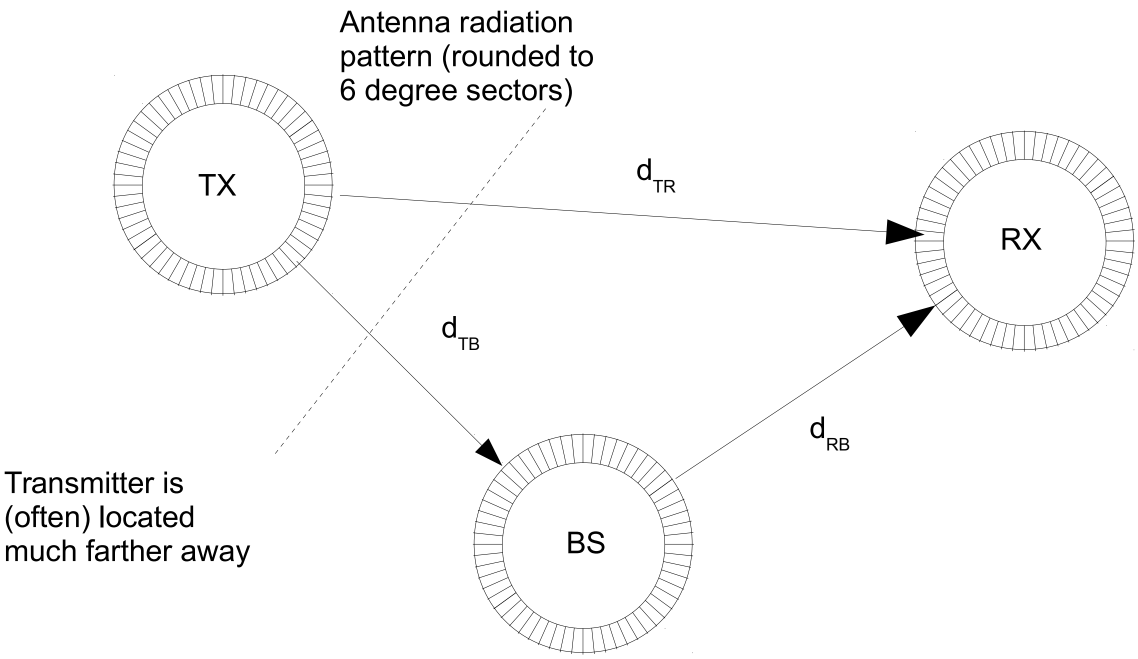

Figure 7: Radio devices and their simplified antenna patterns.

can be either transmitting (double or heavy outer circle) or not (thin outer circle) and it can be the device of interest aBS_k (grey disk) or an interfering one (white disk).

Limitations and assumptions

In order to keep the simulator's functionality within the scope of this thesis, the following assumptions are made:

- Simulation is stationary and in two dimensions only.
- The surrounding medium is air or vacuum.
- Reflections from the surroundings are considered insignificant.
- Rescattering (aBS–aBS) is considered insignificant.
- There are no transmission lines causing delay or losses.
- Far-field radio communication is the basic assumption.
- Modulation by OOK is selected as it is possible for both aBS-types.

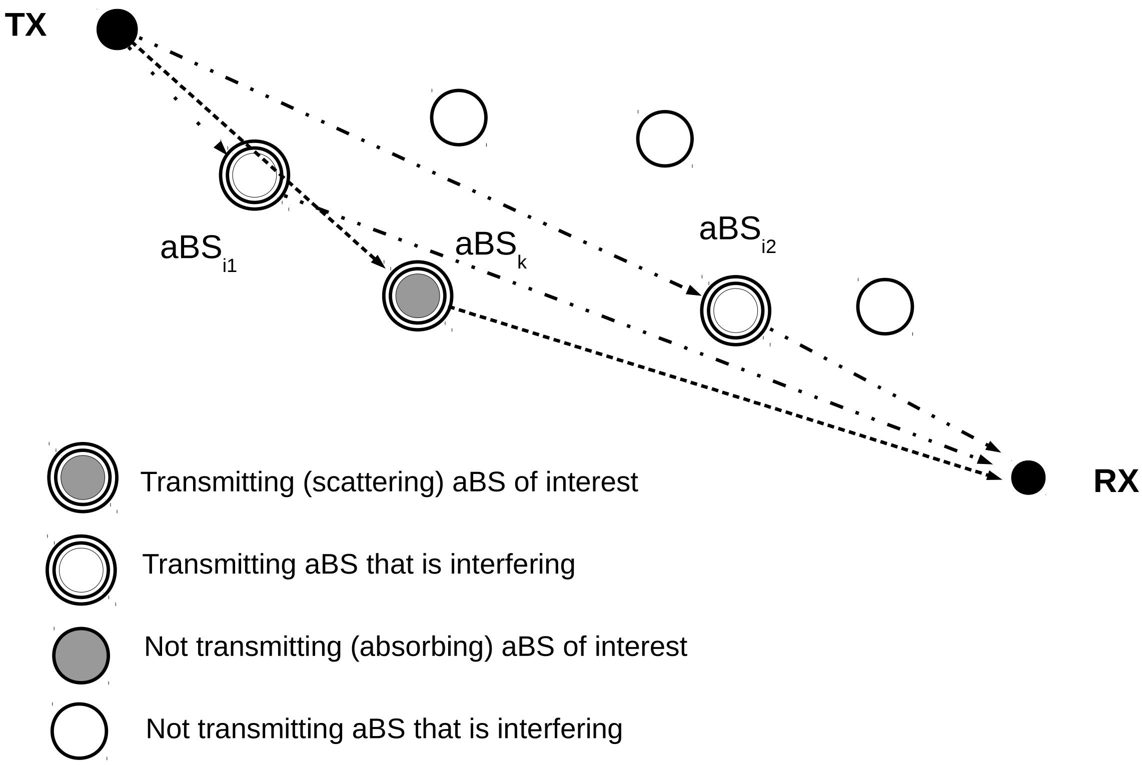

Figure 8: One interesting aBS transmitting, two interfering and three interfering are not transmitting.

– The energy harvesting circuit efficiency is assumed to be 100%.

– All aBS-devices are assumed to perform linearly over their whole operating range.

Data

In this subsection the data that are used for input of the simulator are given. The Aalto prototypes are passive aBS-devices built by the Aalto University Comnet laboratory. Aalto prototype numbers 1–4 were developed first and prototype numbers 5–8 were developed later. The scattering parameters were measured on frequencies between 100 MHz and 2420 MHz for devices 1–4 and between 590 MHz and 2420 MHz for devices 5–8. The devices 5–8 were originally color-coded blue, brown, green and orange according to the color of the connecting wires. The numbers were given in this work for consistency. These data were extracted from graphs produced by a vector network analyzer (VNA). The s_{11} values at frequencies around 590 MHz and 2400 MHz were chosen because these are common for all Aalto prototypes. In the 2.4 GHz band the exact frequencies differ by 20 MHz (2400 and 2420). The data are listed in Table 2 and Table 3.

Table 2: Aalto prototype s_{11} parameters in dB and degrees at 590 MHz.

Number	$\|s_{11(OFF)}\|$	$\|s_{11(ON)}\|$	$\angle s_{11(OFF)}$	$\angle s_{11(ON)}$
1	−28.11	−0.4042	79.046°	74.271°
2	−17.342	−0.2669	151.31°	73.767°
3	−13.693	−1.0709	158.11°	63.618°
4	−34.823	−7.502	118.75°	77.517°
5	−26.871	−0.2961	116.0°	126.04°
6	−26.995	−0.2725	114.61°	127.42°
7	−28.636	−0.3002	143.78°	129.44°
8	−26.987	−0.2980	115.1°	126.33°

Table 3: Aalto prototype s_{11} parameters in dB and degrees at 2.4 GHz.

Number	$\|s_{11(OFF)}\|$	$\|s_{11(ON)}\|$	$\angle s_{11(OFF)}$	$\angle s_{11(ON)}$
1	−19.229	−2.2087	−150.06°	120.52°
2	−3.2944	−2.3321	−178.53°	112.85°
3	−3.754	−4.9113	122.65°	95.704°
4	−26.212	−8.8998	−99.455°	120.11°
5	−17.656	−2.121	57.164°	−27.314°
6	−17.991	−1.8433	58.905°	−22.359°
7	−19.17	−2.3075	106.02°	−28.785°
8	−18.028	−2.0713	60.05°	−26.322°

Manual calculations

In the following example there are manually calculated the power levels at the system receiver from two aBS-devices according to the same method that the MATLAB simulator uses. The calculations are shown in steps with intermediate results. The following parameters apply (coordinates in meters, antennas are isotropic):

- TX position $(-2, 0)$, power 10 mW
- RX position $(2, 0)$, input impedance 50 Ω pure resistance
- aBS$_k$ position $(0, 0)$ (interesting)
- aBS$_i$ position $(1, 0)$ (interfering)
- aBS 590 MHz s_{11} parameters Aalto for Prototype 1

For prototype 1, s_{11} values can be found in the first row of Table 2). The antenna patterns are circular and rounded to sectors of 6° so the radiated power to one sector is 1/60th of the total power. With these data, Equation 1 yields the impinging power to the aBS$_k$-device in watts:

$$P_{TBk} = 0.01\ \text{W} \cdot \frac{1}{60} \cdot \left(\frac{0.50812\ \text{m}}{4 \cdot \pi \cdot 2\ \text{m}}\right)^2 = 6.8125 \cdot 10^{-8}\ \text{W}$$

Next multiply the result with the $|s_{11}|$ value converted to an absolute number. When aBS$_k$ is in off-state, the power out of the device's antenna is:

$$P_{RBk(OFF)} = 6.8125 \cdot 10^{-8}\ \text{W} \cdot 10^{\frac{-28.11}{10}} = 1.0527 \cdot 10^{-10}\ \text{W}$$

alternatively, when aBS$_k$ is in on-state:

$$P_{RBk(ON)} = 6.8125 \cdot 10^{-8}\ \text{W} \cdot 10^{\frac{-0.4042}{10}} = 6.207 \cdot 10^{-8}\ \text{W}$$

This power is distributed so that only one of the 60 sectors radiates towards the receiver. The off-state power from aBS$_k$ across distance d_{BRk} at the receiver's antenna is:

$$P_{RXk(OFF)} = 1.0527 \cdot 10^{-10}\ \text{W} \cdot \frac{1}{60} \cdot \left(\frac{0.50812\ \text{m}}{4 \cdot \pi \cdot 2\ \text{m}}\right)^2 = 7.1715 \cdot 10^{-16}\ \text{W}(-121.4\ \text{dBm})$$

similarly the on-state power at the receiver's antenna:

$$P_{RXk(ON)} = 6.207 \cdot 10^{-8}\text{W} \cdot \frac{1}{60} \cdot \left(\frac{0.50812\ \text{m}}{4\pi \cdot 2\ \text{m}}\right)^2 = 4.2285 \cdot 10^{-13}\ \text{W}(-93.7\ \text{dBm})$$

Equation 1 is again used for power level calculations with aBS$_i$. First, the impinging power from the transmitter to aBS$_i$ is:

$$P_{TBi} = 0.01\ \text{W} \cdot \frac{1}{60} \cdot \left(\frac{0.50812\ \text{m}}{4 \cdot \pi \cdot 3\ \text{m}}\right)^2 = 3.0278 \cdot 10^{-8}\ \text{W}$$

next multiply with the $|s_{11}|$ value converted to an absolute number when aBS$_i$ is in off-state, to get the power to aBS$_i$'s antenna:

$$P_{RBi(OFF)} = 3.0278 \cdot 10^{-8}\ \mathrm{W} \cdot 10^{\frac{-28.11}{10}} = 4.6787 \cdot 10^{-11}\ \mathrm{W}$$

alternatively, aBS$_i$ in on-state:

$$P_{RBi(ON)} = 3.0278 \cdot 10^{-8}\ \mathrm{W} \cdot 10^{\frac{-0.4042}{10}} = 2.7587 \cdot 10^{-8}\ \mathrm{W}$$

Next, the off-state power from aBS$_i$ to the receiver is:

$$P_{RXi(OFF)} = 4.6787 \cdot 10^{-11}\ \mathrm{W} \cdot \frac{1}{60} \cdot \left(\frac{0.50812\ \mathrm{m}}{4 \cdot \pi \cdot 2\ \mathrm{m}}\right)^2 = 1.2749 \cdot 10^{-15}\ \mathrm{W}(-118.9\ \mathrm{dBm})$$

and the on-state power:

$$P_{RXi(ON)} = 2.7587 \cdot 10^{-8}\ \mathrm{W} \cdot \frac{1}{60} \cdot \left(\frac{0.50812\ \mathrm{m}}{4\pi \cdot 2\ \mathrm{m}}\right)^2 = 7.5174 \cdot 10^{-13}\ \mathrm{W}(-91.2\ \mathrm{dBm})$$

For interference calculation, signal phase angles are needed. The initial phase Φ_0 of the wave leaving the transmitter antenna is taken as the reference point and set to zero. Using the number of wavelengths from the transmitter to the aBS$_k$-device, we get the impinging phase angle. Adding the phase at on- and off-states of the aBS-device $\angle s_{11}$ and the path effect from aBS-device to the receiver, we get phase angles of aBS$_k$'s signal for the off-state (in degrees):

$$\left(0^\circ + 360^\circ \cdot \frac{2\ \mathrm{m}}{0.50812\ \mathrm{m}} + 79.046^\circ + 360^\circ \cdot \frac{2\ \mathrm{m}}{0.50812\ \mathrm{m}}\right) \bmod 360^\circ = 313.97^\circ$$

and for the on-state:

$$\left(0^\circ + 360^\circ \cdot \frac{2\ \mathrm{m}}{0.50812\ \mathrm{m}} + 74.271^\circ + 360^\circ \cdot \frac{2\ \mathrm{m}}{0.50812\ \mathrm{m}}\right) \bmod 360^\circ = 314.88^\circ$$

The phase angle of aBS$_i$'s signal are calculated in the same way as with aBS$_k$, first for the off-state:

$$\left(0^\circ + 360^\circ \cdot \frac{3\ \mathrm{m}}{0.50812\ \mathrm{m}} + 79.046^\circ + 360^\circ \cdot \frac{1\ \mathrm{m}}{0.50812\ \mathrm{m}}\right) \bmod 360^\circ = 313.97^\circ$$

and for the on-state

$$\left(0^\circ + 360^\circ \cdot \frac{3\ \mathrm{m}}{0.50812\ \mathrm{m}} + 74.271^\circ + 360^\circ \cdot \frac{1\ \mathrm{m}}{0.50812\ \mathrm{m}}\right) \bmod 360^\circ = 314.88^\circ$$

It is no coincidence that the arriving phase angles of the interesting aBS and the interfering aBS are the same because the total distance from TX to aBS to RX in this example is the same and the devices are of the same type. Finally, the voltage of each signal in the receiver's input resistance of 50Ω which is the magnitude of the complex signal. The wanted signal's voltage, off and on:

$$U_{RXk(OFF)} = \sqrt{P_{RXk(ON)} \cdot R} = \sqrt{7.1715 \cdot 10^{-16}\ \mathrm{W} \cdot 50\Omega} \approx 1.8936 \cdot 10^{-7}\ \mathrm{V}$$

$$U_{RXk(ON)} = \sqrt{P_{RXk(OFF)} \cdot R} = \sqrt{4.2285 \cdot 10^{-13}\ \text{W} \cdot 50\Omega} \approx 4.5981 \cdot 10^{-6}\ \text{V}$$

and the unwanted signal's voltage, off and on:

$$U_{RXi(OFF)} = \sqrt{P_{RXi(OFF)} \cdot R} = \sqrt{1.2749 \cdot 10^{-15}\ \text{W} \cdot 50\Omega} \approx 2.5248 \cdot 10^{-7}\ \text{V}$$

$$U_{RXi(ON)} = \sqrt{P_{RXi(ON)} \cdot R} = \sqrt{7.5174 \cdot 10^{-13}\ \text{W} \cdot 50\Omega} \approx 6.1308 \cdot 10^{-6}\ \text{V}$$

Summing the complex wanted and unwanted signal will yield the total voltage at the receiver's antenna terminals is done as follows:

$$x_k + x_i = U_k\left(\cos\phi_k + j \cdot \sin\phi_k\right) + U_i\left(\cos\phi_i + j \cdot \sin\phi_i\right)$$

For all combinations of aBS_k and aBS_i states this gives the voltages and powers in table 4. Power is calculated as $P = |U|^2/R$ (where U is complex): Comparing the

Table 4: Manually calculated voltages and powers

device pair	abs.volts V	total P W	total P dBm
aBS_k off, aBS_i off	$4.4184 \cdot 10^{-7}$	$2.3022 \cdot 10^{-12}$	-86.379
aBS_k off, aBS_i on	$6.3202 \cdot 10^{-6}$	$7.9889 \cdot 10^{-13}$	-90.975
aBS_k on, aBS_i off	$6.3202 \cdot 10^{-6}$	$4.7057 \cdot 10^{-13}$	-93.274
aBS_k on, aBS_i on	$1.0729 \cdot 10^{-5}$	$2.3022 \cdot 10^{-12}$	-86.379

total powers to those calculated earlier for aBS_k the effect of interference can be seen. Also when the interfering aBS_is are off, they scatter back a small amount of the signal which adds to the interference.

Simulation cases

The simulations are divided into groups. Each group contains multiple simulation cases and parameters are varied between the groups in order to bring out performance differences in the devices. Every simulation of an interesting aBS-device is run twice: the off-state simulation and the on-state simulation. The total number of aBS-devices in a simulation is N and of these n can be transmitting simultaneously. In cases where a fraction of $N-1$ is used for interfering devices, the number is rounded down to the nearest integer.

Group 1 sets a benchmark where the frequencies that were used for evaluating the Aalto prototypes, from now on called aBS-devices p1–p8, and the transmitter frequencies that were used in prior art works in Table 1. Cases are run at 590 MHz and 2.4 GHz for passive aBS-devices p1–p8 and at 5.5 GHz and 2.4 GHz for active aBS-devices a1 and a2. One aBS-device of interest, aBS_k, is then moved through the test bed along the x-axis from $(-1.75, 0)$ to $(1.75, 0)$ in steps of 0.25 m. The transmitter and the receiver are located in the opposite ends of a 4 m long segment of the x-axis, in positions $(-2, 0)$ (TX) and $(2, 0)$ (RX). No other devices are placed in the test bed. The backscattered signal level is measured at the receiver for both off- and on-states.

Group 1 case summary (no interference):

- Case 1: Move single aBS-device p1–p8, 590 MHz, measure the level
- Case 2: Case 1 at 2.4 GHz
- Case 3: Move single aBS-device a1,a2, 5.5 GHz, measure the level
- Case 4: Case 3 at 2.4 GHz

Group 2 adds interference to the simulations. 32 interfering aBS-devices (aBS_i) and aBS_k are placed in the simulated test bed and set alternatively off and on. SINR is measured at the receiver and plotted with 4 curves in each graph for each aBS-device so that the effect of interference can be seen. The cases in this group are executed using the same parameters as were used in Group 1 cases, but only for the 2.4 GHz carrier frequency. The same simulation test bed as in the previous groups is used (dimensions, transmitter and receiver placement). One aBS-device of interest, aBS_k, is then moved through the interfering ones in the same way as in the previous simulations. There are 15 positions through which the aBS_k will move and 32 positions where the interfering aBS_i devices are placed. aBS_k will move from $(-1.75, 0)$ to $(1.75, 0)$ along the x-axis.

Group 2 case summary ($N-1$ interferers aBS_i randomly placed):

- Case 5: Move single aBS-device p1–p8, 2.4 GHz, measure SINR
- Case 6: Case 5 with a1 and a2 at 5.5 GHz
- Case 7: Case 6 at 2.4 GHz

Group 3 (cases 8 and 9) simulations repeat Group 1 cases 2 and 4 with stepped instead of constant transmitter power, only at 2.4 GHz. The same initial power, 0.01 W, as in all the previous simulations is used first, then the power is increased with 3 dB in 7 rounds, making a total of 8 simulation runs. The transmitter power fluctuation is thus 21 dB. The simulation output data from Group 3 cases 8 and 9 will be used for plotting SNR and BER graphs.

Group 3 case summary:

- Case 8: Move single aBS-device p1–p8, 2.4 GHz, measure the level at the receiver with power levels 0.01–1.28 W.
- Case 9: Case 8 with active devices a1 and a2, 2.4 GHz.

4 Results

The results from the actually executed simulation cases are given in this section. In the beginning of this section, the raw data from single device simulations are plotted to give an overview of the power that can be received from the simulated aBS-devices in their backscattering and non-backscattering cases. In these simulation cases a single device was measured in different positions. These are the Group 1 results. Next, simulations where interferers were added aim to visualize the difference in received signal with and without them. An interesting aBS$_k$-device was moved in the test bed where it was surrounded by a number of randomly placed interfering aBS$_i$-devices of the same type. The number of transmitting aBS$_i$'s from all of them was kept constant. These are the Group 2 results. Finally, a simulation group of transmitter power fluctuation cases was run. The location of an aBS-device on the x-axis was kept constant. The middle position was chosen for the weakest received signal for all device types. Then the transmitter power was increased in steps from which the received signal strength was gathered. SNR values were calculated from the results of these simulations. ASK-modulation at a given bit rate where both on- and off-states are equiprobable was used. BER, the bit error probability was then calculated from the SNR values. These are the Group 3 results.

In all simulations the dimensions of the test bed, receiver and transmitter locations and the steps in device movement were the same. In interference simulations, a single random placement was used for every simulation case. For brevity, the backscattering state is called the "on-state" and the nonbackscattering state the "off-state" in figure captions. This section ends with a review of the results and discussion of reliability (and the degree of realism) in the simulations.

Group 1, cases 1–4

Group 1 simulations were executed on 590 MHz and 2.4 GHz for passive devices p1–p8 and on 2.4 GHz and 5.5 GHz for active devices a1 and a2, with fixed transmitter power 0.01 W, bit rate 500 kbit/s and temperature 302.15 K. The curves show the level of backscattered aBS$_k$ signal at the receiver in the on-state (red curve) and off-state (blue curve). The x-axis is the position of aBS$_k$ between the receiver and the transmitter. Figure 9 shows passive aBS-device p1–p4 levels at 590 MHz and Figure 10 shows passive aBS-device p5–p8 levels at 590 MHz. Figure 11 shows passive aBS-device p1–p4 levels at 2.4 GHz and Figure 12 shows passive aBS-device p5–p8 levels at 2.4 GHz. Figure 13 shows active aBS-device a1 and a2 levels at 5.5 GHz. Phase angles of the s_{11} parameter are unmodified, Figure 14 shows active aBS-device a1 and a2 levels at 2.4 GHz. Phase angles of the s_{11} parameter are set to 0° and 30°. These devices were simulated also with different $\angle s_{11}$ values: $60°, 90°$ and 120° but because there was no difference in the received signal strength (naturally, as the phase angle has no role in Equation 1), the graphs are not included here.

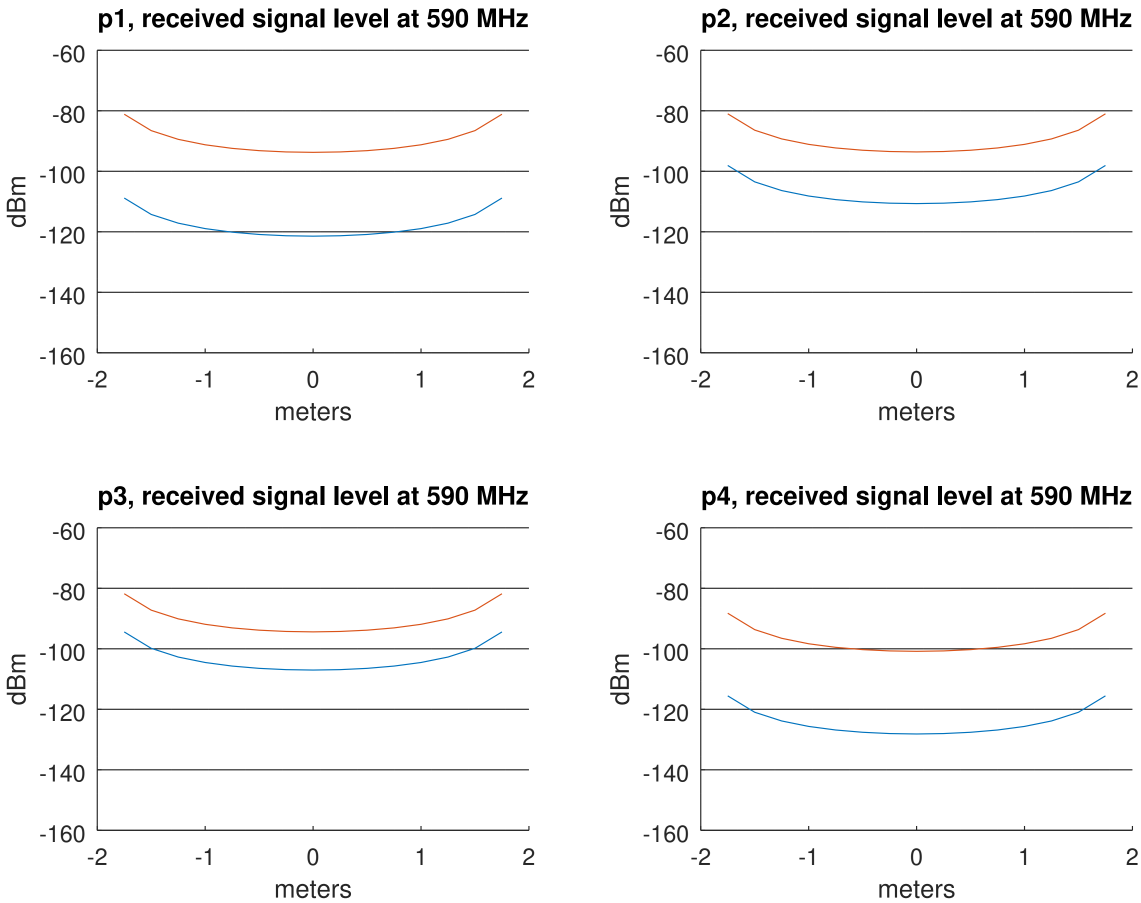

Figure 9: Signal levels of p1–p4 as a function of position, 590 MHz. Red curve ON-state, blue curve OFF-state.

Group 2, cases 5–7

Group 2 simulations were executed on 2.4 GHz for all devices and also on 5.5 GHz for active devices a1 and a2, with fixed transmitter power 0.01 W, bit rate 500 kbit/s and temperature 302.15 K. The curves without markers show simulation results with interference (actual SINR curves) and the curves with markers are aBS$_k$ SINRs without interferers (i.e. reduced to SNRs). SINR and SNR are shown as a function of aBS$_k$ position on the x-axis. Figure 15 shows passive aBS-device p1–p4 SINR and SNR and Figure 16 shows passive aBS-device p5–p8 SINR and SNR. Figure 17 shows active aBS-device a1 and a2 SINRs Figure 18 shows active aBS-device a1 and a2 SINRs at 5.5 GHz.

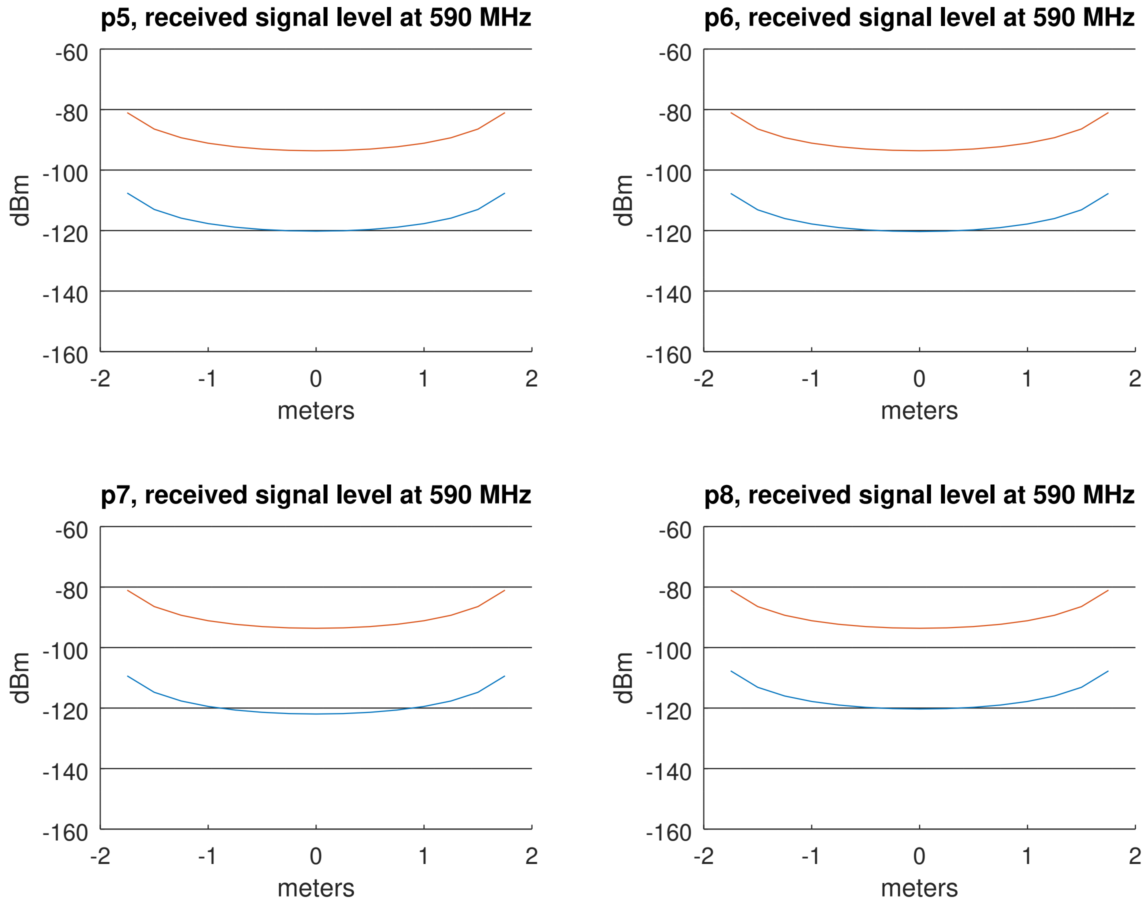

Figure 10: Signal levels of p5–p8 as a function of position, 590 MHz. Red curve ON-state, blue curve OFF-state.

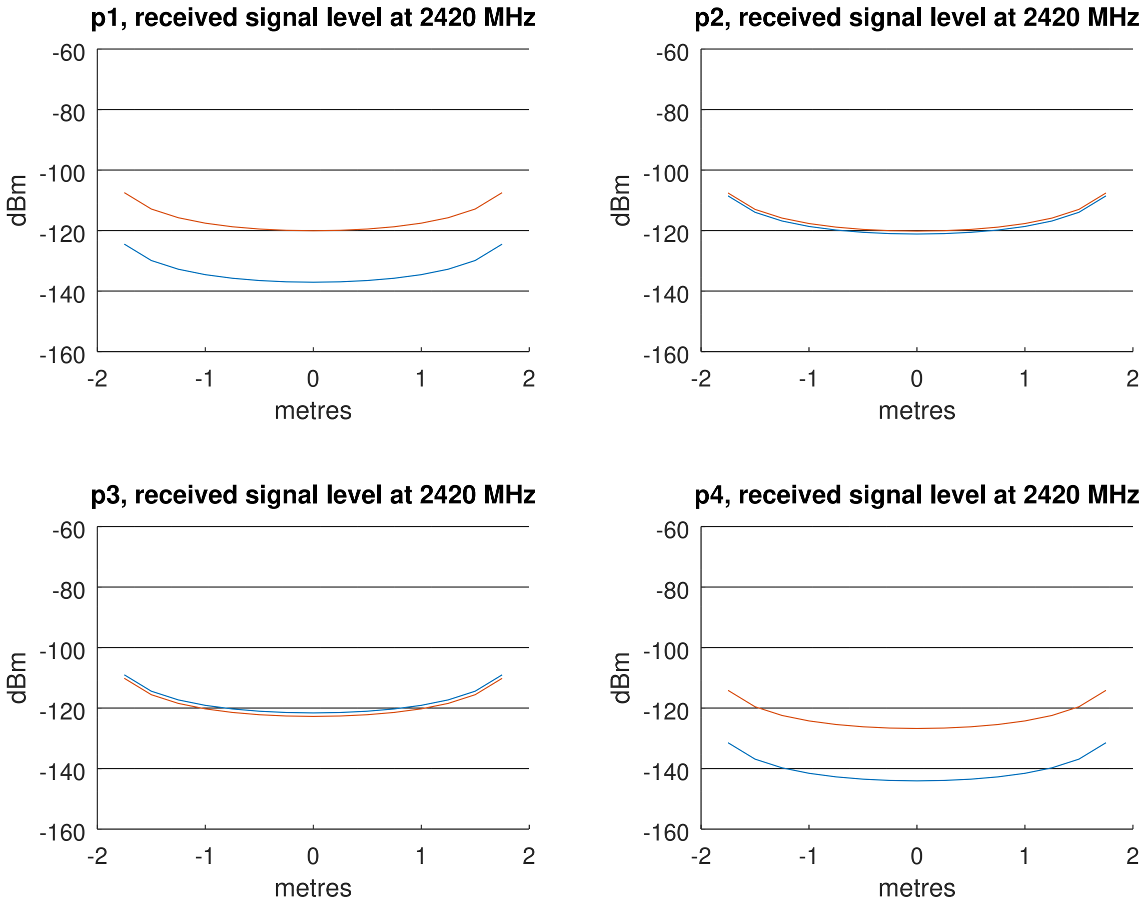

Figure 11: Signal levels of p1–p4 as a function of position, 2.4 GHz. Red curve ON-state, blue curve OFF-state.

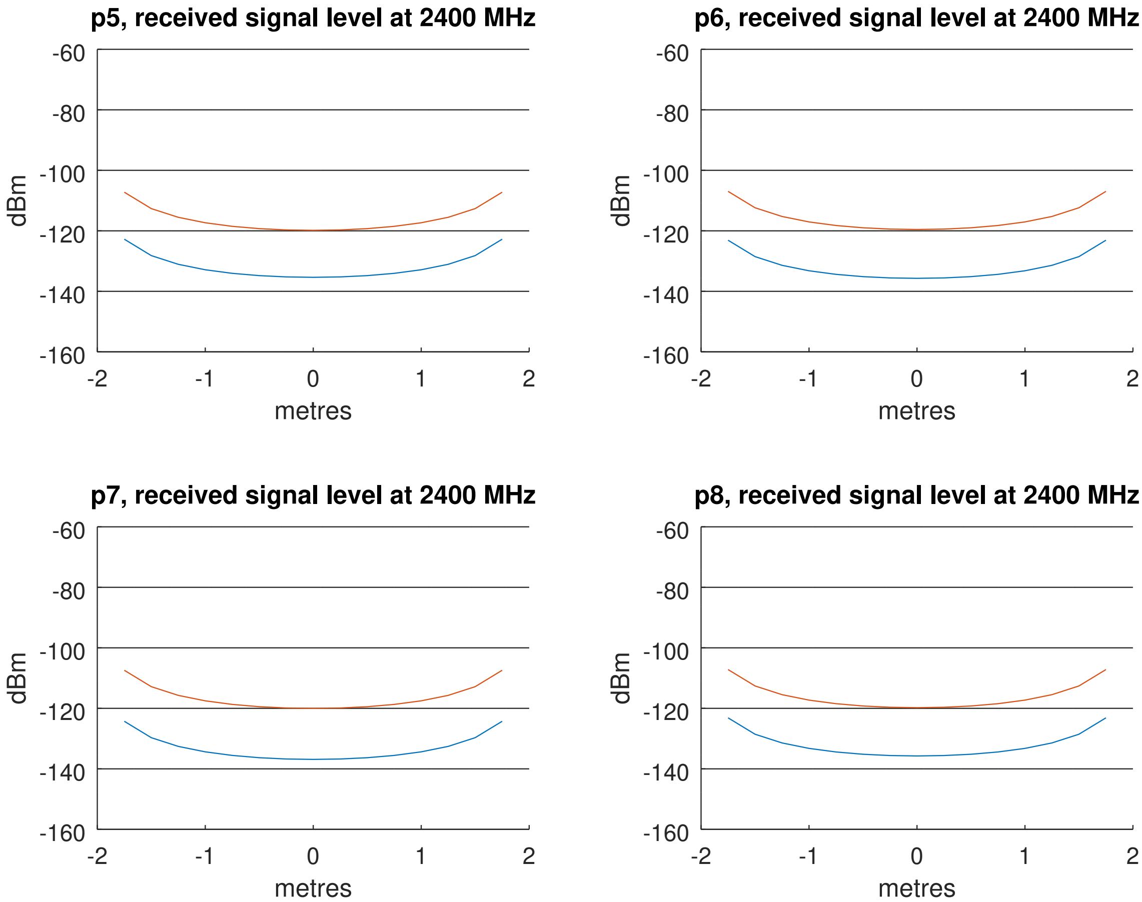

Figure 12: Signal levels of p5–p8 as a function of position, 2.4 GHz. Red curve ON-state, blue curve OFF-state.

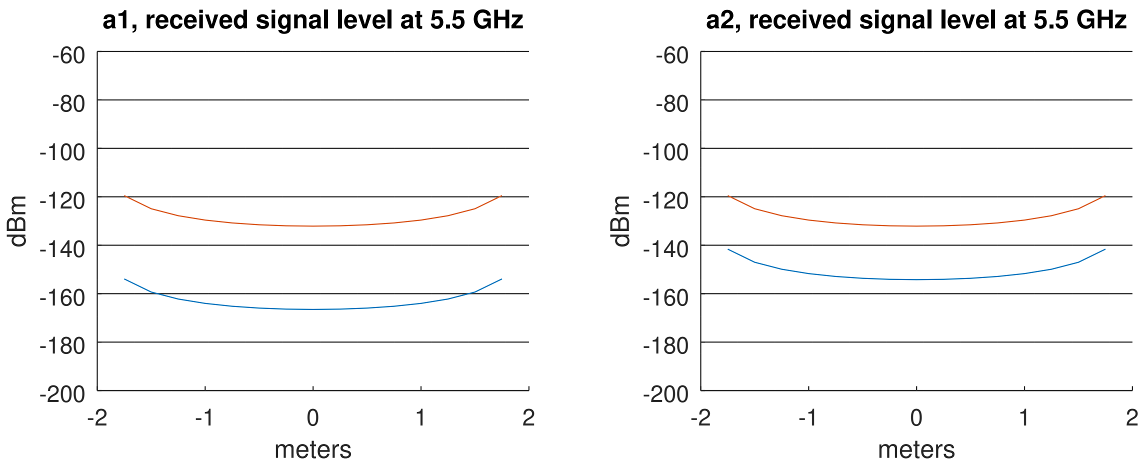

Figure 13: Signal levels of a1 and a2 in different positions, 5.5 GHz. Red curve ON-state, blue curve OFF-state.

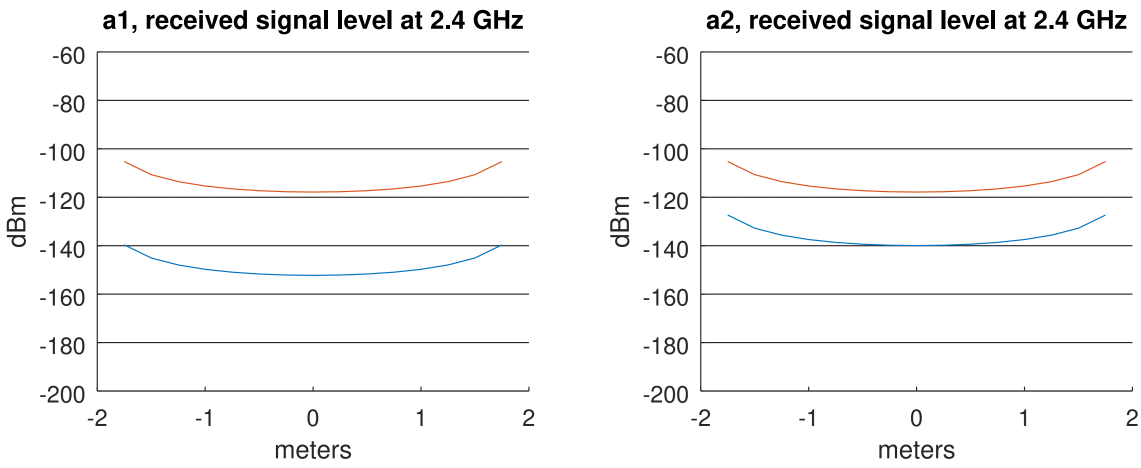

Figure 14: Signal levels of a1 and a2 in different positions, 2.4 GHz, 30°$\angle s_{11}$. Red curve ON-state, blue curve OFF-state.

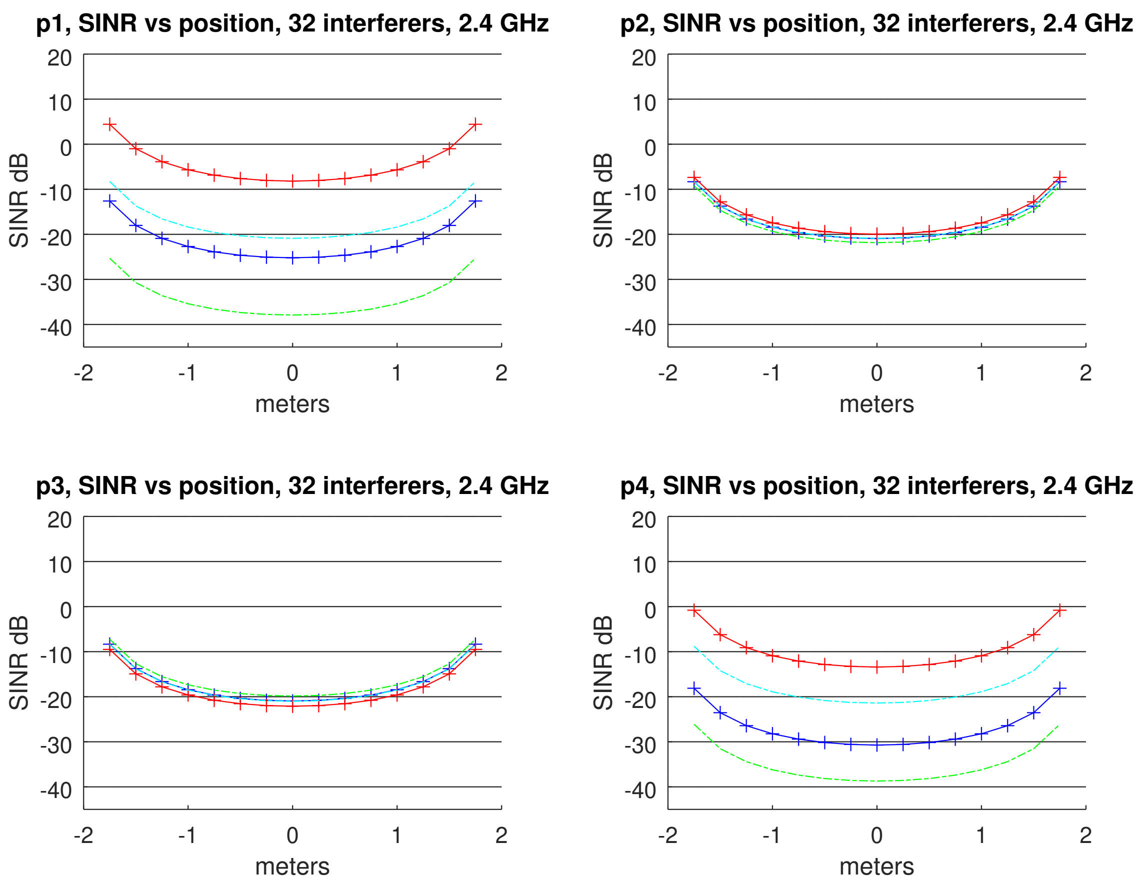

Figure 15: SINR of p1–p4 with 32 interferers (plain curves), 2.4 GHz. Curves with markers are uninterfered cases. Blue and green are OFF, red and cyan are ON.

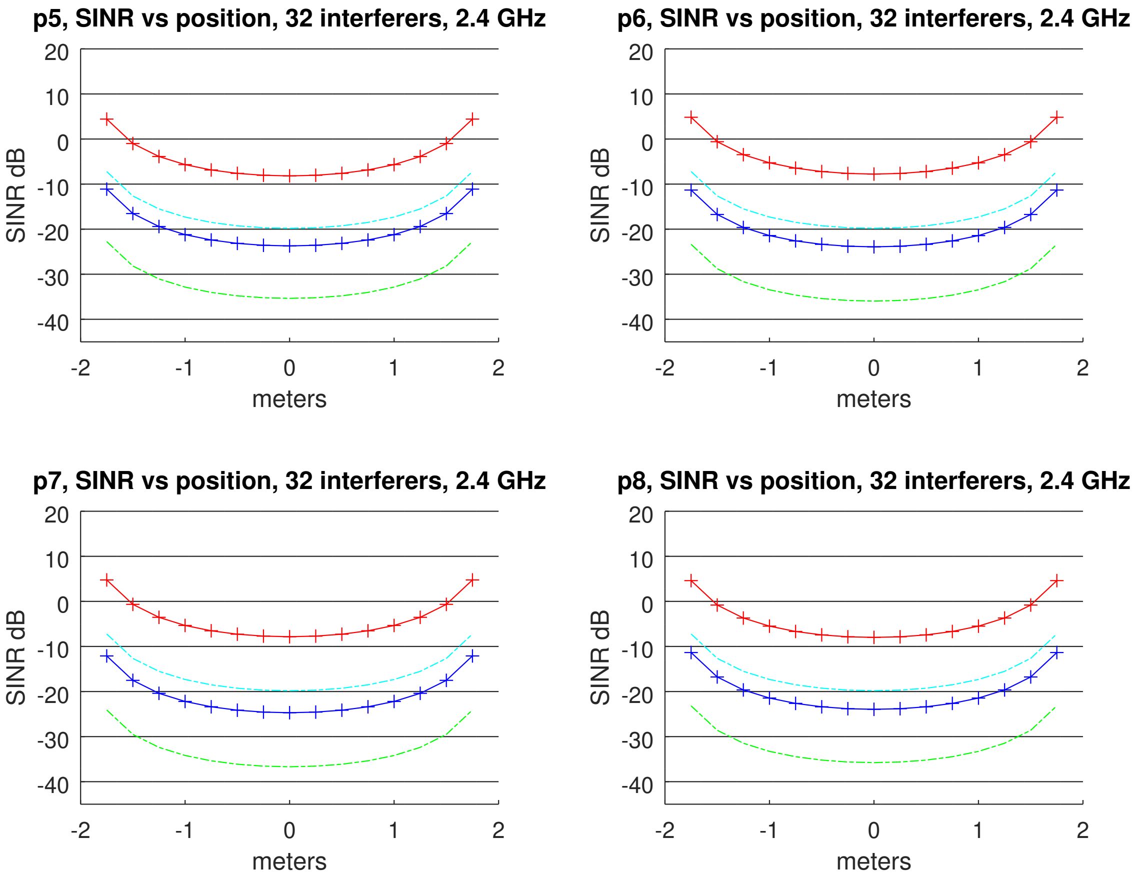

Figure 16: SINR of p5–p8 with 32 interferers (plain curves), 2.4 GHz. Curves with markers are uninterfered cases. Blue and green are OFF, red and cyan are ON.

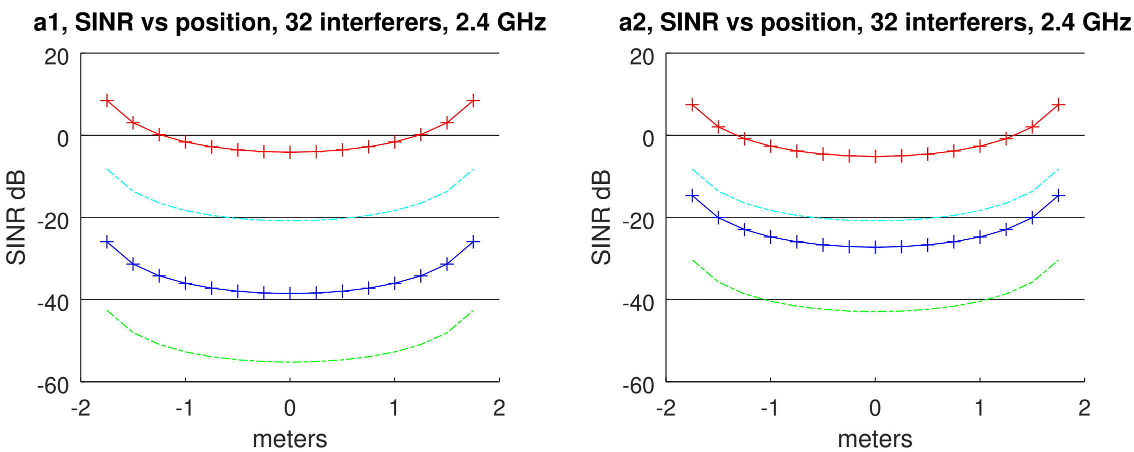

Figure 17: SINR of a1 and a2 with 32 interferers (plain curves), 2.4 GHz. Curves with markers are uninterfered cases. Blue and green are OFF, red and cyan are ON.

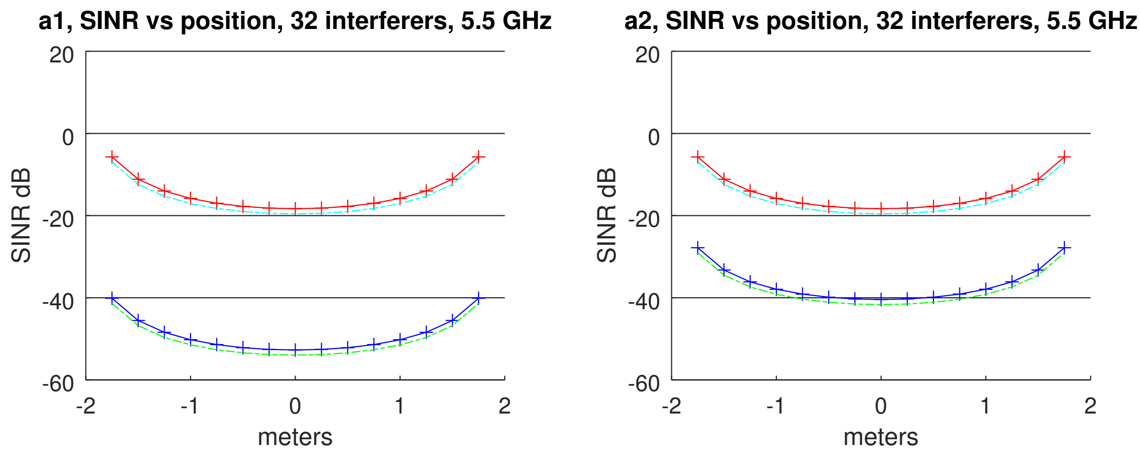

Figure 18: SINR of a1 and a2 with 32 interferers (plain curves), 5.5 GHz. Curves with markers are uninterfered cases. Blue and green are OFF, red and cyan are ON.

The minimum SINR values at 2.4 GHz for p1–p8 are in Table 5, minimum SINR values at 5.5 GHz for active aBS-devices a1 and a2 in Table 7 and the minimum SINR values at 2.4 GHz for active aBS-devices a1 and a2 in in Table 6.

Table 5: Minimum SINR-values of aBS-devices p1–p8, 2.4 GHz, 32 interferers

passive aBS-device	aBS_k off, interference off	aBS_k on, interference off	aBS_k off, interference on	aBS_k on, interference on
p1	−25.2	−8.2	−37.9	−20.9
p2	−20.9	−20.0	−21.8	−20.9
p3	−20.9	−22.1	−19.8	−21.0
p4	−30.7	−13.4	−38.7	−21.4
p5	−23.7	−8.2	−35.4	−19.8
p6	−23.9	−7.8	−36.0	−19.8
p7	−24.7	−7.8	−36.7	−19.8
p8	−23.9	−8.0	−35.7	−19.8

Table 6: Minimum SINR-values of aBS-devices a1 and a2, 2.4 GHz, 32 interferers

active aBS-device	aBS_k off, interference off	aBS_k on, interference off	aBS_k off, interference on	aBS_k on, interference on
a1	−38.5	−4.1	−55.2	−20.8
a2	−27.2	−5.1	−42.9	−20.8

Table 7: Minimum SINR-values of aBS-devices a1 and a2, 5.5 GHz, 32 interferers

active aBS-device	aBS_k off, interference off	aBS_k on, interference off	aBS_k off, interference on	aBS_k on, interference on
a1	−52.7	−18.3	−54.0	−19.6
a2	−40.4	−18.3	−41.7	−19.6

Group 3

The SNR simulation results with increasing transmitter power ("ptx") are in Figure 19 for passive aBS-devices p1–p4. in Figure 20 for passive devices p5–p8 and in Figure 21 for active devices a1 and a2.

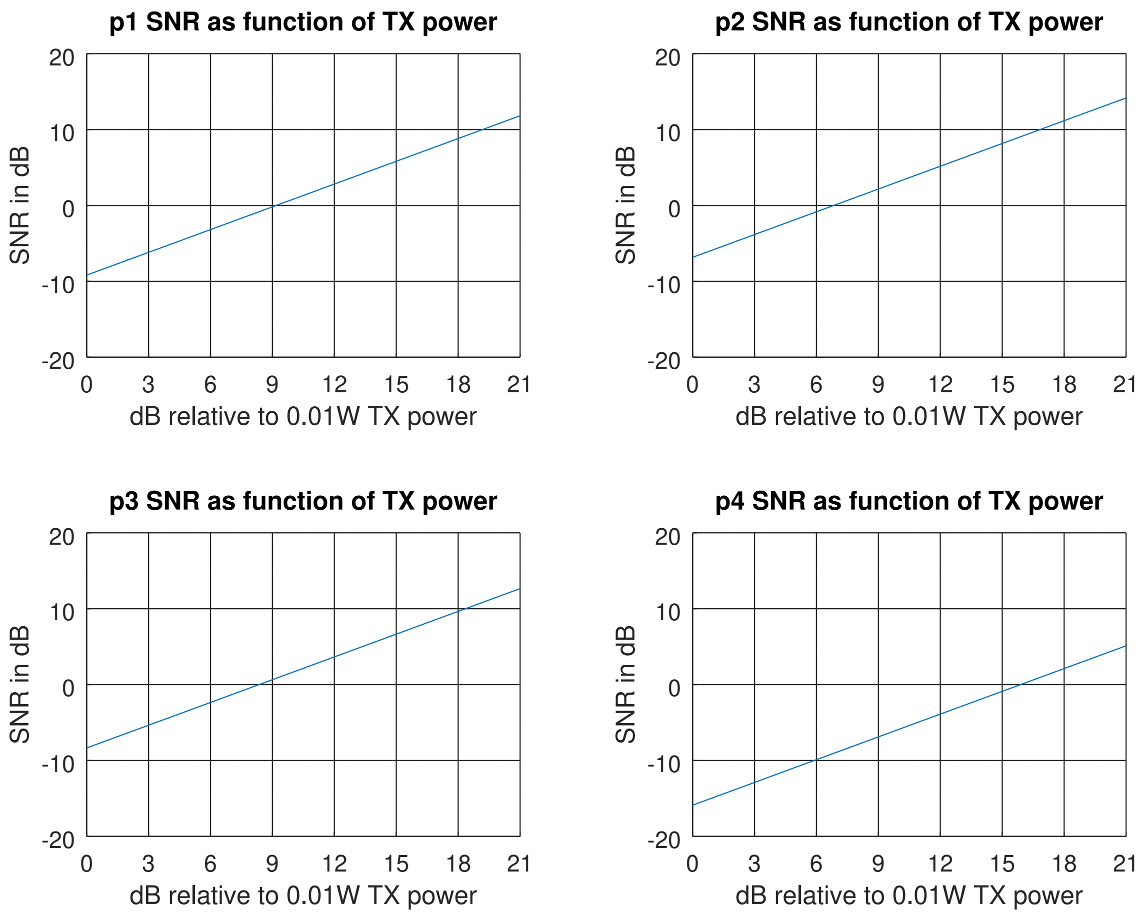

Figure 19: SNR of p1–p4 with increasing TX power, center location, 2.4 GHz

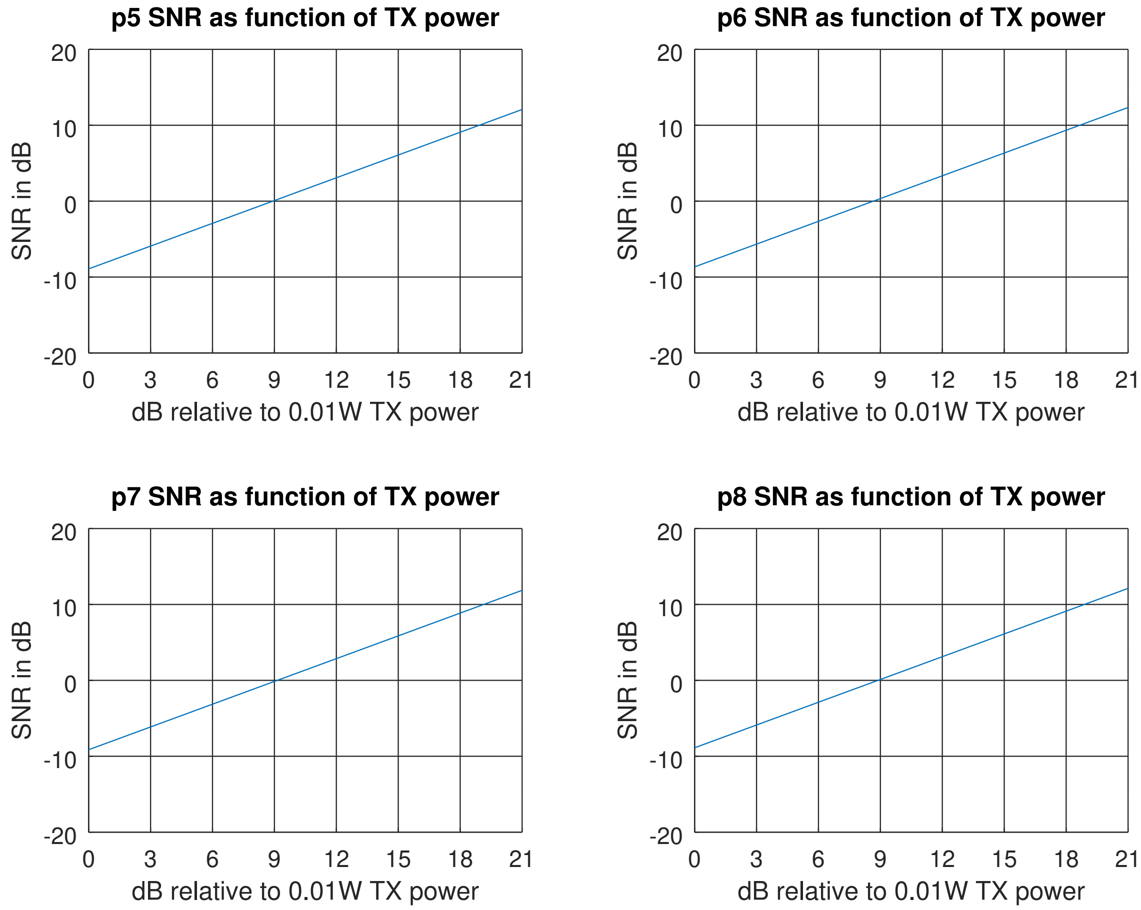

Figure 20: SNR of p5–p8 with increasing TX power, center location, 2.4 GHz

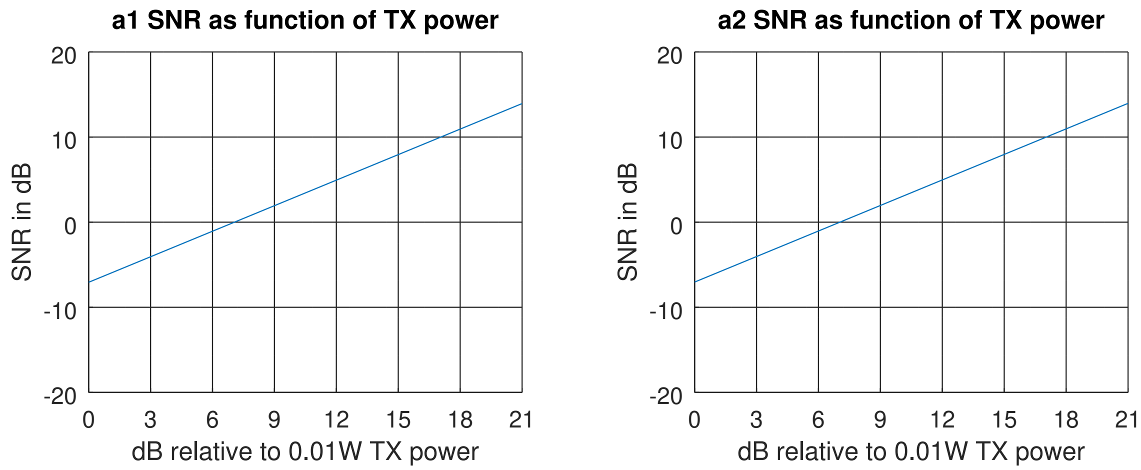

Figure 21: SNR of a1 and a2 with increasing TX power, center location, 2.4 GHz

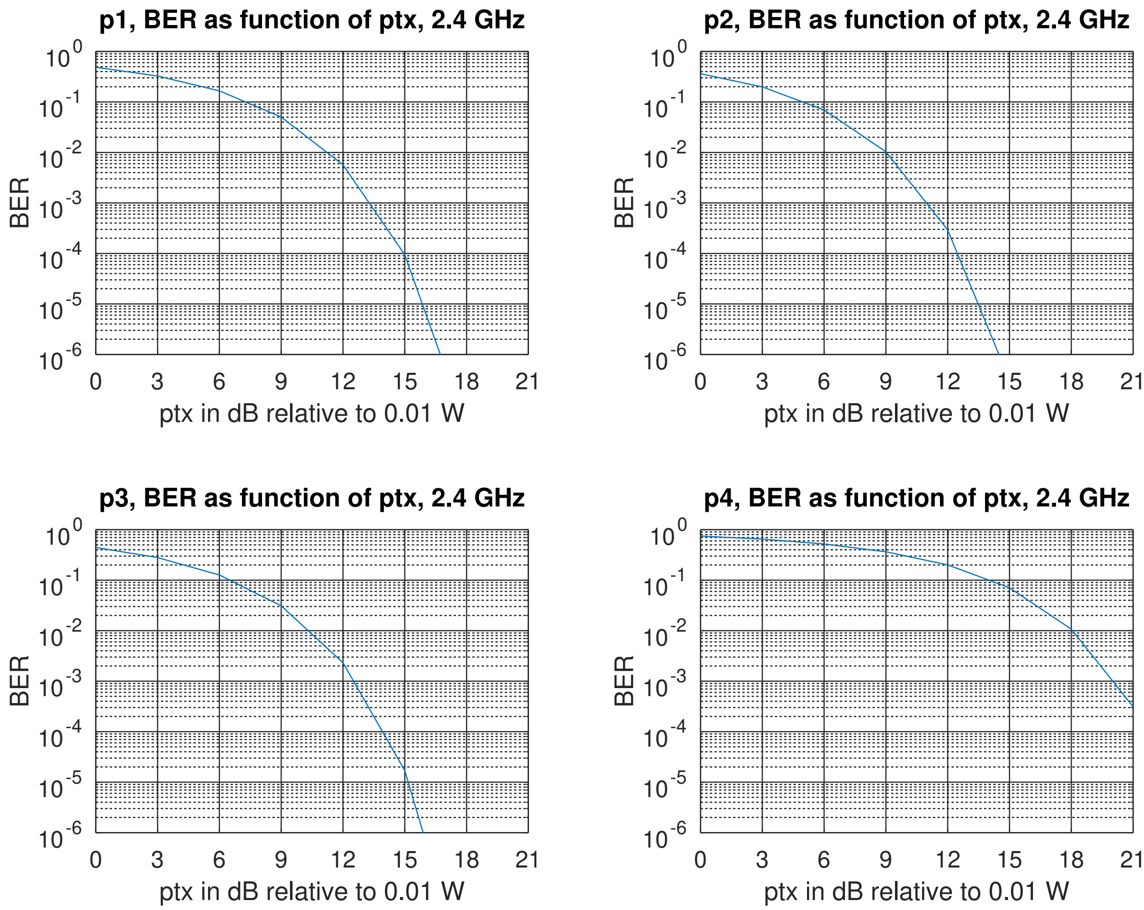

Figure 22: BER of p1–p4 with increasing TX power, center location, 2.4 GHz

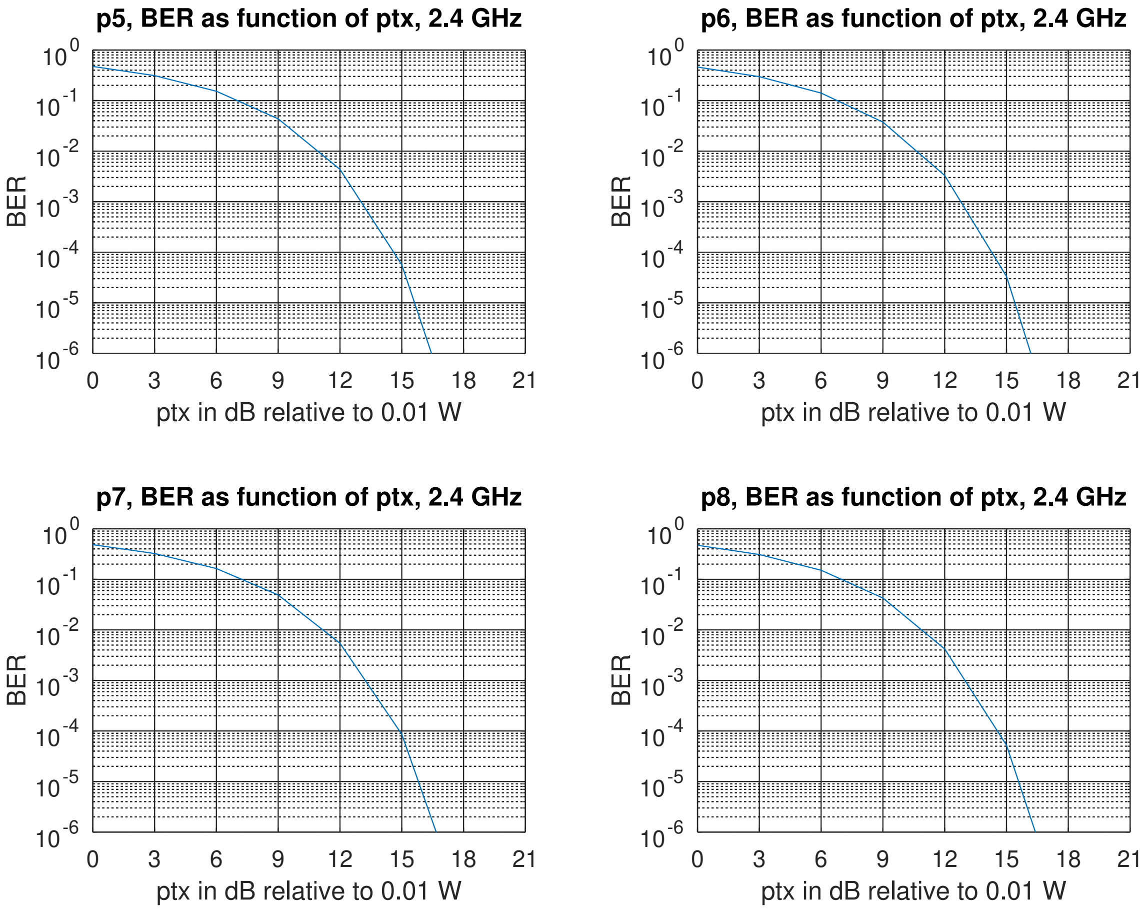

Figure 23: BER of p5–p8 with increasing TX power, center location, 2.4 GHz

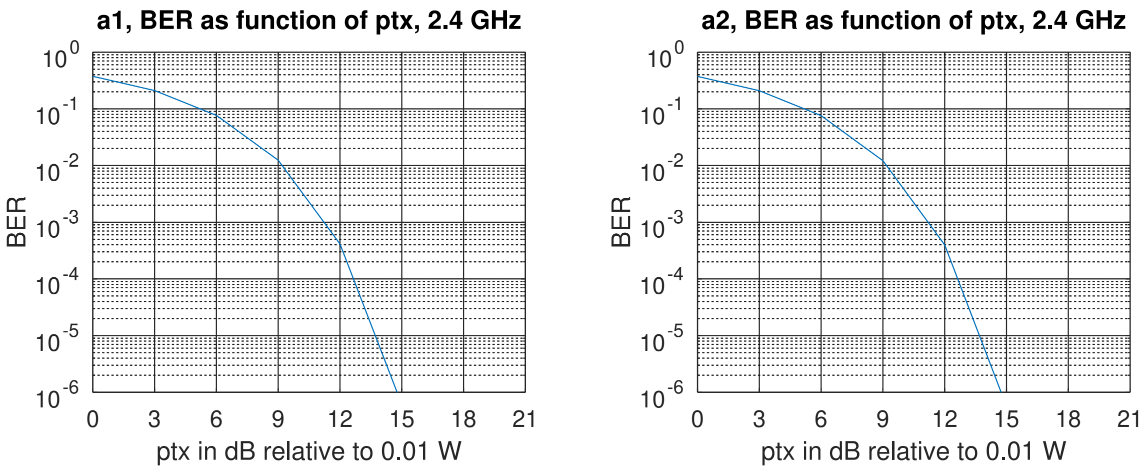

Figure 24: BER of a1 and a2 with increasing TX power, center location, 2.4 GHz

5 Summary

This thesis work has studied Ambient Backscatter prior art and other backscatter radio communications research results for gaining an understanding of how aBS communication systems work, and to apply the theoretical background and prior art in practice. A MATLAB/GNU Octave simulator program was written with which active and passive backscatter devices were simulated. Data on device scattering parameters were acquired from backscatter prior art for constructing device models. The device models were used in simulation cases pertaining to achievable range, interference susceptibility and maximum useful bit rate of the devices. The acquired results were analyzed and presented graphically.

Results from both aBS-communications and RFID prior art were used for creating active device models can be considered realistic. With the simulation cases it has been possible to visualize the performance differences of the simulated devices and therefore it is possible to answer the thesis goal questions to a degree. The results come, however, from a very limited amount of simulation rounds so discussion of reliability of the results follows in the end.

Range conclusions

Group 1 case results give some direction as to what signal levels can be expected at the system receiver's antenna. In the Group 1 simulations the transmitter power was so low that the received signal levels could not support any communication, nevertheless they can be used for comparison. Comparing the passive aBS-devices p1–p8 with each other, the following behavior can be seen:

- p1 and p4 have a larger ASK modulation depth than p2 and p3 at both 590 MHz and 2.4 GHz;
- p2 and p3 become useless at 2.4 GHz as ASK-modulated devices;
- p5, p6, p7 and p8 are remarkably similar in their performance.

There was nothing outside what was expected. The s_{11} parameter magnitude of the devices affects the received signal level in both on- and off-states uniformly. In the SNR simulations of Group 3, device p1 seems to perform best. For the active aBS-devices a1 and a2, the following is noted:

- a1's larger ASK modulation index can be seen in the received signal's power changes directly;
- there were no surprises in their performance at 5.5 GHz;
- the performance of both a1 and a2 is on par with the best passive devices at 2.4 GHz.

The "powersweep" simulation cases of Group 3 confirm the above. Varying the transmitter power did not change the ranking of the devices in terms of received power relative to the transmitter power when aBS_k was kept stationary. Active devices a1 and a2 were a good match for p1 at the achieved signal to noise -ratio. The largest question that these simulations cannot answer is the energy economics of the devices, i.e. the power-up budget and its effect. Because there is no power requirement data to base the simulations on, only heuristics can be applied here. If the electronics in an active aBS-device consume more energy for transmitting K bits at rate R_b than a passive one before the supply must be replenished, its transmission period must be shorter. Otherwise it would simply require more energy. However, this is more a throughput question than a range question. Power-hungry active devices would fall outside the range of the passive ones performing otherwise similarly. On the other hand if the gain from having an amplifier in the device allows a longer range towards the system receiver, active devices could be a better choice in a setup where the devices are closer to the transmitter, and thus better "fed", than the receiver. Conclusion is therefore that the passive aBS-device p1 and either active device a1 or a2 come out as winners that cannot easily be put in order of preference.

Rate conclusions

The BER of all simulated devices can act as an achievable bit rate indicator when all the aBS-devices are positioned at the halfway point between the transmitter and receiver. Of the passive devices p1–p8, devices p2 and p3 rather surprisingly stand out. This is due to their ability to scatter back a strong carrier signal on average, although the baseband signal level is low because of the small modulation index. An analogy in traditional radio could be an AM station nearby sending classical music—one can distinguish the pianissimo parts from the transmission because the average received radio signal is much higher than environmental noise. Another AM transmitter further away sending the same music would be audible over the noise only in the fortissimo parts of the music. The active devices a1 and a2 are outperformed by the passive device p2 in the bit error rate by little, which is an interesting outcome. Also, the passive device p4 is the worst, somewhat against expectations, in its BER performance.

Interference conclusions

In the interference cases the number of simulations with randomly placed interfering devices is too small for statistical analysis. If some conclusion can be drawn from the data that were collected, looking into the SINR curves reveals that the passive device p1 is better than either active device and slightly better than or equal to p5–p8.

Preferred types of devices

Considering only ASK-modulation and the simulated aBS-devices in this thesis, the active devices containing an amplifier of the tunneling type could give a benefit over passive ones when it comes to device range, provided that the power-up link budget suffices. In terms of best bit rate, active devices in this thesis have been slightly better. Interference conclusions are best left not drawn due to the small amount of simulation rounds.

Reliabililty of the results

The following points affect the reliability of the thesis results:

- The total number of simulations is small;
- The amount of interference cases is small;
- Random placement of devices is ran only once;
- The dimensions of the simulation test bed were fixed;
- Multipath effect was ignored, especially the ground reflections;
- There is a probability of erroneous calculations even after several reviews of code and results.

It is difficult to give numerical estimations on reliability. Nevertheless the simulator is based on radio theory and elementary geometry functions so it does form a benchmark that could be used as a basis for a larger more complex simulation framework.

Development ideas and final thoughts

MATLAB and GNU Octave possess such processing power that enables more complex simulated systems than what were made in this thesis. The software libraries provide tools for simulating a radio channel between mobile devices actually transfering data. A properly made computer simulation of an aBS system should provide results that bring out any significant differences in performance of aBS devices of different types, if such differences exist. A simulation will probably give benefit when it is used on the side with prototyping and actual measurements in the radio signal environment. The limitations of the simulator made for this thesis work should be kept in mind, however, as there are simplifications and assumptions that cannot be fully disregarded in the real world.

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Appendix

A Simulation result tables

These tables show samples of the data from which the graphs in Section 4 were plotted. 5 of total 15 received signal strengths in dBm values from the aBS_k device path in range simulations are listed. The positions are in meters relative to the center between TX $(-2, 0)$ and RX $(2, 0)$, i.e. the x-coordinates of aBS_k.

Passive aBS_k p1 to p8, state OFF, 590 MHz

dist. / dev.	-1.5	-0.75	0.00	0.75	1.5
p1	-144.26	-150.13	-151.44	-150.13	-144.26
p2	-133.50	-139.36	-140.68	-139.36	-133.50
p3	-129.85	-135.71	-137.03	-135.71	-129.85
p4	-150.98	-156.84	-158.16	-156.84	-150.98
p5	-143.02	-148.89	-150.20	-148.89	-143.02
p6	-143.15	-149.01	-150.33	-149.01	-143.15
p7	-144.79	-150.65	-151.97	-150.65	-144.79
p8	-143.14	-149.00	-150.32	-149.00	-143.14

Passive aBS_k p1 to p8, state ON, 590 MHz

dist. / dev.	-1.5	-0.75	0.00	0.75	1.5
p1	-116.56	-122.42	-123.74	-122.42	-116.56
p2	-116.42	-122.28	-123.60	-122.28	-116.42
p3	-117.22	-123.09	-124.40	-123.09	-117.22
p4	-123.66	-129.52	-130.84	-129.52	-123.66
p5	-116.45	-122.31	-123.63	-122.31	-116.45
p6	-116.43	-122.29	-123.61	-122.29	-116.43
p7	-116.45	-122.32	-123.63	-122.32	-116.45
p8	-116.45	-122.32	-123.63	-122.32	-116.45

Passive aBS_k p1 to p8, state OFF, 2.4 GHz

dist. / dev.	-1.5	-0.75	0.00	0.75	1.5
p1	-159.90	-165.77	-167.08	-165.77	-159.90
p2	-143.97	-149.83	-151.15	-149.83	-143.97
p3	-144.43	-150.29	-151.61	-150.29	-144.43
p4	-166.88	-172.75	-174.06	-172.75	-166.88
p5	-158.18	-164.05	-165.36	-164.05	-158.18
p6	-158.52	-164.38	-165.70	-164.38	-158.52

```
p7  -159.70  -165.56  -166.88  -165.56  -159.70
p8  -158.56  -164.42  -165.74  -164.42  -158.56

Passive aBS_k p1 to p8, state ON, 2.4 GHz
  dist.
dev.  -1.5     -0.75     0.00     0.75     1.5
    -------------------------------------------
p1  -142.88  -148.74  -150.06  -148.74  -142.88
p2  -143.00  -148.87  -150.18  -148.87  -143.00
p3  -145.58  -151.45  -152.76  -151.45  -145.58
p4  -149.57  -155.44  -156.75  -155.44  -149.57
p5  -142.65  -148.51  -149.83  -148.51  -142.65
p6  -142.37  -148.24  -149.55  -148.24  -142.37
p7  -142.84  -148.70  -150.02  -148.70  -142.84
p8  -142.60  -148.46  -149.78  -148.46  -142.60

Active aBS_k a1 and a2, state OFF, 2.4 GHz
  dist.
dev.  -1.5     -0.75     0.00     0.75     1.5
    -------------------------------------------
a1  -175.07  -180.94  -182.25  -180.94  -175.07
a2  -162.77  -168.64  -169.95  -168.64  -162.77

Active aBS_k a1 and a2, state ON, 2.4 GHz
  dist.
dev.  -1.5     -0.75     0.00     0.75     1.5
    -------------------------------------------
a1  -140.67  -146.54  -147.85  -146.54  -140.67
a2  -140.67  -146.54  -147.85  -146.54  -140.67

Active aBS_k a1 and a2, state OFF, 5.5 GHz
  dist.
dev.  -1.5     -0.75     0.00     0.75     1.5
    -------------------------------------------
a1  -189.33  -195.20  -196.51  -195.20  -189.33
a2  -177.03  -182.90  -184.21  -182.90  -177.03

Active aBS_k a1 and a2, state ON, 5.5 GHz
  dist.
dev.  -1.5     -0.75     0.00     0.75     1.5
    -------------------------------------------
a1  -154.93  -160.80  -162.11  -160.80  -154.93
a2  -154.93  -160.80  -162.11  -160.80  -154.93
```

B Configuration file examples

A test constant CSV-file's contents are shown below with values that were used in all the simulations. The other configuration CSV-files have two comment lines for documentation in their header that are skipped at reading. The testconstants.csv -file contains only the data line after a modification was made for the power sweeping simulation. The header comment is shown here for reference only and must be removed from the file when simulating. (The hash character is not mandatory in the front of the comment lines.)

testconstants.csv:

```
# m   ; m   ; m   ; m   ; W   ; ohms  ; power  ; bps     ; deg K
# xtx ; ytx ; xrx ; yrx ; ptx ; rxzin ; steps  ; bitrate ; T
-2    ; 0   ; 2   ; 0   ; 0.01; 50    ; 7      ; 500000  ; 302.15
```

In this sample testconstants.csv file the "power steps" specify the number of 3 dB increments (positive) or decrements (negative) in transmitter power, starting from the "ptx" level. A position-file for aBS-devices is shown below. The two first columns are (x, y) -coordinates in meters and the two last columns are flags: whether a device is transmitting (1) or not (0) and whether it is interesting aBS_k (1) or interfering aBS_i (0). There are multiple interesting aBS-device locations but only one device walks through the given positions in the order which they are given in the configuration file. Here the aBS_k is off in all positions. Two simulation rounds are therefore required for both on- and off-state results, with aBS_k transmitting as 1 and 0 respectively. Interferers, aBS_is, can be added in any order, as the "not interesting" positions, each individually transmitting or not.

```
% skip the two first lines when reading this file.
% x-coord ; y-coord ; transmitting OFF; interesting
-1.75 ; 0 ; 0 ; 1
-1.50 ; 0 ; 0 ; 1
-1.25 ; 0 ; 0 ; 1
-1.00 ; 0 ; 0 ; 1
-0.75 ; 0 ; 0 ; 1
-0.50 ; 0 ; 0 ; 1
-0.25 ; 0 ; 0 ; 1
 0.00 ; 0 ; 0 ; 1
 0.25 ; 0 ; 0 ; 1
 0.50 ; 0 ; 0 ; 1
 0.75 ; 0 ; 0 ; 1
 1.00 ; 0 ; 0 ; 1
 1.25 ; 0 ; 0 ; 1
 1.50 ; 0 ; 0 ; 1
 1.75 ; 0 ; 0 ; 1
```

C Simulator output example

Below is a sample output CSV-file contents where there are 32 interfering aBS-devices and one interesting aBS-device.The file contents are shown here as copied from the screen and edited in order to save space. This output is from a 590 MHz simulation of passive aBS p2 without interferers. The output is from GNU Octave and the numbers have 14 decimals. In the output CSV there are no header comment lines. The test constants are repeated on every row.

```
file basictest-p2-590-on.csv (split into two sets of columns)

columns 1 to 13 (frequency, aBS id, TX power W, RX Zin, aBS type,
bitrate, T in K, RX noise power W, TX x, TX y, RX x, RX y, TX direct
signal at RX in W):

590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;
590;2;0.01;50;0;500000;302.15;1.668e-14;-2;0;2;0;1.703e-08;

columns 14 to 19 (aBS x, aBS y, aBS transmitting, aBS interesting,
aBS power at RX in W, aBS power at RX in dBm):

-1.75;0;1;1;7.945067688503277e-12;26.77935925244606
-1.5;0;1;1;2.280153354481169e-12;21.3580238067153
-1.25;0;1;1;1.175305871080366e-12;18.4798922930297
-1;0;1;1;7.758855164553979e-13;16.67635968604794
-0.75;0;1;1;5.909554479052025e-13;15.49393064367481
-0.5;0;1;1;4.965667305314546e-13;14.73815942588681
-0.25;0;1;1;4.504006626135642e-13;14.31437344448805
0;0;1;1;4.364356030061614e-13;14.17758495388194
0.25;0;1;1;4.504006626135642e-13;14.31437344448805
0.5;0;1;1;4.965667305314546e-13;14.73815942588681
0.75;0;1;1;5.909554479052025e-13;15.49393064367481
1;0;1;1;7.758855164553978e-13;16.67635968604794
```

```
1.25;0;1;1;1.175305871080366e-12;18.4798922930297
1.5;0;1;1;2.280153354481169e-12;21.3580238067153
1.75;0;1;1;7.945067688503277e-12;26.77935925244606
```