Signal Processing Aspects of Bistatic Backscatter Communication

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Abstract

Passive Internet-of-Things (IoT), a new paradigm based on battery-free devices, is a promising technology to enable several use cases that require connectivity with stringent requirements in terms of cost, complexity, and energy efficiency. These use cases span critical sectors, such as healthcare, transportation, and agriculture. Passive IoT relies on the development of technologies such as radio frequency (RF) energy harvesting, low-power computing, and backscatter communication. Particularly, backscatter communication allows devices to modulate its information on external RF signals that are backscattered to the receiver or reader.

BC considers the following elements: a carrier emitter (CE), a reader, and a backscatter device (BD). The main BC configurations are monostatic BC (MoBC), ambient BC (AmBC) and bistatic BC (BiBC). In a MoBC setup, the CE and reader are co-located and share parts of the same infrastructure. A monostatic system suffers from round-trip path loss, and requires full-duplex technology if the same antennas are simultaneously used for transmission and reception. In an AmBC setup, CE and reader are in different locations, while the CE is not considered dedicated. AmBC uses ambient sources to transmit information, such as Wi-Fi, Bluetooth, and TV signals. In BiBC, the CE and reader are also spatially separated from each other, but there is a dedicated CE. In addition, BiBC can operate in half duplex mode, thus avoiding the complexity associated to the full-duplex operation.

Due to the double path-loss effect on the two-way backscatter link, the received backscattered signal is typically weak compared to the direct link interference (DLI) from a CE. This requires a high dynamic range of the circuitry in the reader. As a result, a high-resolution analog-to-digital converter (ADC) is required to detect the weak backscattered signal under heavy DLI; this represents a great limitation because ADCs are major power consumers. Nonetheless, the benefits provided by multiple-antenna and distributed multiple-input multiple-output (MIMO) technologies can be explored to circumvent the limitations of BiBC, which is the main focus of this thesis.
In this context, the contributions of this thesis are two-fold. First, we propose a novel transmission scheme that includes a protocol for channel estimation at the multiple-antenna CE as well as a transmit beamformer design to suppress the DLI between the two ends of a bistatic link (namely CE and reader) and increase the detection performance of the BD symbol. Further, we derive a generalized log-likelihood ratio test (GLRT) to detect the symbol/presence of the BD and provide an iterative algorithm to estimate the unknown parameters in the GLRT. Simulation results show that the required dynamic range of the system is significantly decreased while the detection performance of the BD symbol is increased, by the proposed algorithm compared to a system not using beamforming at the CE.

For the second part, we consider BiBC in the context of cell-free MIMO networks by exploring the optimal selection of CE and reader among multiple access points, leveraging prior knowledge about the area where the BD is located. First, a maximum a posteriori probability (MAP) detector to decode the BD information bits is derived. Then, the exact probability of error for this detector is obtained. In addition, an algorithm to select the best CE-reader pair for serving the specified area is proposed. Finally, simulation results show that the error performance of the backscatter communication (BC) is improved by the proposed algorithm compared to the benchmark scenario.
Populärvetenskaplig
Sammanfattning

Passiv sakernas internet (IoT), en ny paradigm baserad på batterifria enheter, är en lovande teknik för att möjliggöra flera användningsområden som kräver anslutning med strikta krav på kostnad, komplexitet och energieffektivitet. Dessa användningsområden sträcker sig över kritiska sektorer som hälsosjukvård, transport och jordbruk. I detta syfte har bakåtspridning kommunikation (eng: backscatter communication) (BC) framträtt som en möjliggörande nyckelteknik för passiv IoT genom att låta enheter modulera sin information på externa radiofrekvens (RF)-signaler som reflekteras till mottagaren eller läsaren.


I BiBC, på grund av den dubbla vägutsläppseffekten på den tvåvägs-backscatter-länken, är den mottagna backscattered-signalen vanligtvis svag jämfört med direktlänksinterferens (DLI) från en CE. Detta kräver ett stort dynamiskt område för kretsen i läsaren. Som ett resultat krävs en högupplöst analog till digital omvandlare (ADC) för att detektera den svaga backscattered-signalen under tung DLI; detta är en viktig övervägande efter-

Vi föreslår en ny överföringsschema som inkluderar en protokoll för kanalestimering vid CE samt en överföringsstrålbildare som undertrycker DLI mellan de två ändarna av en bistatisk länk (nämlichen CE och läsare) och ökar detektionsprestandan för BD-symbolen. Dessutom härleder vi en generaliserat log-likelihood kvot-test (GLRT) för att detektera symbolen/närvaron av BD. Vi tillhandahåller också en iterativ algoritm för att uppskatta de okända parametrarna i GLRT. Simuleringsresultaten visar att det krävda dynamiska området för systemet minskar betydligt, och detektionsprestandan för BD-symbolen ökar genom den föreslagna algoritmen jämfört med ett system som inte använder strålbildning vid CE.

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Ahmet Kaplan
Linköping, March 2024
List of Abbreviations

3GPP  third-generation partnership project
ADC  analog-to-digital converter
AmBC  ambient BC
AP  access point
BC  backscatter communication
BD  backscatter device
BER  bit error rate
BF  beamforming
BiBC  bistatic BC
BS  base station
CE  carrier emitter
CSI  channel state information
DFT  discrete Fourier transform
DLI  direct link interference
FDD  frequency-division duplexing
GLRT  generalized log-likelihood ratio test
GS  grid search
IoT  Internet-of-Things
**LoS** line-of-sight

**LS** least-squares

**MAP** maximum a posteriori probability

**MIMO** multiple-input multiple-output

**MoBC** monostatic BC

**MRT** maximum-ratio transmission

**OtA** over-the-air

**P1** Phase I

**P2** Phase II

**PanA** Panel A

**PanB** Panel B

**PCSI** perfect channel state information

**PGD** projected gradient descent

**PL** path loss

**RCS** radar cross section

**RF** radio frequency

**SDR** software defined radio

**SI** self interference

**SINR** signal-to-interference-plus-noise ratio

**SISO** single-input single-output

**SMC** specular multipath component

**SNR** signal-to-noise ratio

**SVD** singular value decomposition

**TDD** time division multiplexing

**WPT** wireless power transfer
Chapter 1

Introduction and Motivation

Internet-of-Things (IoT) is a promising technology to enable several use cases that require connectivity with stringent requirements in terms of cost, complexity, and energy efficiency. These use cases help monitor and control the surrounding environment, thus applications span critical sectors, such as healthcare, logistics, manufacturing, and agriculture. There were almost 15 billion IoT connections in 2021, and this number is expected to reach 30 billion by 2027 [1]. Deploying and operating such a massive number of IoT devices is a significant challenge.

Passive IoT refers to a new paradigm that focuses on IoT deployments with battery-free devices, and the race toward the definition and standardization of passive IoT has already been initiated; for instance, the third-generation partnership project (3GPP) has run initial studies of use cases and requirements in Release 18 [2,3]. For their operation, passive IoT should rely on the evolution of critical technologies, namely environment energy harvesting, low-power computing and backscatter communication (BC). In this thesis, we contribute to the development of BC technology, as a promising communication solution for large-scale deployment owing to its low cost, low complexity, and potential to enable energy-efficient solutions for battery-free IoT devices and sensors. Furthermore, in this thesis, we explore the benefits of multiple-input multiple-output (MIMO) technology to enhance the performance of BC by addressing important limitations of BC, namely communication range, direct link interference, and initial access.
1 Introduction and Motivation

1.1 Thesis Outline

In Chapter 2, we provide an overview of BC to set the background for the thesis. First, we introduce the basic system model of the BC and explain the working principle of a backscatter device (BD). Next, we provide details of three different BC setups: monostatic BC (MoBC), bistatic BC (BiBC), and ambient BC (AmBC). In addition, we discuss some of the main challenges for BC. In Chapter 3, we introduce the concept of the distributed MIMO technology. In Chapter 4, the included/excluded papers are listed. In Chapter 5, we give the conclusion and discuss future research directions. Finally, we present the contributions of this thesis enclosed in two papers, i.e., Paper A and Paper B.
Chapter 2

Backscatter Communication

In this chapter, we first mention the history of wireless power transfer (WPT) and then introduce a historical background of BC and the main elements of a BC system. Then, we present the three main configurations for a BC system: MoBC, BiBC, and AmBC. Finally, we introduce the main challenges in BC.

2.1 Wireless Power Transfer

The idea of WPT started with Maxwell, who claimed that power could be transferred in free space using electromagnetic waves [4]. Hertz later experimentally validated Maxwell’s equations, showing that power indeed can be transmitted in free space. In the 19th century, Tesla conducted the pioneering experiments of long-range WPT [5]. However, due to the lack of technology, WPT was inefficient and got limited attention. The advent of high-power vacuum tubes marked a turning point, enabling the generation of microwaves. Consequently, WPT over long-distances became possible by the generation of narrow beams. In 1963, Brown demonstrated WPT to a small helicopter using microwave frequencies [6,7].

The popularity of wireless power transfer (WPT) has increased with the development of technology [8,9]. One of the main applications of far-field WPT is for low-power IoT devices and BC. In this chapter, we will discuss the importance of WPT and energy harvesting for low-power nodes in BC.

2.2 Backscatter Communication

Information transmission using reflections was first used in photophone technology discovered by Alexander Graham Bell [10]. In this technology,
the sound waves are projected onto a mirror using a special instrument, and vibrations are created in the mirror. These vibrations are captured and transmitted to a receiver mirror in the form light, as shown in Figure 1a. The vibrations in the receiver mirror are then converted to sound waves. 

The heliograph shown in Figure 1b is another device that uses sunlight to transmit information. To that purpose, the heliograph reflects the sunlight based on Morse code to send data to the receiver station. It was mainly used in the military during the 19th and 20th centuries. In 1945, The Thing, a passive listening device for spying, was designed by Leon Theremin [11] and placed in the residence of the US Ambassador in Russia. This device is hidden inside a wooden carving, as shown in Figure 1c, and operates without the need of external power sources by reflecting radio frequency (RF) signals. For its operation, sound waves vibrate a membrane inside the device, and these vibrations provoke variations on the reflection coefficient of the antenna that enable the transmission of information by the reflected RF signals.

BC proposed in [12] in 1948 also uses the reflection principle to transmit information. In this system, we have the following elements: a BD, a carrier emitter (CE), and a reader. The BD has the capability to change the frequency, amplitude, and phase of the incoming RF signal and transmit information by the scattered signal. Base stations, smart watches, Wi-Fi access points (APs), smartphones, and software defined radios (SDRs) are some examples of the devices that can be used as a CE and a reader [13–17]. Table 1 gives some examples of possible setups. A BC system can be implemented in three different types, namely MoBC, AmBC, and BiBC, which are later introduced in this chapter.
2.2. Backscatter Communication

Table 1: Type of CE, reader and BD in the literature

<table>
<thead>
<tr>
<th>Papers</th>
<th>CE</th>
<th>BD</th>
<th>Reader</th>
</tr>
</thead>
<tbody>
<tr>
<td>[15]</td>
<td>Smart watch</td>
<td>Contact lens</td>
<td>Wi-Fi device (smartphone)</td>
</tr>
<tr>
<td>[18]</td>
<td>SDR</td>
<td>Battery-free camera</td>
<td>AP (SDR)</td>
</tr>
<tr>
<td>[19]</td>
<td>Ambient sources</td>
<td>Sensors to measure climate data</td>
<td>Base stations</td>
</tr>
<tr>
<td>[20]</td>
<td>Distributed antenna panels</td>
<td>Zero-energy devices</td>
<td>Distributed antenna panels</td>
</tr>
</tbody>
</table>

![Block diagram of the BD.](image)

Figure 2: Block diagram of the BD.

2.2.1 Backscatter Device

This subsection explains the basic working principle of the BD, illustrated in Figure 2. The BD is designed to be energy-efficient, and it consists of several components: an RF antenna, a backscatter modulator, an RF energy harvesting circuit, a power splitter, a microcontroller, and IoT sensors. The power splitter block is used to select the operation mode of the BD as energy harvesting or BC.

The energy harvesting block comprises a matching circuit, a rectifier, and an energy storage block. The matching circuit ensures that the maximum power is transferred from the BD antenna to the rectifier. The rectifier then converts the incoming RF power to DC power, which is then stored in the energy storage block.

We assume the microcontroller is connected to an information source, such as a temperature sensor, humidity sensor, and accelerometer. The
energy harvesting block supplies power to the microcontroller which controls
the RF switch to change the impedance of the load connected to the antenna
to modulate the scattered RF signal. The reflection coefficient of the BD,
which is the ratio of the complex amplitudes of the scattered signal to the
incoming signal, is defined as [21–23]
\[ \gamma_i = \frac{Z_i - Z_a^*}{Z_i + Z_a^*}, \] (1)
where \( i = 1, \ldots, n \), \((\cdot)^*\) denotes conjugate, and \( Z_i \) and \( Z_a \) are the complex
impedance values of the load and the BD antenna, respectively. Here, \( n \)
denotes the number of different loads that can be connected to the BD
antenna.

2.2.2 Link Budget Analysis

In Figure 2, the CE sends an RF signal to the BD, and the BD modulates
the incoming RF signal and scatters it to the reader. The received power at
the BD in free-space is given by the Friis transmission equation and bistatic
radar range equation as [21]
\[ P_r = \sigma_i \left( \frac{\lambda}{4\pi d_1 d_2} \right)^2 P_t G_t G_r \frac{4\pi}{4\pi}, \] (2)
where \( P_r \) and \( G_r \) are the received power and the received antenna gain,
respectively, and \( P_t \) and \( G_t \) stand for the transmit power and the transmit
antenna gain, respectively. The distances between the CE and BD, and
between the reader and BD are \( d_1 \) and \( d_2 \), respectively. The term \( \lambda \)
stands for the wavelength of the transmitted signal, and \( \sigma_i \) is the radar cross section
(RCS) of the BD antenna defined as [21]
\[ \sigma_i = \frac{\lambda^2}{4\pi} G_b |\gamma_i - A_s|, \] (3)
where \(|\cdot|\) denotes absolute value, \( G_b \) is the BD antenna gain, reflection
coefficient \( \gamma_i \) corresponds to antenna mode, and \( A_s \) corresponds to the
structural mode of the BD antenna and is independent of the load. The term
\( A_s \) depends on the antenna type, size, and material. The incident RF signals
are backscattered according to the structural mode and antenna mode of the
BD. The structural mode models the scattered signal due to the interaction
of the incident RF signal and the BD antenna structure, while the antenna
mode represents the load-dependent scattering. The BD changes its RCS
2.3 Types of Backscatter Communication

As seen in Figure 3, there are three types of BC:

- **Monostatic**: In MoBC, the CE and the reader are collocated and can share parts of the same infrastructure such as antennas. First, the CE sends a carrier signal to the channel, and then the BD modulates the scattered signal by changing the load connected to its antenna [26]. The scattered signal is received by the reader and demodulated. The MoBC system suffers from the round-trip path loss (PL) effect and requires full-duplex operation if the same antennas are simultaneously used for transmission and reception.

- **Bistatic**: In BiBC, the CE and the reader are spatially separated from each other [27]. Therefore, BiBC does not require full-duplex communications. Although it also suffers from the round-trip PL effect, this effect can be decreased by optimizing the location of the CE and the reader.

Figure 3: The main BC setups.

by changing the load-dependent reflection coefficient $\gamma_i$ to modulate the scattered signal.

In addition, the structural mode can be assumed stationary if the BD and nearby objects move slowly or stay constant [24]. As a result, a homodyne receiver at the reader side can be used to cancel the received structural mode scattering [23–25].
• **Ambient**: Similar to BiBC, in AmBC, the reader and the CE are spatially separated from each other. However, there is no dedicated CE in AmBC, and the BD modulates the RF signals transmitted from ambient sources such as TV towers, base stations, Wi-Fi APs, and Bluetooth devices [26].

2.4 **Challenges in Backscatter Communication**

In this section, we describe some of the main challenges in BC, namely initial access, energy harvesting, communication range, and direct link interference.

2.4.1 **Initial Access**

The initial access in BC is one of the critical problems. Before the initial access, the BD can be in sleep mode and cannot send any pilot signal for the estimation of the BC cascade channel. Without channel state information (CSI) of the BD, the beamforming (BF) based on CSI cannot be applied to focus power to the BD.

To start the initial access procedure, it is necessary to activate the BD by supplying a sufficient amount of power that surpasses the BD RF front-end sensitivity threshold. This sensitivity threshold represents the minimum required power to awaken the BD, and a typical value for it can be around $-10$ dBm to $-25$ dBm [28–30]. Some of the possible solutions for the initial access problem are random BF, codebook-based BF, and geometry-based BF [31,32]. While the first two methods may suffer from the fading due to the multipath propagation, the latter requires geometric information about the communication environment, such as the location of the BD, CE, objects in the room, and room size.

2.4.2 **Energy Harvesting**

BC is a promising solution for low-power IoT applications with battery-free devices. However, energy harvesting is one of the challenging problems in BC. A typical RF energy harvesting block consists of a matching circuit, rectifier, and energy storage component. The efficiency of the energy harvesting block is defined as [33]

$$\eta = \frac{\text{DC output power}}{\text{Received RF power in the BD antenna}}.$$  \hspace{1cm} (4)

The efficiency of the harvested energy depends on the design of the rectifier, the BD antenna, and the accuracy of the matching circuit in the operation.
frequency [34]. Therefore, the efficiency can be increased by optimizing the designs of components of the RF energy harvesting block for specific use cases and operating frequencies [33–35]. For example, one of the solutions to harvest more energy is multi-band energy harvesting with multiple antennas in the BD [33,36,37]. However, this requires a unique rectifier design for high efficiency. Receive and transmit BF techniques can also be utilized to increase the harvested energy [14,32,38].

2.4.3 Communication Range

A passive BD does not have power-hungry active components, e.g., power amplifiers and RF synthesizers. In addition, BC suffers from the round-trip PL effect. Therefore, the communication range of the BC setup is another crucial problem to address. There are two different links in BC which are the links from the CE to the BD and from the BD to the reader. While the first communication distance is primarily dependent on the BD sensitivity and the PL between CE-BD, the second distance is primarily dependent on the round-trip PL and the sensitivity of the reader.

Increasing the transmit power does not always solve the problem because of the regulations on the transmit power limit [39–42]. Multiple-antenna technology can be used for the transmit and receive beamforming to increase the communication range in the BC [14,32,38]. In addition, LoRa and LoRea technologies are capable of achieving long-range communication by improving the reader sensitivity using low data rates from tens of bps to kbps, but they may require customized hardware and an active BD [16,43].

To decrease the round-trip PL effect, distributed MIMO can also be explored. In Paper B, we explore the optimal selection of the CE and the reader among multiple APs in a distributed MIMO setup to decrease the PL effect. We propose an algorithm to select the best CE-reader pair to serve a known area where a BD is located.

2.4.4 Direct Link Interference

In BC, the reader receives both the backscattered signal and the signal coming from the CE, which creates direct link interference (DLI). The dynamic range of the received signal in the reader is proportional to the ratio of the signal strengths between the weak backscattered signal and the received interference from the direct link [44,45]. This interference is strong compared to the backscattered signal suffering from the round-trip PL effect. As a result, the dynamic range of the received signal, a reliable indicator of the
necessary dynamic range of the reader circuitry, is high. Therefore, the reader
requires high resolution analog-to-digital converters (ADCs) to detect the
backscattered signal due to the DLI causing quantization errors. However,
ADCs are power-hungry devices and one of the major power consumers,
especially with multiple-antenna technology [46]. Additionally, the BD signal
is shifted towards the least significant bits of the ADC because of the DLI,
which causes low signal-to-interference-plus-noise ratio (SINR).

In a MoBC setup, the DLI is called self interference (SI). The SI can
be canceled by regenerating the transmitted carrier signal using specially
designed reader architectures [47–49]. However, the solutions are usually
complex and require high power consumption in MoBC. In AmBC and BiBC,
receive beamforming techniques [50, 51], frequency shifting [15–17, 52], and
coding in BD [53] can be utilized to decrease the effect of the DLI.

In Paper A, we propose a transmission scheme that first uses a transmit BF
technique to cancel the DLI and then apply a novel generalized log-likelihood
ratio test (GLRT) to detect the BD symbol in BiBC.
Chapter 3

Distributed MIMO Systems

In this chapter, we briefly discuss collocated and distributed massive MIMO systems. We also mention some of the challenges in distributed MIMO.

3.1 Introduction to Massive MIMO

Massive MIMO, introduced in [54], is considered a key technology for the 5G and beyond communication systems because it satisfies the high data rate, low latency, high reliability, and massive device connectivity requirements for the current and future wireless communication systems. Massive MIMO uses a large number of antennas in an AP and can serve multiple users simultaneously. This technology offers several benefits for wireless communication [55]:

- Increased capacity resulting from increased spectral efficiency and multiplexing capability by using BF techniques and serving several users at the same time and frequency resources.
- Increased coverage area due to using large antenna arrays and BF techniques.
- Interference mitigation owing to favorable propagation and BF techniques that allow focusing power to a specific user.
- Increased energy efficiency by focusing the available energy into a small area.
- Increased resilience against fading due to channel hardening [56].

By the law of large numbers, a statistical channel behaves like a deterministic channel after applying simple signal processing algorithms in the
APs such as maximum-ratio transmission (MRT) [57]. This phenomenon is referred to as channel hardening. As a result, fluctuations in the channel will be minimized, reducing the overhead for the scheduling, power allocation, and interference cancellation [56]. The latency is also reduced since users do not experience fading dips [55].

In distributed MIMO, the APs are spread over a large area and connected via a backhaul/fronthaul link. In this setup, the APs can share information using the backhaul/fronthaul link when necessary. Distributed MIMO comes with additional benefits, i.e., macro-diversity and multiplexing gain, besides the advantages of collocated MIMO [58]. Different from collocated MIMO, where the cell-edge users can suffer due to the PL effect, in distributed MIMO, spatially distributed base stations (BSs) are capable of increasing the communication performance, which is referred to as macro-diversity gain. Consequently, the users will have uniformly distributed quality of service. In addition, the multiplexing gain in distributed MIMO may be higher than that in collocated MIMO because the BSs are distributed geographically.

Both in conventional MIMO and distributed MIMO systems, there are two transmission modes: frequency-division duplexing (FDD) and time division multiplexing (TDD). In FDD, uplink and downlink operate simultaneously and use different frequencies, and both the downlink and uplink channels should be estimated. In TDD, downlink and uplink operate at the same frequency at different time instances within a coherence interval of the channel. In TDD, due to the channel reciprocity, the wireless channel in downlink and uplink are the same, and uplink channel estimation is sufficient. Therefore, in multiple antenna systems, TDD is the preferred transmission mode compared to FDD for a more efficient communication system design.

3.2 Challenges in Distributed MIMO

In distributed MIMO systems, the implementation complexity of the backhaul/fronthaul links is one of the challenges. The computational capability and backhaul/fronthaul link capacity of the system need to be scalable with the increasing number of APs and users [58]. In addition, the antennas need to work phase-coherently to ensure optimal performance in MIMO systems. In this section, we discuss the calibration required in distributed MIMO systems to improve the system performance.

Reciprocity calibration is critical for MIMO systems working in TDD operation mode. However, each antenna has its own transceiver chain, and each AP is driven by its local oscillator. Therefore, hardware imperfections
3.2. Challenges in Distributed MIMO

can lead to performance degradation due to the lack of calibration. Even though the uplink and downlink propagation channels are reciprocal, the estimated uplink channel using the pilot signals from the users is different than the downlink channel due to hardware imperfections. To illustrate this, let us assume there are $M$ distributed APs, each with an antenna, and $K$ users. Assuming noiseless communication, the estimated uplink channel can be written as

$$G_{UL} = T_{UE} G R_{AP}, \tag{5}$$

where $G \in \mathbb{C}^{M \times K}$, diagonal matrix $T_{UE} \in \mathbb{C}^{M \times M}$, and diagonal matrix $R_{AP} \in \mathbb{C}^{K \times K}$ denote the uplink propagation channel, the phase and amplitude offsets introduced by the transmit chains in the users and the receive chains in the APs, respectively. The downlink channel is given by

$$G_{DL} = T_{AP} G^T R_{UE}, \tag{6}$$

where $(\cdot)^T$ denotes transpose. Here, $T_{AP} \in \mathbb{C}^{M \times M}$ and $R_{UE} \in \mathbb{C}^{K \times K}$ denote the phase and amplitude offsets introduced by the transmit chains in the APs and the receive chains in the users, respectively. As seen in Eqs. (5) and (6), the uplink and downlink channels are different due to the hardware imperfections, and the uplink channel estimation cannot be directly used for downlink BF because the transmitted signals by different APs do not add up coherently in the users.

One of the solutions to solve the reciprocity calibration problem in distributed MIMO is over-the-air (OtA) protocols [59–66]. For example, each AP can transmit sequentially using beam-sweeping, and then the received signals can be used to compute the reciprocity calibration coefficients. This procedure allows reciprocity-based BF methods after the calibration process [59]. In [60], the OtA measurements are used for both reciprocity and full calibration of distributed antennas. The two individually calibrated arrays, which can be distributed or collocated arrays, can also be jointly calibrated using simple bi-directional and uni-directional measurements between the antenna arrays. In [61], the OtA bi-directional measurements are used for reciprocity calibration in different topologies, e.g., line and ring networks, and the error in the calibration process is analyzed. It is shown that the optimal approach is the calibration of the all APs in the given topology rather than the calibration of the selected APs that will be used to serve a specific user [61]. It is also possible to estimate the phase offset, introduced by transceiver chains, based on geometric information of the environment, i.e., the locations of transmitter and receiver antennas, assuming there is a strong line-of-sight (LoS) component [67].
In the case of two individually calibrated but not jointly calibrated antenna arrays, there will be an unknown residual phase offset between the antenna arrays as follows: $G_{UL} = e^{j\phi}G_{DL}^r$. In Paper A, our proposed DLI cancellation algorithm also works in the case of non-jointly calibrated distributed antenna arrays. In Paper A, we also provide a modified version of our proposed detector for the non-jointly calibrated antenna array case.
Chapter 4

Contributions of the Thesis

This thesis focuses on the BiBC setup in distributed MIMO and presents two main contributions enclosed in two papers, Paper A and Paper B. In Paper A, we propose an algorithm to cancel the DLI in BiBC setup with multiple antennas using a transmit beamformer. In Paper B, we propose an algorithm for the optimal selection of CE and reader among all APs.

To make the thesis self-contained, we provide some details on the singular value decomposition (SVD) and projection matrices in Appendix A and in Appendix B, respectively. These are used in the design of the transmit beamformer in Paper A.

4.1 Included Papers

Paper A: Direct Link Interference Suppression for Bistatic Backscatter Communication in Distributed MIMO

Authored by: Ahmet Kaplan, Joao Vieira, Erik G. Larsson


Abstract: Backscatter communication (BC) is a promising technique for future Internet-of-Things (IoT) owing to its low complexity, low cost, and potential for energy-efficient operation in sensor networks. There are several network infrastructure setups that can be used for BC with IoT nodes. One of them is the bistatic setup where typically there is a need for high dynamic range and high-resolution analog-to-digital converters at the reader. In this paper, we investigate a bistatic BC setup with multiple antennas. We propose a novel transmission scheme, which includes a protocol for channel estimation...
at the carrier emitter (CE) as well as a transmit beamformer construction that suppresses the direct link interference between the two ends of a bistatic link (namely CE and reader), and increases the detection performance of the backscatter device (BD) symbol. Further, we derive a generalized log-likelihood ratio test (GLRT) to detect the symbol/presence of the BD. We also provide an iterative algorithm to estimate the unknown parameters in the GLRT. Finally, simulation results show that the required dynamic range of the system is significantly decreased, and the detection performance of the BD symbol is increased, by the proposed algorithm compared to a system not using beamforming at the CE.

**Paper B: Access Point Selection for Bistatic Backscatter Communication in Cell-Free MIMO**

Authored by: Ahmet Kaplan, Diana P. M. Osorio, Erik G. Larsson

Accepted for the publication in the proceedings of 2024 IEEE International Conference on Communication (ICC).

**Abstract:** Backscatter communication (BC) has emerged as a key technology to satisfy the increasing need for low-cost and green Internet-of-Things (IoT) connectivity, especially in large-scale deployments. Unlike the monostatic BC (MoBC), the bistatic BC (BiBC) has the possibility to decrease the round-trip by having the carrier emitter (CE) and the reader in different locations. Therefore, this work investigates the BiBC in the context of cell-free multiple-input multiple-output (MIMO) networks by exploring the optimal selection of CE and reader among all access points, leveraging prior knowledge about the area where the backscatter device (BD) is located. First, a maximum a posteriori probability (MAP) detector to decode the BD information bits is derived. Then, the exact probability of error for this detector is obtained. In addition, an algorithm to select the best CE-reader pair for serving the specified area is proposed. Finally, simulation results show that the error performance of the BC is improved by the proposed algorithm compared to the benchmark scenario.

### 4.2 Excluded Papers

The author has decided to maintain the following paper out of the core of the thesis because all significant results therein are included in Paper A.
Dynamic Range Improvement in Bistatic Backscatter Communication Using Distributed MIMO

Authored by: Ahmet Kaplan, Joao Vieira, Erik G. Larsson

Published in the proceedings of IEEE Global Communications Conference (GLOBECOM), 2022, pp. 2486-2492.

This paper contains preliminary results of Paper A.

Abstract: Backscatter communication (BC) is a promising solution for Internet-of-Things (IoT) connections due to its low-complexity, low-cost, and energy-efficient solution for sensors. There are several network infrastructure setups that can be used for BC with IoT nodes/passive devices. One of them is a bistatic setup where there is a need for high dynamic range and high-resolution analog-to-digital converters at the reader side. In this paper, we investigate a bistatic BC setup with multiple antennas. We propose a novel algorithm to suppress direct link interference between the carrier emitter (CE) and the reader using beamforming into the nullspace of the CE-reader direct link to decrease the dynamic range of the system and increase the detection performance of the backscatter device (BD). Further, we derive a Neyman-Pearson (NP) test and an exact closed-form expression for its performance in the detection of the BD. Finally, simulation results show that the dynamic range of the system is significantly decreased and the detection performance of the BD is increased by the proposed algorithm compared to a system not using beamforming in the CE, which could then be used in a host of different practical fields such as agriculture, transportation, factories, hospitals, smart cities, and smart homes.
4 Contributions of the Thesis
Chapter 5

Conclusions and Future Work

This chapter briefly describes what has been achieved in this thesis and potential future directions. Detailed conclusions are given in the included papers.

5.1 Conclusions

In Paper A, we present a novel transmission scheme, including transmit BF, to eliminate the DLI in BiBC with multiple antenna CE and reader. We show that the proposed transmission scheme substantially reduces the DLI, and consequently, the required dynamic range in the reader circuitry is significantly decreased. This reduction allows the use of low-resolution ADCs.

In Paper B, we show that when APs have isotropic antenna radiation patterns, selecting a single AP as CE and assigning the remaining APs as readers minimize the bit error probability in BiBC in the cell-free MIMO setup. We also propose an algorithm to select the optimal CE and reader pair among all APs. We show that the probability of error in BC is improved because of the optimal selection that effectively mitigates the PL effect by leveraging the benefits of the distributed MIMO setup.

5.2 Future Research Directions

BC is a promising solution for massive machine-type communication and IoT applications requiring low-power consumption and low-cost devices. To further enhance the performance of BC, some potential directions for future research are as follows:
5 Conclusions and Future Work

- The communication range and data rate are limited in BC due to the round-trip PL effect and low-complexity design constraint on the BD. Multiple-antenna system with energy beamforming is a promising solution to these problems [14,32,38]. Additionally, a beamformer design for a mobile BD is another challenging problem. Another research direction to improve the data rate is exploring advanced modulation techniques for BC.

- Energy harvesting is crucial for a passive BD. Researchers focus on the design of rectifier circuits and multi-band energy harvesting [33–37]. In addition, the design of BD with reduced device sensitivity increases the energy harvesting distances [68].

- A passive BD does not have a battery. Therefore, initial access is an important challenge, especially when the channel of the BD is unknown. Initial access scheme to wake up the BD and estimate the BC channel is a popular research area. Researchers work on designing different BF techniques to supply sufficient energy to the BD to exceed the device sensitivity [32].

- DLI is a significant problem reducing the performance of BC. The research is ongoing to develop other signal processing algorithms with multiple antennas to mitigate the interference.

- Due to the broadcast nature of the wireless channel, communication security is threatened by adversary nodes, such as an eavesdropper. Traditional security algorithms are unsuitable for BC due to the BD’s low complexity and power-efficient design. Hence, researchers work on novel physical layer security algorithms for BC. Some of the proposed solutions are to generate artificial noise to degrade the channel quality of adversary nodes and tune the reflection coefficient to increase the security of the communication link [69–73].
Appendix A: Singular Value Decomposition

### Singular Value Decomposition

Consider a complex matrix $A \in \mathbb{C}^{N \times M}$ with rank $r \leq \min\{N, M\}$. The SVD of $A$ is given as
\[
A = U \Sigma V^H,
\]
where $(\cdot)^H$ denotes Hermitian transpose, and $U \in \mathbb{C}^{N \times N}$ and $V \in \mathbb{C}^{M \times M}$ are unitary matrices. The rectangular diagonal matrix $\Sigma \in \mathbb{C}^{N \times M}$ contains the singular values of $A$, i.e., $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_r = 0 = \sigma_{r+1} = \ldots = \sigma_q$ where $q = \min\{N, M\}$, on the diagonal. The columns of $U$ and $V$ are called left-singular vectors and right-singular vectors of $A$, respectively. We can partition the SVD of $A$ as follows:
\[
A = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \tilde{\Sigma} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_1^H \\ V_2^H \end{bmatrix},
\]
where $U_1 = [u_1, \ldots, u_r], U_2 = [u_{r+1}, \ldots, u_N], V_1 = [v_1, \ldots, v_r], V_2 = [v_{r+1}, \ldots, v_M]$, and $\tilde{\Sigma} = \text{diag}(\sigma_1, \ldots, \sigma_r)$.

The columns of $U_1$, $U_2$, $V_1$ and $V_2$ contain a basis of the following subspaces of $\mathbb{C}^N$ and $\mathbb{C}^M$:
- The columns of $U_1$: Orthonormal basis for the column space, $C(A)$,
- The columns of $U_2$: Orthonormal basis for the left nullspace, $N(A^H)$,
- The columns of $V_1$: Orthonormal basis for the row space, $C(A^H)$,
- The columns of $V_2$: Orthonormal basis for the nullspace, $N(A)$.

The matrix $A$ can be written as a sum of rank-1 matrices as
\[
A = \sum_{i=1}^{r} \sigma_i u_i v_i^H.
\]

We can use the SVD of a matrix to find the best rank-$k$ approximation of the matrix. The low-rank approximation problem is defined as follows:
\[
\min_{B \in \mathbb{C}^{N \times M}, \text{rank}(B) = k \leq r} \| A - B \|^2,
\]
where $\| \cdot \|$ denotes the Frobenius norm. The optimal solution for the problem in Eq. (10) is given by [74]
\[
B = \sum_{i=1}^{k} \sigma_i u_i v_i^H.
\]
APPENDIX B

Projection Matrix

A square matrix $P \in \mathbb{C}^{N \times N}$ is called a projection matrix if and only if $P^2 = P$. The projection matrix is idempotent, giving projection from $N$-dimensional vector space to a subspace. The eigenvalues of a projection matrix are $\lambda \in \{0, 1\}$. This can be shown easily as follows:

$$Pv = \lambda v = P^2v = \lambda^2 v,$$

where $v \neq 0$ denotes the eigenvector of $P$, and the only solution for $\lambda^2 = \lambda$ is either $\lambda = 0$ or $\lambda = 1$. A projection matrix satisfies

$$\text{rank}(P) = \text{trace}(P)$$

because the number of non-zero eigenvalues of the projection matrix (which is equal to its rank) is the same as the sum of its eigenvalues (which is the trace of $P$) due to $\lambda \in \{0, 1\}$.

In addition, if $P^H = P$ is satisfied along with $P^2 = P$, then $P$ is an orthogonal projection matrix. Let $a_i$ ($i = 1, 2, \ldots, n$) denote the columns of $A$. Then the orthogonal projection matrix to the subspace spanned by the columns of $A$ is given by

$$P = A(A^HA)^{-1}A^H,$$

where it is assumed that $A^HA$ is invertible. If we assume that $a_i$ are mutually orthonormal, $A^HA = I$, where $I_M$ denotes $M \times M$ identity matrix. In this special case, the orthogonal projection matrix can be simplified as

$$P = AA^H.$$ 

The projection matrix designed to project onto the orthogonal complement of the subspace spanned by the vectors $a_i$ ($i = 1, 2, \ldots, n$) is defined as $P^\perp = I_N - P$.

Next, we explore the design of the different projection matrices using SVD of matrix $A$. There are four possible projection matrices as follows:

- $P_{C(A)} = U_1(U_1^H U_1)^{-1}U_1^H = U_1 U_1^H$,
- $P_{N(A^H)} = U_2(U_2^H U_2)^{-1}U_2^H = U_2 U_2^H$,
- $P_{C(A^H)} = V_1(V_1^H V_1)^{-1}V_1^H = V_1 V_1^H$. 

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Appendix B: Projection Matrix

- $P_N(A) = V_2 (V_2^H V_2)^{-1} V_2^H = V_2 V_2^H,$

where $P_C(A)$, $P_N(A)$, and $P_{C(A)}$ are the projection matrices designed to project onto $C(A)$, $N(A)$, and $C(A)$, respectively. Note that, $U_1^H U_1 = I_r$, $U_2^H U_2 = I_{N-r}$, $V_1^H V_1 = I_r$, and $V_2^H V_2 = I_{M-r}$.

In Paper A, the SVD, low-rank approximation, and the projection matrix are used in the design of the transmit BF vector to cancel the DLI between CE and reader.
Bibliography


Included Papers
Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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