Digital Comprehensive Summaries of Uppsala Dissertations
from the Faculty of Science and Technology 2396

Multi-Tag Backscatter Networks

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ACTA UNIVERSITATIS
UPSALIENSIS
2024

ISSN 1651-6214
ISBN 978-91-513-2109-7
urn:nbn:se:uu:diva-526292

UPPSALA
UNIVERSITET

Dissertation presented at Uppsala University to be publicly examined in Eva von Bahr (100195), Regementsvägen 1, Uppsala, Monday, 3 June 2024 at 09:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Xavier Vilajosana (Universitat Oberta de Catalunya).

Abstract
Piumwardane, D. 2024. Multi-Tag Backscatter Networks. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 2396. 55 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-2109-7.

There are billions of Internet of Things (IoT) devices distributed across the globe, and this growing number of interconnected IoT devices demand seamless networking and low-power communication. While many devices are powered with batteries, their limitations such as maintenance and environmental impact call for battery-free alternatives. Small battery-free devices are attractive for sensing as they can use backscatter communication and operate on harvested energy from their surroundings. This dissertation presents a collection of novel techniques for backscatter communication, a method that reduces energy consumption by several orders of magnitude compared to standard low-power radio communication. Backscatter communication provides a direction for implementing widespread networks of battery-free devices that can be used for ubiquitous sensing. However, real-world deployment of backscatter tags encounters challenges due to their constrained power budgets. Adding mechanisms for identification, scheduling, querying and relaying for backscatter should be done carefully offloading power consuming components and delegating tasks whenever possible to an external powerful device.

This dissertation advances the state of the art in two different kinds of backscatter networks: digital backscatter networks and analog backscatter networks. Like conventional RF devices, protocol-based digital backscatter tags encode and communicate binary data in packets, allowing these tags to interoperate with conventional IoT devices using protocols such as IEEE 802.15.4. Applications such as dense networks require tag-to-tag multi-hop communication which introduces challenges as the tags rely on an external signal. For digital backscatter, I present protocol-based multi-hop communication and develop a tool to test large tag-to-tag networks. By contrast, analog backscatter directly communicates the sensor readings by modulating the external signal. As the analog tags lack a packet structure and onboard computation, these tags require new ways to provide key network functionality. For analog backscatter I propose and implement novel techniques for identification, querying and reading high resolution sensor data without significantly increasing the limited power budget on the tag. The contributions outlined in this dissertation enable practical deployment of backscatter tags for sensing and communication applications.

Keywords: Backscatter Communication, Wireless Communication, Identification, Internet of Things, Analog Backscatter

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ISSN 1651-6214
ISBN 978-91-513-2109-7
URN urn:nbn:se:uu:diva-526292 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-526292)

Dedicated to my family

List of Papers

This dissertation is based on the following papers, which are referred to in the text by their Roman numerals.

I Carlos Perez-Penichet, Georgios Theodoros Daglaridis, **Dilushi Piumwardane**, and Thiemo Voigt. "Modelling Battery-free Communications for the Cooja Simulator". In: *Proceedings of the 2019 International Conference on Embedded Wireless Systems and Networks*. EWSN '19. Beijing, China: Junction Publishing, 2019, pp. 47-58

II **Dilushi Piumwardane**, Christian Rohner, and Thiemo Voigt. "Reliable Flooding in Dense Backscatter-based Tag-to-Tag Networks". In: *2021 IEEE International Conference on RFID (RFID)*. 2021, pp. 1-8. DOI: 10.1109/RFID52461.2021.9444320

III **Dilushi Piumwardane**, Madhushanka Padmal, Vaishnavi Ranganathan, Christian Rohner, and Thiemo Voigt. "HarmonicID: An Identification System for Low-Power Analog Backscatter Tags". In: 2022 IEEE International Conference on RFID (RFID). 2022, pp. 1-6. DOI: 10.1109/RFID54732.2022.9795971

IV **Dilushi Piumwardane**, Madhushanka Padmal, Vaishnavi Ranganathan, Kasun Hewage, Christian Rohner, and Thiemo Voigt. "Unlocking the Potential of Low-cost High-resolution Sensing with Analog Backscatter". *under submission.* 2024

V **Dilushi Piumwardane**, Madhushanka Padmal, Carlos Perez-Penichet, Christian Rohner, and Thiemo Voigt. "Desynchronized Querying of Analog Backscatter Tags". *under submission.* 2024

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Additional Papers

In addition to the papers included in this dissertation, I have authored or co-authored the following papers and posters during my doctoral studies.

- **Dilushi Piumwardane**, Carlos Perez-Penichet, Christian Rohner, and Thiemo Voigt. "Backscatter Communication for Wireless Robotic Materials". In: *Proceedings of the 2019 International Conference on Embedded Wireless Systems and Networks, EWSN 2019, Beijing, China, February 25-27, 2019*. ACM, 2019, pp. 336-340

- **Dilushi Piumwardane**, Carlos Perez-Penichet, Christian Rohner, and Thiemo Voigt. "Poster: Backscatter Communication for Wireless Robotic Materials". In: *Proceedings of the 2019 International Conference on Embedded Wireless Systems and Networks, EWSN '19. Beijing, China.* Junction Publishing, 2019, pp. 224-225

- Carlos Perez-Penichet, **Dilushi Piumwardane**, Christian Rohner, and Thiemo Voigt. "TagAlong: Efficient Integration of Battery-free Sensor Tags in Standard Wireless Networks". In: *2020 19th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*. 2020, pp. 169-180.
DOI:10.1109/IPSN48710.2020.00022

- Carlos Perez-Penichet, **Dilushi Piumwardane**, Christian Rohner, and Thiemo Voigt. "A Fast Carrier Scheduling Algorithm for Battery-free Sensor Tags in Commodity Wireless Networks". In: *IEEE INFOCOM 2020 - IEEE Conference on Computer Communications*. Toronto, ON, Canada: IEEE Press, 2020, pp. 994-1003.
DOI:10.1109/INFOCOM41043.2020.9155241

- **Dilushi Piumwardane**, Madhushanka Padmal, Kasun Hewage, Vaishnavi Ranganathan, and Thiemo Voigt. "Towards Low-cost Sensing with Mobile Backscatter". In: *Proceedings of the 29th Annual International Conference on Mobile Computing and Networking*. New York, NY, USA: Association for Computing Machinery, 2023

- **Dilushi Piumwardane**, and Thiemo Voigt. "Poster: HarmonicID - Identifying Analog Backscatter Tags with Harmonics". *Presented at Womencourage '23,Trondheim, Norway.* 2023

- Wenqing Yan, **Dilushi Piumwardane**, Madhushanka Padmal, Thiemo Voigt, and Christian Rohner. “Decomposing Radiometric Fingerprints in Backscatter Systems”. *under submission.* 2024

Contents

Acknowledgements

The work presented in this dissertation would not have been possible without the support of the people around me, to whom I owe a great deal of gratitude.

First and foremost, I am really thankful to have had my amazing supervisor Prof. Thiemo Voigt during my PhD journey. He worked closely with me and gave me the freedom to work on a wide range of projects. His expertise and guidance improved the quality of my research and writing skills. I am especially grateful for his understanding and support throughout challenging times: whether navigating the complexities of the Covid pandemic or the demands of parenthood. His availability, hard work and dedication to the success of his students are truly inspiring. I could not have wished for a better supervisor.

I thank my co-supervisor Prof. Christian Rohner. His knowledge across a wide range of technical areas significantly enhanced the quality of the work presented in this dissertation. I truly appreciate his willingness to share his expertise. He has been a very nice person to me and my family. I'd like to express my sincere appreciation to my colleague, co-supervisor and co-author Dr. Carlos Pérez-Penichet. From welcoming me to Uppsala to offering early mentorship on your research, I've always valued your presence and frequent discussions. Next I thank my long-term collaborator and friend, Dr. Vaishnavi Ranganathan for igniting my passion for sensing and systems research. Your unwavering support, from late-night brainstorming sessions to sharing your knowledge in signals and systems, has been invaluable. I thank Prof. Mikael Sternad, for teaching me the core concepts of Signal processing, taking time to help with doubts in my research and appreciating my research efforts. My sincere gratitude goes to my undergraduate research advisors Dr. Chamath Keppitiyagama, Prof. Kasun De Zoysa, Dr. Ruvan Weerasinghe and Dr. Asanka Sayakkara for introducing me to research that led to my first publication and eventually, my pursuit of a PhD at Uppsala University.

I want to thank my friends and co-authors Dr. Kasun Hewage and Dr. Wenqing Yan. I have learned a lot from you and your support improved the quality of my publications. I thank Laura Feeney for the willingness to review my work and provide feedback and for being a good friend throughout my PhD. Then I thank my colleagues and people who shared the corridor especially Prof. Per Gunningberg, Dr. Ambuj Varshney, Dr. Lorenzo Corneo, Dr. Harris Orfanidis, Sam Hylamia, George Daglaridis, Tobias Mages, Ahmed El Yaacoub, Konrad-Felix Krentz, Saba Akbari, Weining Song and colleagues at SICS. I am deeply grateful for your willingness to help me in different aspects through fruitful discussions and friendly company.

Words cannot express my gratitude to my family for their unwavering love, support and heartfelt prayers. Dad, thank you for believing in my dreams and letting me to pursue my PhD in Sweden, even when it meant that you will not see me everyday. I adore your frequent visits. You gave me the best childhood and life a child could wish for. Mom, your sacrifice of your dream job to raise me is a testament to your boundless love. Thank you for always being a listening ear, no matter the time. No one in this world champions my success quite like you and wishes the best for me always. My sister, you've filled my life with laughter and motivation. Thank you for trying to fill the void that was left by the noisy person at home. For encouraging me in everything I do and being my role model in life. I was brought up with immense privilege. I am incredibly grateful to the wonderful people who raised me with unconditional love: my grandparents, aunt Nexta, and uncle George.

I am profoundly grateful to my husband, co-author and best friend Padmal. Your expertise in electronics, sharing of your knowledge and unwavering dedication made collaborating on our papers a true pleasure. You're not only a brilliant mind but also a kind, fun, and amazing person sharing joyful and exciting days as well as the sleepless and tiring parenting nights. I couldn't have asked for a better colleague and I'm so blessed to have you in my life.

I thank my Sri Lankan friends in Uppsala for welcoming me and providing company throughout my stay in Sweden. I thank my friends in Sweden and in Sri Lanka, church friends and extended family for encouraging me.

Finally my infinite gratitude goes to my little Hailey, for your smile that brightens my heart and refreshes me every day.

Dilushi Piumwardane
Uppsala, April 2024

This work has been funded by the Swedish Foundation for Strategic Research (SSF) and Vetenskapsrådet (Swedish Research Council).

List of Acronyms

FFT Fast Fourier Transform

IoT Internet of Things

MAC Medium Access Control

CPU Central Processing Unit

PCB Printed Circuit Board

RF Radio Frequency

RFID Radio Frequency Identification

LO Local Oscillator

SDR Software Defined Radio

FDMA Frequency Division Multiple Access

OQPSK Offset Quadrature Phase Shift Keying

PWM Pulse Width Modulation

CSS Chirp Spread Spectrum

UWB Ultra Wideband

Part I:
Dissertation Summary

1. Introduction

The advancement of the Internet of Things (IoT) has resulted in billions of globally distributed devices. This increasing network of connected devices relies on sensing and communication to collect data and share information. Such growth demands seamless networking and communication services. One major hurdle is powering these devices. While batteries remain a common solution, their inherent limitations in terms of maintenance and environmental impact create a compelling case for miniature, battery-free alternatives.

Small battery-free devices are attractive for sensing as they can operate on harvested energy from their surroundings [1, 2, 3]. Common harvesting modalities include Radio Frequency (RF) harvesting and solar harvesting. However the substantial power requirements for communication constrain the capabilities of battery-free devices, limiting their functionality. My work is based on backscatter communications, that reduces power consumption in data transmissions by three orders of magnitude compared to standard low-power radio communication.

Backscatter transmissions differ from conventional radios as they reflect an external signal to convey information. A backscatter based sensing system is therefore composed of extremely constrained backscatter "tags" that sense some physical quantity such as the temperature, along with a set of conventional RF devices that generate the external signal and receive the reflected signal. Practical deployment of backscatter tags requires networking strategies for managing multiple constrained devices such as device identification, communicating over a shared channel and interference avoidance [4, 5, 6]. Typically all coordination has to be offloaded to remote powerful devices.

This dissertation advances the state of the art with respect to two different kinds of backscatter systems: Like conventional RF devices, protocol-based *digital* backscatter tags explicitly encode and communicate binary data [7, 8]. Notably, such tags can interoperate with conventional IoT devices such as devices compatible with IEEE 802.15.4 protocol [7]. My work addresses the problems of interference and multi-hop communication in large, dense backscatter networks. By contrast, *analog* backscatter tags communicate sensor readings directly by modulating the carrier [1, 9, 10]. Analog tag designs allow joint sensing and communication with lower power consumption than digital backscatter. My work addresses the problems of identifying, querying and reading high resolution sensor data in analog backscatter.

Applications such as wireless robotic materials inherently require dense networks [11]. The low power demand and small form factor, comprising

of a few components makes backscatter tags ideal for dense deployment scenarios. Dense networks pose new challenges such as receiving packets amidst interference from neighboring tags located in close proximity. In this context, we consider digital backscatter tags that are not only able to transmit, but also have very low power digital receivers making tag-to-tag multi-hop communication possible. In order to coordinate transmissions among tags within tag-to-tag networks, a mechanism like a Medium Access Control (MAC) protocol is required. A simple way to forward packets is flooding. In network-wide flooding, nodes in the network re-broadcast the received packet which would eventually reach the furthest node in the network. However, this approach poses risks of congestion and interference and therefore the development of tools and models to assess the performance of flooding in backscatter networks is needed. To address this, we incorporate multi-hop communication and flooding techniques for packet forwarding among tags. The work in this dissertation, demonstrates multi-hop tag-to-tag networks with real hardware experiments and evaluates the feasibility of flooding with simulations.

Battery-free tags, with their inherent resource constraints, demand low power solutions such as passive, analog designs. Analog operations are appealing since they reduce the operating power required on the sensing platform. Compared to their digital counterparts, purely analog tags excel in low-power consumption, enabling them to operate for longer periods on harvested energy. This makes them ideal for various sensing and communication applications where minimizing power consumption is crucial. The possibility to sense many aspects of the physical world has use cases such as health monitoring, environment sensing and precision agriculture. The first passive RF sensor invented was a listening device called the Great Seal Bug, invented in 1945 [12]. This fully battery free and passive device harnessed a unique approach, using a passive cavity resonator coupled with an antenna to wirelessly transmit captured sound waves. Considered an engineering marvel at the time, it has inspired many widely used RF "things" such as RFID tags. We use analog backscatter to communicate sensor data from passive sensor tags. While analog backscatter offers a compelling solution for passive sensor tags due to its low power operation, it presents unique challenges. Unlike digital communication, analog backscatter lacks a packet structure. When multiple tags are deployed identifying and querying of tags without interference from other tags is challenging. This dissertation provides possible solutions to address the challenges encountered with analog tags while maintaining their performance and small power budget.

1.1 Research Questions

My work addresses challenges encountered when deploying multiple backscatter tags for sensing and communications purposes. The first section of my

dissertation addresses the challenges in protocol-based tag-to-tag networks. Commodity IoT devices such as WiFi, Bluetooth or Zigbee systems are vastly deployed around us, making sensor tags that can communicate directly with them attractive [7, 9]. They significantly lower the operation cost compared to dedicated Radio Frequency Identification (RFID) readers used to query tags. Recent advancements show that when a carrier is provided these tags can transmit or receive packets from existing IoT devices [7, 13]. The ability to receive packets makes tag-to-tag networking possible. Tag-to-tag networks enable a network of tags that can communicate with commodity IoT devices as well as other tags enabling multi-hop communication in tags. Tag-to-tag networks allow for novel applications such as wireless robotic materials consisting of a large number of sensors and actuators that inherently require dense networks of such tags [11]. Such applications require communication for triggering actuation tasks on sensor events. In case the sensor cannot directly reach the actuator, it is beneficial if tags can forward the packets to other tags in the network with multi-hop communication. Maintaining a MAC protocol or transmission schedule requires time-synchronization among tags which adds an overhead to tags operating on a low power budget. Flooding is an alternative where each tag re-broadcasts the received packet so that nodes within the communication range receive it. However, unlike traditional wireless networks the backscatter transmissions, low-power reception and the communication range of the tags depend on the carrier. The feasibility of multi-hop communication and flooding is unexplored for these networks. A simulator tool would provide a method to form, explore and analyze large networks with many tags. So we ask: *Is it possible to enable large tag-to-tag networks with such resource constrained devices? What is the impact of the external carrier on these tag-to-tag networks? Is flooding a reliable technique for these dense networks?*

The second section of my dissertation addresses the challenges in analog backscatter tags that enable ultra-low-power communications. Analog backscatter tags consist of purely analog components which consumes lower power than digital bacskcatter tags [1, 9]. They can be built using a few components, namely an energy storage (or harvesting) device, an oscillator, an RF switch and passives. Analog tags are simple in design which makes them easy to deploy for sensing and communication purposes. However, this simplicity comes at the cost of lacking fundamental communication elements, such as a Central Processing Unit (CPU) for computations or digital processing and lack of structured packet format. Hence, analog tags are incompatible with widely adopted IoT protocols and do not have mechanisms like MAC protocols for managing transmissions. Adding these functionalities would increase the component count which increases the design complexity and power budget of the tag. Although analog tags are attractive, these challenges hinders their ability to be widely deployed. Overcoming these obstacles demands innovative solutions that deviate from traditional wireless communication paradigms.

First there is the issue of identifying analog backscatter tags. In our analog tag design, the sensor value is encoded as a shifted frequency, transmitted over a carrier frequency. When multiple tags are deployed, the sensor values may be translated to the same or different frequencies of other existing tags causing interference. One solution commonly used is to separate tags by allocating different frequencies. This is achieved by allocating unique frequency shift bands to the tags. This approach faces limitations due to the generation of multiple strong harmonics when performing the frequency shift. Hence, the number of frequencies that can be allocated are limited. Another critical problem, typically overlooked in the literature, arises from the inherent simplicity of analog backscatter tag design. Simple analog tag design leads to frequency-agnostic behavior, meaning that even though the tag is matched to perform well in a specific frequency band, it does not completely limit its performance in other frequency-bands and may transmit in other frequency bands. So we ask the questions: *How do we identify analog backscatter tags in a spectrum efficient way, when multiple tags are deployed? How do we query the tags when multiple tags are deployed? Can we allow concurrent transmissions from multiple tags without interference to reduce the querying time?*

Analog backscatter tags offer a simplified design, making them an ideal choice for mobile sensing applications. These tags require only a continuous wave carrier for excitation, readily provided by off-the-shelf IoT devices through test modes. However, a trade-off exists between sensor resolution and power consumption. A wider sensor output range necessitates a larger frequency shift for encoding data, which in turn demands a higher tag oscillator switching frequency and increase the power consumption at the tag. As the sensor values are encoded in frequency, a simple receiver such as a TV-tuner or a cheap Software Defined Radio (SDR) radio like a RTL-SDR is sufficient to receive the signal. While a smaller frequency range saves tag's power, it requires computation of large Fast Fourier Transform (FFT)s with small bin sizes to retrieve the sensor data. However, large FFT computations are not feasible for low-power receiver processing units like micro-controllers. Also, if the frequency range is small and appears close to the carrier, the strong carrier signal masks these frequencies. So we ask the question: *How do we enable high resolution mobile sensing with analog backscatter tags coupled with low-power receivers, to unlock their true potential for sensing applications?*

1.2 Methods

Most of my dissertation work involves experiments with hardware devices. Figure 1.1 shows two main tag prototypes we used for analog and digital backscatter. Some work in this dissertation also include analytical and simulation methods. The experiments follow the iterative scientific method: hypoth-

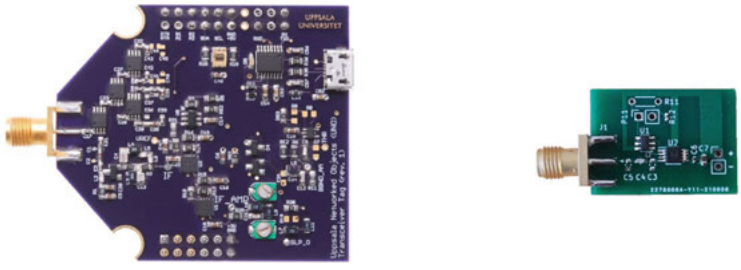

Figure 1.1. Tag frontend prototypes used for experiments. The Digital Backscatter tag front-end (left) was connected to an FPGA to process baseband computation logic. The Analog Backscatter tag (right) has a significantly reduced component count and has no onboard computation elements.

esis formulation, test validity of the hypothesis through experiments and reformulating the initial hypothesis if needed, thereby repeating previous steps.

For the experiments in Paper I and Paper II, we use the tag prototypes built for previous work by Perez-Penichet [7, 13]. This tag has a front end to backscatter (transmit) signals and receive signals. Digital baseband processing for Offset Quadrature Phase Shift Keying (OQPSK) modulation and demodulation is done with a connected FPGA board.

For analog backscatter work, (Papers III,IV,V), there was no hardware available to test our design. As a result, we designed hardware artifacts from scratch using custom Printed Circuit Board (PCB)s and components for RF front ends. The purpose of our tag prototypes is to demonstrate the feasibility of the ultra-low-power battery-free communication techniques we propose. They do not operate without batteries but could be equipped on existing harvesting designs [1]. This is because building optimized energy harvesting designs is out of scope of this dissertation. Further, we propose different mechanisms to existing analog backscatter tags, without increasing their operating power budget. Therefore for our experiments, providing external power helps us isolate the design choices we made and only evaluate them without adding the overhead of handling energy harvesting components and providing harvesting sources (such as RF or light). It also reduces the form factor of our tags.

Conducting repeatable and reliable RF experiments is difficult due to the uncontrollable, dynamic and unpredictable environment, especially for tag-to-tag networks where the transmission signals are weak and reception on the tag is sensitive. We manage this problem in different ways with increasing level of practicality. When possible, to test our initial setup we perform small-scale experiments with cables, avoiding the effects of multipath and interference. Then we perform experiments in an anechoic chamber where we are also safe from multipath and interference, to evaluate the limits of wireless links and set a benchmark. Then we finally perform indoor experiments starting from small

ranges and high carrier power and then increasing the ranges and reducing the carrier power. To provide high carrier power (still within FCC limits) we use USRP B210 devices. To analyze a wideband spectrum for tag transmissions we use a specturm analyzer. Then we eventually use Zolertia firefly motes to provide a carrier and use the same device to receive packets from backscatter tags in Paper I.

1.3 Contributions

The overall contribution of my dissertation is to identify and provide solutions to challenges that occur when multiple backscatter tags are deployed for practical use. For protocol-based digital backscatter, we provide reliable multi-hop communication in dense networks. This extends the communication range of the otherwise restricted backscatter tags and has the potential to unlock advancements in backscatter communication such as increasing the reliability in packet reception. In our analog backscatter work we show how to read high resolution sensor data from tags and identify and query multiple tags while avoiding interference. I believe that these contributions can enable a smooth deployment of backscatter tags for sensing and communication purposes.

Specifically the contributions of my works are described as follows.

Multi-hop Communication for Tag-to-tag networks

We extend the Cooja simulator [14] for backscatter communication (Paper I). In particular we implement the low-power receiver model proposed by Perez-Penichet et al. [13] along with a traditional backscatter transmitter model. The extension we implemented enables the simulator as a tool to develop and analyze protocols (for MAC layer and above) for backscatter devices and test and implement functionality, without having to deploy the setup physically. It further provides a platform to study different parameters specific to backscatter such as the effect of carrier strength on the communication range that are hard to evaluate in a real setup due to weak signals and interference. We further extend this simulator to support tag-to-tag communication that enables multi-hop communication. We show that flooding is a viable solution to forward packets in dense backscatter-based networks (Paper II).

The simulator is useful to analyze tag-to-tag networks with a large number of tags, which is otherwise not feasible as there are no testbeds for large backscatter networks. Our simulation and analysis show how the carrier power and position affect these networks. This is the first study that we are aware of, that analyzes and simulates the carrier impact on tag-to-tag networks. Motivated by the simulation results, we also demonstrate multi-hop tag-to-tag networks on hardware that support the Zigbee protocol. This is the first tag-to-tag network that we are aware of in which it is possible for the tags to decode, modify packets and forward them to other tags.

Identification and Desynchronized Querying of Analog Backscatter Tags
Analog tags do not have digital frame structures and therefore they lack an identification mechanism. We propose, design and implement a fully analog identification mechanism for analog backscatter tags without increasing the power budget on the tag (Paper III). Our identification mechanism is based on harmonics which are inherently generated as a result of the square wave nature of backscatter signals. These harmonics are generally disregarded as undesirable and spurious transmissions but we leverage signal conditioning to modify these harmonics to use them for identification purposes. We demonstrate the feasibility of the approach by deploying tags in an indoor environment. In Paper V we discuss limitations of such identification when multiple tags are active and provide a scalable mechanism to enable desynchronized querying for analog backscatter tags. Backscatter tags are known for their frequency agnostic behaviour, and reflect any given carrier frequency. When multiple tags are deployed, all of these tags are activated by the carrier, making it difficult to identify the tag and associate the data. We propose match network based tag querying to limit the activation frequencies of the tags without modifying the backscatter module of the tag. This method also enables concurrent querying, reducing the querying time of the tags.

High-Resolution Sensing with Analog Backscatter Tags
To represent high bandwidth sensor data in frequency-shifted analog backscatter, a larger switching frequency at the tag is needed which increases the power consumption at the tag. We introduce a mechanism leveraging a property of harmonics to enable high-resolution sensing without increasing the power budget for analog backscatter tags, even when using low-cost receivers to decode the data (Paper IV). This approach facilitates the practical deployment of a portable backscatter platform for sensing and communication, crucial for applications like wildlife monitoring where cost and deployability are critical factors. We demonstrate reading sensor data encoded in backscatter signal harmonics using a low-cost RTL-SDR dongle connected to an Android device.

1.4 Roadmap

The dissertation is divided in to two parts: Part I presents a comprehensive summary that includes several chapters that describe the work done. In Chapter 2 I discuss background information that is necessary to understand the foundations of the work done in this dissertation. Chapter 3, contains summaries of the five peer-reviewed publications. In Chapter 4 I discuss a summary of related work. Chapter 5 consists of concluding remarks and future work. Part II contains a reprint of the five papers included in the dissertation.

2. Background

This section provides an introduction to the basic principles of operation in backscatter, harmonics produced by the backscatter operation and other background that is necessary to understand the results of my dissertation.

2.1 Backscatter Communication

Backscatter communication utilizes the reflection of an external carrier signal [8, 15, 16]. This method leverages the variation in the backscatter tag's antenna impedance in the presence of an incident wave. The incident wave, known as the carrier signal in backscatter, is the incoming signal. Impedance is a measure of resistance to electrical flow. When a wave encounters a boundary between materials with differing impedances, the wave is partially reflected back to the same medium as the incident wave.

Backscatter tags exploit this principle to transmit data. Backscatter tags control the reflections of the carrier signal when it approaches the antenna of the tag. By carefully controlling how this signal reflects, the tag can transmit data. The simplest way to encode information is by using two distinct reflection states: one state absorbs the carrier signal, while the other reflects it back. To achieve this, low power backscatter tags have a switch that toggles between two impedance states of the antenna. This switching alters a parameter called the reflection coefficient (Γ) of the antenna. The reflection coefficient is a parameter that describes how much of the incident wave is reflected. This value varies depending on the load attached to the antenna.

The reflection coefficient is,

$$\Gamma = \frac{Z_l - Z_a}{Z_l + Z_a} \tag{2.1}$$

where Z_a is the characteristic impedance of the antenna and Z_l is the load impedance attached to it. Both are complex valued-quantities. In a perfectly matched antenna, the load is properly terminated to minimize reflections (Γ is close to zero), signifying the absorbing state. Otherwise, Γ is high representing a reflecting state.

Signal Strength and Range of Backscatter

The power (P_r) of a backscattered signal as observed at the receiver can be derived applying the Friis free-space propagation equation twice. First, for the

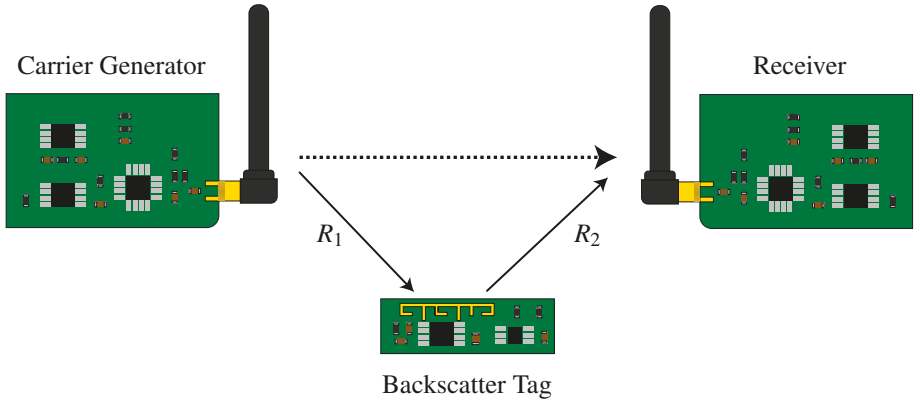

Figure 2.1. Bistatic backscatter setup. The carrier generator produces an unmodulated signal which is received by both the backscatter tag and the receiver. The tag modulates this signal and the receiver separates the tag's signal to decode tag data.

path loss from the carrier generator to the backscatter device (distance R1) and then for the path loss from the backscatter device to the receiver (distance R2). In a monostatic setup, the carrier generator and the receiver are in one unit and therefore $R_1 = R_2$. It is commonly seen in RFID systems and in systems where the carrier and the receiver need to share a clock for time synchronization [17, 18]. In contrast to that, most backscatter work including the work in this dissertation, use a bistatic setup in which the carrier generator is separated from the receiver. This setup improves the range of the system and often reduces the complexity of the carrier generator and the receiver. The backscatter tag setup we describe is in Figure 2.1. The path loss equation can be written as:

$$P_r = \left(\frac{\lambda^2 P_t G_t}{16\pi^2 R_1^2}\right)\left(G_b^2 \alpha \frac{|\Delta\Gamma|^2}{4}\right)\left(\frac{\lambda^2 G_r}{16\pi^2 R_2^2}\right) \tag{2.2}$$

Where P_t is the output power of the carrier generator, G_t, G_b and G_r are the antenna gains of the carrier generator, battery-free device and receiver respectively, λ is the wavelength of the signal, α is a constant that describes losses incurred in modulating the signal using backscatter and Γ is the backscatter coefficient. For a backscatter system with fixed configuration that has static parameters for P_t, G_t, G_b, G_r, Γ, α and λ the range depends on the carrier generator to the backscatter tag distance (R_1) and the backscatter tag to the receiver distance (R_2).

According to the inverse-square law dependence in ranges in this equation, the signal strength of the backscatter device increases as it approaches either the receiver or the carrier generator, but decreases towards the central point between the two [7]. This behavior contrasts with traditional radio links, where signal strength primarily decreases with increasing distance from the transmitter.

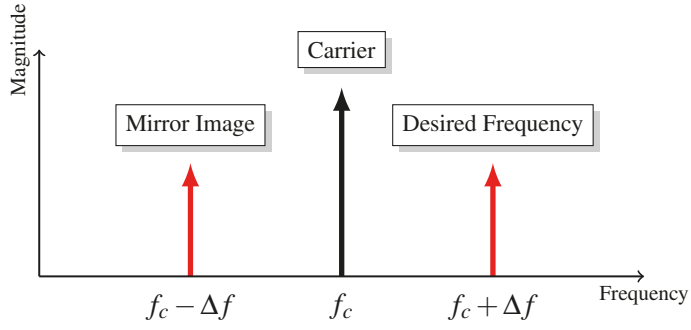

Figure 2.2. Illustration of the frequency-shifted backscatter spectrum. Carrier frequency is shifted by the tag by mixing the tag local oscillator's baseband signal. A mirror image often discarded as a spurious transmission is also generated due to the use of real signals.

Frequency-Shifted Backscatter

In a backscatter communication system, the receiver encounters two incoming signals. One is the powerful carrier signal from a carrier generator and the other is a much weaker data carrying signal reflected by the backscatter tag (Figure 2.1). These signals interfere at the receiver and the signal we are interested in is the data carrying signal from the backscatter tag. An important technique used to avoid the self-interfering unmodulated carrier signal at the receiver is shifting the frequency of the backscatter signal [1, 7, 8, 19]. This allows the receiver to avoid interference from the strong carrier and receive the weak backscatter signal by placing it at a different frequency than the carrier frequency. The signal observed at the receiver is the superposition of the backscatter signal and the carrier.

Consider an external unmodulated carrier signal of frequency f_c and a sinusoidal signal of frequency Δf.

$$2\sin(f_c t)\sin(\Delta f t) = \cos\left[(f_c - \Delta f)t\right] - \cos\left[(f_c + \Delta f)t\right] \tag{2.3}$$

Using trigonometry we can represent frequency-shifted backscatter as in Eq. 2.3. The use of real signals generate spectrum copies as shown in Figure 2.2. The frequency Δf can be approximated as the fundamental frequency of a square wave which is produced by the backscatter switch that is periodically switching among impedances.

2.2 Receiver Sensitivity and Range

In Paper II, we use a model of a low-power receiver that uses an unmodulated carrier signal to receive IEEE 802.15.4 packets [13]. This receiver employs a diode mixer for low-power downconversion of RF signals. However, unlike

traditional receivers with a fixed sensitivity, the sensitivity of this receiver depends on the strength of the unmodulated carrier signal. The reason lies in the inherent conversion loss of the diode mixer. The efficiency of the diode mixer (conversion loss), depends on the strength of the unmodulated carrier.

The sensitivity of the receiver affects the communication range. Therefore, similar to backscatter transmitters, there are two zones where the receiver performs well: When it is placed close to the carrier generator and when it is close to the transmitter. In our multi-hop tag-to-tag networks, the transmitter is a backscatter tag. So the receiver sensitivity and the backscatter path loss affects the communication range in these networks. As it is not straightforward to understand the behavior of such networks we study the communication range and the effect of the carrier generator on the backscatter network in Paper II.

2.3 Analog Backscatter

Analog backscatter designs avoid computational blocks on the tag and instead communicate sensor information at tens of microwatts of power [1, 9]. A receiver decodes the signal. The key idea behind this technique is to take the analog sensor output as a variable and embed it in the backscatter transmissions. This backscatter signal modifies a characteristic of the carrier signal, such as its frequency [1] or amplitude [20] according to the analog signal from the sensor. In our work we use of this concept in the design of our sensor tags to map analog sensor readings to a frequency shift.

Analog Backscatter vs Digital Backscatter

In common designs, both analog and digital backscatter have a switch to toggle between antenna impedances. Analog backscatter is simple in design and transmits raw sensor data. Digital backscatter forms a packet structure to embed data and often requires onboard computation which increases the tag's complexity. Digital backscatter mainly aims to extend the range or focuses on achieving compatibility with existing protocols.

2.4 Harmonic Generation

We use harmonics to identify analog tags in Paper III. We also use harmonics to read high resolution sensor data in Paper IV. In this section we introduce how harmonics are generated and some of their properties that are useful in understanding the concepts in the papers.

In backscatter, the RF switch operates as a square function toggling between two impedances (reflecting and absorbing), modulating the carrier. The Fourier Series of the square pulse train can be written as in Eq. 2.4. Harmonics

are inherently generated due to the square wave nature of the signal produced by the switch [21, 22]. Harmonics appear at integer multiples of the fundamental frequency of the signal. For a square pulse, the signal power in each harmonic component scales as $1/n^2$, where n is the harmonic number for odd harmonics ($n = 1,3,5,7...$).

$$f(x) = \frac{4}{\pi} \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{n} \sin(n\omega t), \text{where } \omega = 2\pi f. \tag{2.4}$$

In Paper III, we modify the duty cycle of the backscatter signal, to create an identity for analog backscatter tags. The duty cycle is the percentage of the high state in a waveform. Ideal square waves with a 50% duty cycle possess only odd-integer harmonic frequency components and these harmonics are spaced at $2f$ (Eq. 2.4) intervals. Rectangular pulse trains share similarities with square waves, but their duty cycle deviates from 50%. The Fourier Series coefficients (C_n) of a rectangular pulse train can be written as,

$$C_n = AD\frac{\sin(\pi nD)}{\pi nD} \tag{2.5}$$

where A is the amplitude and D is the duty cycle.

According to Eq. 2.5, for the coefficients to be zero, the function should have integer multiples of π. Hence n and D are closely related.

The duty cycle D of a signal, expressed as $D = p/q$ (where p and q have no common factors), determines the presence of specific harmonics. All harmonics with indices $n = k \cdot q$ ($k = 1,2,\ldots$) are zero. For example a duty cycle of 50% (p = 1, q = 2) leads to the absence of all even harmonics (Figure 3). Similarly for a duty cycle of 30% where $p = 3$ and $q = 10$, all harmonics with indices that are multiples of 10 are zero. These baseband harmonics shift by f_c, upon mixing with the carrier signal at f_c. The resulting two-sided wideband harmonics are generated around the center frequency, with zero-coefficient harmonics falling below the noise floor in the tag's frequency response.

We identify the duty cycle levels for each signal where it has a unique set of one or more harmonic components absent. The absent harmonics are at zero energy level in the spectrum. We expect this method of tag identification to be robust since absent harmonics are not affected by multipath and other effects of the wireless channel.

Spreading of Harmonics in the Frequency Spectrum

As discussed in the previous section, harmonics occur at integer multiples of the fundamental frequency. The fundamental frequency is determined by the frequency-shift in backscatter. Therefore, if the fundamental shift is larger, the harmonics spread over a wide bandwidth [21]. Figure 2.3 shows how for a 1 MHz fundamental frequency, the harmonics spread over 50 MHz of bandwidth. Keeping the fundamental frequency shift small is beneficial for the

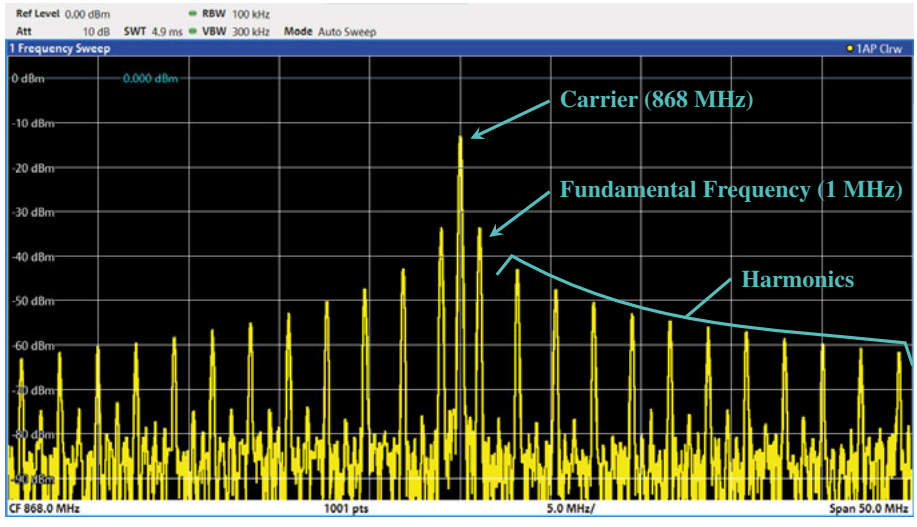

Figure 2.3. Spreading of Harmonics in the Frequency Spectrum. Harmonics appear at multiples of the fundamental frequency and spread over a wideband. The mirror image of the signals occupy the spectrum to the left of the carrier frequency.

tag, as it requires slower switching at the tag but this also limits the sensor resolution. The switching rate is directly proportional to the tag's power consumption as the oscillator consumes the most power at the tag [7, 23].

Another effect of reducing the fundamental shift is that we reduce the spread of the harmonics in the frequency spectrum. An ideal shift would be high enough to avoid the carrier, low enough to save power at the tag and wide enough to provide the needed resolution to convey sensor data. In Paper IV we use the property of frequency expansion in higher harmonics to reduce the shift and still achieve high sensor resolution. When harmonics spread over a wide bandwidth, they can pollute the frequency spectrum. Therefore many works try to avoid these harmonics [22, 24, 25, 26, 27]. This often requires complex circuitry at the tag, which contradicts with the idea of using simple analog backscatter designs. Instead, we leverage harmonics to achieve identification and high resolution sensing in analog backscatter tags.

3. Summary of Papers

3.1 Paper I

Carlos Perez-Penichet, Georgios Theodoros Daglaridis, Dilushi Piumwardane, and Thiemo Voigt. "Modelling Battery-free Communications for the Cooja Simulator". In: *Proceedings of the 2019 International Conference on Embedded Wireless Systems and Networks*. EWSN '19. Beijing, China: Junction Publishing, 2019, pp. 47–58

Summary

In this paper we implement a tool to simulate battery-free communication models. The battery-free simulation model includes a traditional backscatter communication model and a low-power receiver model that both depend on an external carrier for operation. The backscatter tag model is capable of transmitting and receiving IEEE 802.15.4 packets. Backscatter transmissions occur as explained in Section 2, using antenna impedances to modulate the carrier to transmit data. For reception of packets, the carrier generator acts as an external Local Oscillator (LO) for the low-power receiver on the tag. We refer to this as carrier-assisted communications, as it enables battery-free devices to communicate using a carrier. A highly effective tool to develop such protocols is a network simulator. We extend Cooja, a well-known network simulator, and present the first framework enabling simulations of carrier-assisted devices alongside conventional nodes. The tool allows the development of MAC layer and higher protocols for carrier-assisted communications. Furthermore, we incorporate models based on parameters gathered from real-world experiments to represent the communication range, energy consumption, and other key characteristics of backscatter links. We used this tool also in Paper II. We illustrate how such a tool can offer valuable insights in the development and evaluation of efficient protocols for carrier-assisted communications.

My Contribution

I am the third author in this paper. This work was initiated by my supervisors Thiemo Voigt, Carlos Perez-Penichet and their masters student, George Daglaridis. I contributed to implementing the battery-free receiver design to integrate it to the Cooja simulator. I also contributed to writing the paper.

3.2 Paper II

Dilushi Piumwardane, Christian Rohner, and Thiemo Voigt. “Reliable Flooding in Dense Backscatter-based Tag-to-Tag Networks”. In: *2021 IEEE International Conference on RFID (RFID)*. 2021, pp. 1-8. DOI: 10.1109/RFID52461.2021.9444320

Summary

This paper presents the first real-hardware demonstration of multi-hop backscatter networks using standards-based protocols. We also propose using network flooding for backscatter tag-to-tag networks. Backscatter communication offers a compelling solution for sensor-actuator networks where sensor data needs to trigger actuator responses. Multi-hop communication becomes essential when the sensor and actuator are beyond direct communication range. This work demonstrates the ability for backscatter tags to receive data from another tag, paving the way for multi-hop tag-to-tag networks, a functionality that was limited in previous backscatter deployments in the literature. The tags used in this work can communicate not only with each other but also with any existing node compatible with the IEEE 802.15.4 protocol. This capability represents a significant step towards integrating backscatter tags seamlessly into existing networks.

Unlike conventional networks, the communication range in these backscatter networks heavily relies on the signal strength of the carrier wave at both the transmitter and the receiver. This work presents analytical and simulation results that show the impact of the output power and the placement of the carrier generator on network reliability. We demonstrate that with a random forwarding delay, simple flooding is efficient to transport data from a source node to a target node, over multiple hops in such networks. The simulations in this paper are done using the tool we built in Paper I. We extended the tool in Paper I to implement the functionality for tag-to-tag communications. The demonstration of multi-hop tag network functionality was conducted using the tags implemented in previous work by Carlos Perez-Penichet.

My Contribution

My supervisor Thiemo Voigt proposed to analyze flooding in the Cooja simulator for tag-to-tag networks. The analysis presented in the paper was done with assistance from my supervisors Christian Rohner and Thiemo Voigt. I carried out all the experiments, including simulations and real-world experiments. I wrote most of the paper and presented it at a virtual conference.

3.3 Paper III

Dilushi Piumwardane, Madhushanka Padmal, Vaishnavi Ranganathan, Christian Rohner, and Thiemo Voigt. "HarmonicID: An Identification System for Low-Power Analog Backscatter Tags". In: *2022 IEEE International Conference on RFID (RFID)*. 2022, pp. 1-6. DOI: 10.1109/RFID54732.2022.9795971

Summary

This paper addresses the challenge of tag identification in analog backscatter systems. Analog backscatter tags achieve power and cost reductions compared to digital backscatter by moving digitization and computation overhead to a remote receiver. Unlike the digital backscatter models explored in Papers I and II, analog tags lack a packet structure due to their simpler design and absence of onboard computation. We present a novel solution for identifying these analog backscatter tags. The key idea we present is inspired my musical instruments. Each instrument has a unique harmonic content and therefore the human ear can distinguish different musical instruments even when they are playing at the same frequency. We enable identification of analog tags by tuning the tags to reflect a unique harmonic content. We create identities for tags by leveraging signal conditioning to modify harmonics, without the need to add dedicated digital blocks for identification purposes. Experiments on our hardware demonstrate that we can successfully identify the tags even in challenging scenarios such as when they are blocked by walls or in motion. Our solution is fully analog and does not increase the low power budget of analog tags.

My Contribution

I proposed the idea of using harmonics for analog tag identification. The formulation of the paper and experiments were discussed with my supervisors. The co-authors Madhushanka Padmal and Vaishnavi Ranganathan helped with the hardware design of the tag. I carried out the experiments. I wrote most of the paper and presented it at a virtual conference.

3.4 Paper IV

Dilushi Piumwardane, Madhushanka Padmal, Vaishnavi Ranganathan, Kasun Hewage, Christian Rohner, and Thiemo Voigt. "Unlocking the Potential of Low-cost High-resolution Sensing with Analog Backscatter". *under submission*. 2024

Summary

In this paper, we propose a solution to another important problem in analog backscatter tags which is achieving high resolution sensing in a low-cost way. In analog sensing tags, a sensor typically changes the resistance or capacitance value that is then translated into a frequency change which is backscattered on top of a carrier. The frequency value is produced by the tag's oscillator which consumes the most power at the tag. Therefore, higher switching frequencies result in higher power consumption at the tag. To accommodate high bandwidth sensors the tags require a larger frequency shift, which increases the tag oscillator's switching frequency and hence the tag's power consumption. To derive sensor data, we propose to use higher order harmonic frequencies, that are inherently generated by square wave backscattering at no extra cost. As higher harmonics expand in frequency range, we can achieve the same resolution using a higher harmonic and save power at the tag. This method also relaxes the receiver computation requirement as small FFTs with wider frequency bins can still decode high-resolution sensor data. Therefore, inexpensive SDRs like RTL-SDRs combined with a micro-controller would be sufficient to decode sensor data. The advantage comes at the cost of reduced system range as higher harmonics are weaker and get buried in the noise. Our system design lowers the cost and power consumption of the analog backscatter system and makes it suitable for mobile sensing applications. We present experimental results that demonstrate the viability of our approach.

My Contribution

I proposed the idea of using higher harmonics to enhance frequency resolution, thereby allowing the use of inexpensive SDRs and reducing power at the tag, resulting in a low-cost analog backscatter platform. Together with my supervisors Thiemo Voigt and Christian Rohner, I fine-tuned the idea of the paper. I carried out all the experiments. I wrote most of the paper. Kasun Hewage, Vaishnavi Rangasnathan and Madhushanka Padmal also helped verify the idea and write the paper. The initial results of this paper was presented as a poster at the MobiCom 2023 conference.

3.5 Paper V

Dilushi Piumwardane, Madhushanka Padmal, Carlos Perez-Penichet, Christian Rohner, and Thiemo Voigt. "Desynchronized Querying of Analog Backscatter Tags". *under submission*. 2024

Summary

This paper presents a fully analog solution to achieve concurrent transmissions from analog backscatter tags overcoming the limitation of frequency agnostic behavior in tags. The frequency agnostic behavior in backscatter tags indicates their ability to reflect any carrier frequency. When multiple tags are deployed, all the tags are activated by the carrier. As discussed in Paper III and Paper IV, backscatter tags also generate harmonics that spread in a wideband. When multiple tags are deployed these frequencies can overlap with each other. This makes it difficult at the receiver when identifying both the backscatter tag and its associated data encoded as a frequency shift. Therefore, enabling querying becomes challenging. A naive solution is to equip tags with narrow bandpass filters. However, achieving higher order narrow passive filters at the tag poses implementation limitations. We propose match network-based tag querying to limit the activation frequencies of the tags without modifying the backscatter module of the tag. We achieve this by modifying the tag front end with a match network and by employing a capacitor to further limit the frequency band. Frequency separation of the tags also allow for concurrent querying with the provision of multiple carrier frequencies.

My Contribution

Together with Madhushanka Padmal, I came up with the idea of using filters and capacitors to limit tag frequency responses. We discussed and fine-tuned the idea with my supervisors Thiemo Voigt, Christian Rohner and Carlos Perez-Penichet. I proposed to use it as a pluggable extension to the existing analog backscatter design. Padmal helped with the hardware design and implementation of the tag. I carried out all the experiments. I wrote most of the paper.

4. Related Work

For more than a decade the research community in the field of systems research has been actively exploring the potential of backscatter communication. Although RFID technology has been around for decades and even been used for sensing, recent advancements and growing interest in low-power backscatter systems stem from several key factors [17, 28].

Firstly, the high cost of RFID readers limits their widespread application in ubiquitous sensing scenarios such as environmental sensing and health monitoring. Moreover, the rapid deployment of commodity devices supporting protocols such as WiFi and Bluetooth has filled our surroundings with readily available RF signals. The idea of leveraging these existing IoT devices as substitutes for dedicated readers presents a significantly more cost-effective approach. The research community has made significant investments in the development of custom RF tags specifically designed to be compatible with readily available, off-the-shelf commodity IoT devices. However, embracing this alternative approach necessitates trade-offs such as unreliable communication, non-standard or non-optimal tag designs, lack of security, repurposing and modifying standard IoT devices to support tag communication, disturbances to existing network traffic and regular schedules [8, 29]. The limited data rate in tags is a common hindrance when trying to achieve protocol compatibility as issues of synchronization and sensor data embedding with existing packet structures need to be carefully handled [8, 30, 31]. Also, some of the commonly used low-power standards such as LoRa are proprietary [16].

Both RFID readers and protocol-based commodity devices may be too complex for simple sensing applications and tags where the only task of the reader is to acquire a single RF frequency component [1]. Additionally, the ability to tailor these tags to specific applications offers a degree of design freedom not found in protocols like RFID Gen 2 [8, 15, 29]. This flexibility allows for simpler designs, such as those employed in analog backscatter, leading to reduced form factors suitable for applications like wind dispersal [32] or placing them in hard-to-reach locations [12, 15, 33].

Improving backscatter communication range has also become a focus [16, 19]. In contrast to RFID technology that offers a few meters of communication range, these low cost backscatter systems provide increased range. Techniques such as employing a bistatic setup, placing the carrier and tag in close proximity, and utilizing modulation schemes like Chirp Spread Spectrum (CSS) [16], combined with the use of narrowband, highly sensitive receivers [19] have been used to significantly increase the backscatter range.

While limited research currently exists on backscatter networks and multi-tag deployments, deploying multiple tags, may enable exciting future applications such as smart dust. The main focus of this dissertation is to identify and provide solutions to problems that occur when multiple tags are deployed. Therefore this section discusses works related to that.

4.1 Analog Backscatter

Analog backscatter offers a sensing and communication approach where the sensed data directly modulates a property of the carrier frequency. This versatile technology has found applications across various domains, from the pioneering "Great Seal Bug" audio sensor to modern health and environmental monitoring systems. Ranganathan et al. explore diverse sensing applications with analog backscatter tags [1]. While our work shares similarities with their tag design, they do not provide a scalable tag identification mechanism or querying of multiple tags. Our work focuses on three key areas within the realm of analog backscatter: tag identification, efficient querying, and facilitating high-resolution sensor readings.

A common way to identify tags is to assign different frequency shifts to tags [21, 34]. However, this approach is not scalable due to overlapping harmonics. When harmonics overlap with the assigned frequency identity (frequency shift) or with other harmonics it is difficult to associate tags to their identification frequency. Talla et al. build a hybrid analog-digital microphone [10] for high data rate battery-free wireless sensing. While they employ digital backscatter for addressability as analog tags lack it, we offer a purely analog solution for identification of tags. To our knowledge, there are no other scalable analog identification systems for frequency-shifted analog backscatter tags besides our work.

Backscatter tags have a frequency agnostic behavior and reply to any carrier within a wide frequency range [35, 36]. Analog tags lack a mechanism to handle this which leads to interference when multiple tags are deployed, hindering efficient and simultaneous data collection. One method is to have bandpass filters at tags. However, sharp passive bandpass filters are difficult to realize and they do not filter adjacent frequencies well. Therefore we propose a novel system that leverages a band-pass filter and a capacitor at the tag level. We are not aware of existing literature that offer other solutions for concurrent querying of analog backscatter tags.

In frequency shifted analog backscatter, the sensor data resolution of tags depends on the assigned fundamental frequency range [1]. Existing works use high frequency oscillators to achieve a high sensing resolution, which increases the power budget on the tag [23]. As opposed to this traditional method, we propose using harmonics to increase sensor data resolution.

Analog Backscatter Modulation

Early designs of analog backscatter tags use amplitude modulation where the sensor value directly changes the impedance of the antenna, thereby, modulating the backscatter signal's power with sensor information [10]. Amplitude modulation provides limited range and is highly susceptible to noise. Pulse Width Modulation (PWM) modulation is also used in Video Backscatter [37]. Some works code the sensor data as phase of the RF signal and enable decoding analog backscatter data with commercial WiFi devices [9]. Their data rate is limited to 5 kbps. In contrast to these, our analog backscatter works do not seek to be protocol compatible and can achieve high data rates often limited by the receiver capabilities such as the sampling frequency and bandwidth of the receiver [1].

4.2 Harmonics in Backscatter

Harmonics are inherently generated in frequency-shifted backscatter due to the square wave nature of the backscatter signal which is obtained by toggling an RF switch between antenna impedances. These harmonics are usually discarded as spurious, weak, out-of-band transmissions carrying redundant information [1, 8]. Most often there are complex tag designs to suppress these harmonics such as modifying front-end designs or employing rectannas to reduce out-of-band emissions [22, 24, 25, 26]. In contrast to these, some work including ours embrace harmonics. Jinxyan et al. use analog backscatter for fast localization of tags [21]. While we use harmonics for identification and enhancing sensor resolution purposes, our tags can also be modified and used for similar applications.

Existing research on harmonics utilize RFID tag harmonics, which arise due to non-linear components within the RFID tag [38, 39, 40, 41]. Most harmonic RFID systems make use of the second harmonic component for harmonic backscattering to isolate the downlink (reader to tag) and uplink (tag to reader) to lower the noise floor and achieve cross-frequency communication or accurate ranging [39]. Recent works also use them for vibration sensing and for fingerprinting [40, 42].

While our works also involve harmonics, they differ in several key aspects. Firstly, the harmonics produced by the switching operation in our tag span a bandwidth of MHz and occur at integer multiples of the fundamental frequency of the tag. Typically ranging from kHz to a few MHz, our fundamental frequencies contribute to a more concentrated distribution of harmonics. In contrast, RFID tag harmonics occur at integer multiples of the carrier frequency and spread over GHz range. The second harmonic in RFID is often weak and since RFID tag harmonics span GHz range, receivers with very wide bandwidth are needed to detect multiple harmonics from a single tag [38]. Additionally, we have the ability to control the frequency of our harmonics by

adjusting the fundamental frequency, offering greater flexibility compared to the fixed frequencies of the RFID harmonics dictated by the protocol.

Some works employ non-linear components to achieve the frequency shift in backscatter. This is done by sending two carrier frequencies where their difference is equal to the required frequency shift [15]. This method also produces several non-linear frequency components. However, these non-linear products are weak and are not easily controllable [29]. Therefore the majority of the frequency-shifted backscatter is produced by controlling the RF switch with a clock frequency obtained by a low-power oscillator on the tag. This process generates the harmonics utilized in our work and these harmonics are more controllable than non-linear products.

Overall, we introduce distinct approaches to utilize harmonics, offering greater flexibility and control compared to RFID harmonics or non-linear products.

4.3 Multi-tag Backscatter Networks

In this section we discuss related work on multi-tag backscatter networks.

4.3.1 Concurrent Transmissions and Scheduling of Backscatter

There is an abundance of work in RFID networks [43, 44, 45] that are mainly centered around avoiding collisions or modifying collisions in tags to communicate efficiently with the reader. Since RFID tags have a protocol to communicate with the reader, all these works are restricted by the protocol parameters such as the bandwidth usage and transmission duration. In contrast to these works, our analog tags are not restricted by protocols and have the flexibility to operate within RF exposure regulations such as FCC limits without disturbing existing traffic. The power consumption of our tags is lower and the cost of receiver units is significantly cheaper compared to RFID based systems.

The related works in low-power backscatter systems that we discuss, also mostly follow the model that multiple backscatter tags transmit their information concurrently to a reader. In early work not included in this dissertation, we propose carrier scheduling mechanisms for backscatter tags to efficiently provide a carrier using Zigbee devices [46, 47] and Perez-Ramirez et al. further improve this work using deep learning [48]. While these works can be incorporated with some modifications to multi-hop backscatter work in this dissertation, it is limited to single-hop backscatter links in tiered networks which limits the range and topology of the network. To expand the range, Ali et al. build a multistatic backscatter network [49] that has multiple carrier generator units and multiple receiver units where the carrier generator unit can be shared like in cellular networks. While this gives promising results, optimal placement of the carrier and receiver units are needed to increase the range of

the system. In contrast to these works, we extend the backscatter network to support tag-to-tag multi-hop communication which extends the communication range achieved by single-hop tag networks.

Hessar et al. demonstrate a backscatter network with 256 devices and enable concurrent transmissions using a distributed coding mechanism [4]. Their transmitter and the receiver are co-located as the system requires time synchronization between carrier, receiver and the tags. While we share the research question of allowing concurrent transmissions from the tags, unlike the digital backscatter nodes they use we are limited by the capabilities of analog tags. Our proposed system offers concurrent transmissions for analog tags and avoids the complicated digital baseband processing and receiver circuitry at the tag used in their work. Further, our system does not require tight time synchronization since we use Frequency Division Multiple Access (FDMA) in which transmissions are separated in frequency.

4.3.2 Multi-hop Backscatter Communication

In sensor networks, direct communication between individual nodes and the end node may not always be feasible. In such scenarios, multi-hop communication plays a critical role, enabling data to be relayed through intermediate nodes to reach the destination [50, 51, 52]. Backscatter networks can also benefit from this multi-hop approach. Relaying of packets has been implemented in different ways in related works in backscatter. One method involves simply "hopping" or passing the wireless signal to another node without altering the packet itself. While this approach has been demonstrated in limited settings for multi-hop backscatter networks, it offers limited flexibility. Modifying packets before forwarding presents several advantages. It allows for targeted changes to specific fields within the packet, such as the payload and relay counters enabling the embedding of new information.

Ambient Backscatter [53] is a tag-to-tag system where one tag decodes the data from the other tag. The backscatter tags in battery-free cellphone [20] also demodulate voice signals from each other. While they employ tags with decoding capabilities, with a single decodable tag they lack the ability to relay information which restricts their function to single-hop communication between two tags. In contrast, we use decodable transceiver tags that be can extended to multi-hop networks increasing scalability. While some proposals, like X-Tandem [54] attempt to achieve multi-hop communication by passively forwarding backscattered signals without decoding, they are limited to two hops. DecRel [55] establishes six-hop communication through a combination of decodable tag relays and distributed excitation. However, this approach introduces significant deployment limitations, as it necessitates the presence of an excitation source close to each sensor node, restricting network flexibility. In contrast, our proposed architecture prioritizes scalability and dynamic

network adaptability where the sensor nodes can move freely within the designated communication area, offering the flexibility to use multi-hop backscatter communication for a wider range of applications. Some tag-to-tag networks implement multi-hop communication but lack decodable message relaying [5, 6]. Another work demonstrates flooding based decodable multi-hop packet relaying [56]. A drawback common to these works is that they employ envelop detectors as receivers which have limited sensitivity and are affected by external interference and ambient traffic [57]. Moreover, they are not able to receive standards-based packets from transmitters since they rely on amplitude-based demodulation rather than demodulation based on phase and frequency. In contrast to these networks, we aim at dense tag-to-tag networks based on standard IoT protocols where tags may relay messages on multiple paths like in sensor networks.

Our research introduces an approach for employing tags equipped with a receiver capable of both decoding and modifying packets before forwarding them. This innovation distinguishes our work from existing multi-hop backscatter systems by enabling tag-to-tag networks where tags can decode protocol-based packets and subsequently relay them. In densely deployed networks, this capability allows for data forwarding along various paths, thereby enhancing overall network reliability.

5. Conclusions and Future Work

In this section we offer our concluding remarks before discussing potential future directions of the work presented.

5.1 Conclusions

Backscatter communication provides a direction for implementing widespread networks of battery-free devices that can be used for ubiquitous sensing. These devices can typically harvest energy from the environment and are activated by readily available unmodulated carriers. Their data can be read using simplified receivers like TV tuners in the case of frequency-shifted analog backscatter. This eliminates the need for bulky and expensive RFID readers commonly found in traditional systems. Backscatter communication enables a promising range of applications. However, when deployed in the real world, backscatter tags are limited by constraints due to the limited power budget on the tag. Adding mechanisms for identification, scheduling, querying and relaying should be carefully done offloading power consuming components and delegating tasks whenever possible to an external device which is not constrained by the low-power requirement. This dissertation explores the challenges associated with deploying multiple backscatter tags and proposes solutions to address them.

We address some of the analog backscatter issues including concurrent transmissions in the analog domain when multiple tags are deployed, identification of analog tags and achieving high-resolution sensor data reading while consuming very low power on the tag. For digital backscatter, we design and demonstrate a scalable multi-hop tag-to-tag network for communication.

In Paper I and Paper II, our focus is on scaling the integration of protocol-based backscatter into existing networks. In Paper I, we present a tool built to support developing networks with battery-free devices. It enables communication between tags and commodity devices for the IEEE 802.15.4 protocol. The tag receiver uses an external LO which makes these devices different from regular radios. Our tool is valuable in understanding the backscatter network's difference compared to regular radios. In the following paper, which is Paper II, we modify and use this tool to simulate tag-to-tag networks. Additionally, Paper II showcases the implementation of multi-hop tag-to-tag networks on real hardware and presents simulations for a scalable tag-to-tag backscatter network. The tags in the network can demodulate, decode and forward packets

to other tags on different paths in the network when a sufficiently strong carrier is provided. We evaluate how the carrier power and position affect these new type of tag-to-tag networks. Our simulation results show that flooding is a reliable technique for packet forwarding in these dense networks. This was the first protocol based tag-to-tag network during the time of publishing.

In Paper III, Paper IV and Paper V we address crucial problems that limit deployment of analog backscatter tags: lack of an identification system, high power consumption at the tag when accommodating high-bandwidth sensors and frequency agnostic behavior. In Paper III, we solve the identification challenge in analog backscatter tags. Identification of analog backscatter tags is challenging as they lack a packet structure and digital components on the tag for onboard computation. Adding extra components for identification increases the power budget and the tag complexity which contradicts the simple design of analog tags. Inspired by musical instruments, we propose an identification mechanism using harmonics generated within the tag, which does not add any power for identification purposes. This work can be integrated with the work in Paper V. The main idea of Paper V is to provide a solution to query analog backscatter tags and enable concurrent querying when multiple tags are deployed. Backscatter tags are frequency agnostic and respond to any given carrier frequency. Hence, when multiple tags are deployed all the tags respond to a given carrier. For power-constraint analog tags, realizing only a passive narrowband filter is challenging. We design a system using a bandpass filter and a capacitor to narrow the frequency response of the tag. The narrow frequency response from the tag can also act as an identification for the tag. By using the techniques in Paper III, we can assign different duty cycles to achieve a more robust ID for the tags.

Paper IV presents a method to read high resolution sensor data with analog tags while maintaining low frequency switching at the tag. We achieve this by leveraging the frequency widening property of higher harmonics. Previous work assigns a wider fundamental frequency shift to achieve high sensor resolution, which increases the power consumption at the tag since it requires fast switching with oscillators. Our method requires very low switching at the tag as we read the higher harmonics to decode finer sensor values.

5.2 Future Work

The past decade has witnessed a surge of research in backscatter communication, laying a strong foundation for future advancements. Building up on the work presented in this dissertation, this section explores possibilities and open problems that remain to be addressed in the future.

Collision Avoidance in Backscatter Networks

Collision avoidance remains a crucial yet often-overlooked aspect in backscatter communication research, typically limited to a few specific protocols [4, 58]. The reason is that backscatter tags are designed to achieve low-power operation and having collision avoiding mechanisms like schedules add extra overhead. Further, in digital backscatter which tries to achieve protocol compatibility, the protocols impose limitations such as bandwidth and active time for the transmissions. As discussed in Paper IV, assigning larger frequency shifts to separate tag responses also increases the tag's power consumption.

To retain the advantages in analog backscatter, the collision avoidance mechanisms should be implemented in analog ways. While our work in Paper V utilizes limited frequencies for Frequency-Division Multiple Access (FDMA), Time-Division Multiple Access (TDMA) mechanisms also hold promise. One potential approach is to involve energy harvesting modules like capacitors to facilitate deterministic or probabilistic collision avoidance. By thresholding the charging and discharging times of the capacitors, we can trigger multiple tags at distinct intervals, thereby reducing collisions. This approach could be further extended probabilistically by employing different capacitor values and thresholds. These methods can also be incorporated in digital backscatter systems.

Furthermore, we can take the advantage of a powerful receiver or a gateway to resolve collisions in backscatter tags. For example, equipping receivers with machine learning and neural network algorithms to identify and resolve collisions in the frequency domain can be done for both digital and analog backscatter tags.

Carrier Scheduling in Backscatter

Carrier scheduling has emerged as a research area within the backscatter research community, as evidenced by recent work [46, 48]. This focus stems from the inherent reliance of backscatter tags on an external carrier signal for communication. To effectively interoperate with other devices within a network, backscatter systems must utilize carrier provision. Carrier provision can be achieved via a single dedicated device such as a USRP, a commodity IoT device operating in radio testmode or a network of distributed devices. A carrier can also act as a query by activating a backscatter tag and also by signalling a receiver to wake up to receive backscatter transmissions. When multiple tags are deployed, they can share a carrier. These multi-tag and multi-carrier scenarios present a rich landscape of research opportunities, similar to traditional networking problems such as scheduling and collision avoidance.

Backscatter in Higher Frequency Bands

Most backscatter research is in the sub-GHz frequency range up to a few GHz in which commodity protocols like WiFi and Bluetooth operate. Backscatter networks in higher frequency bands like mm-wave and THz frequencies

enable many novel applications [34, 59, 60]. Research on multiple tag deployments in these frequencies is limited. Higher frequencies such as THz can offer high data rates for digital backscatter and there is more free bandwidth available in these frequency bands. Our work on Paper V can be tested for these high frequencies with more bandwidth to accommodate more tags and more concurrent transmissions. Further, high frequencies enable accurate ranging and can offer precise localization when combined with wide bandwidth techniques like Ultra Wideband (UWB). However, such high frequencies experience higher path loss compared to sub-GHz frequencies and their range is limited. Therefore, techniques like MIMO and beamforming are used to increase range and performance in backscatter tags [34].

Security in Backscatter

Another key area for future work is security in backscatter. Various security mechanisms can be implemented for digital backscatter. One way is to embed a low power pseudo random code to the data using one time pads (XOR logic). Deliberately introducing bit flips that only a sensitive receiver can decode is another way to authenticate backscatter tags [61, 62].

RF fingerprinting that exploits signal response variations caused by the design and manufacture faults in components offers a secure passive way of identifying tags. Fingerprinting offers promising results for secure tag identification [63, 64]. However, analog tags have fewer components compared to digital backscatter tags resulting in fewer sources of imperfections contributing to the fingerprint. Therefore it may not be scalable and result in fewer unique tag identities. If more components such as the passive filters used in Paper V are introduced, the component count will increase and fingerprinting would give more robust results.

Apart from these key areas, there are many other interesting future works for backscatter. Since backscatter tags have a small form factor, multiple tags can be deployed in a dense area. This enables applications such as smart dust and wireless robotic materials that require a dense deployment of tags that can communicate with each other [65].

Analog backscatter offloads computation tasks because computation often requires onboard digital baseband processing. However, for simple applications where analog backscatter tags are used, smaller computations such as comparison or addition of multiple sensor values would be beneficial. Analog computation is appealing for such applications and is an interesting future research area.

6. Summary in Swedish

Sakernas intenet (Internet of Things, IoT) beskriver kommunikation mellan maskiner. Ett snabbt växande nätverk av sammankopplade enheter samlar in data via sensorer och delar information mellan miljarder enheter över hela världen. Detta har lett till en växande efterfrågan på sömlösa nätverks- och kommunikationstjänster. Strömförsörjningen av dessa enheter, speciellt av små sensorer, utgör dock ett problem. Batterier är en vanlig lösning, men deras begränsningar vad gäller livslängd, underhåll och miljöpåverkan har skapat ett behov av batterifria alternativ.

Bakspridningskommunikation (Backscatter Communications) är ett koncept som möjliggör att man kan ta emot information från ett stort antal batterilösa sensorer. Sensorerna utnyttjar reflektionen av en extern radio-bärvåg. De sänder data genom att påverka reflektionens egenskaper. Detta görs genom att delar av deras antenn kopplas på och av via ett elektriskt strömbrytare, t.ex en diod. De behöver inte sända ut någon radiovåg, bara påverka en existerande våg. Kommunikations-delen av dessa enheter kräver så lite energi att energin i allmänhet kan fångas in (skördas) från omgivningen, t.ex från ljus eller vibrationer. Enheterna (taggarna) aktiveras av den omodulerade radiobärvågen och deras påverkan på bärvågen kan detekteras av enkla radiomottagare. Exempel på mottagare är enheter som stöder WiFi- och Bluetooth-protokoll eller t.o.m. analoga TV-mottagare i fallet med frekvensskiftande analog bakspridning. Jämfört med traditonell RFID (Radio Frequency Identification)-teknik så minskas driftskostnaderna avsevärt pga de enkla radiomottagarna. Detta möjliggör ett stort antal nya tillämpningar.

Kravet på mycket låg strömförbrukning medför dock stora begränsningar på hur bakspridande kommunikationsenheter (s.k. bakspridnings-taggar) kan konstrueras och hur komplicerade de kan tillåtas vara. Mekanismer för en tagg, t.ex för att identifiera sig för schemaläggning av sändningar, för att fråga om en tagg har data att sända och för att vidarebefordra meddelanden behöver konstrueras omsorgsfullt. Om så är möjligt ska uppgifter lösas av de enheter i kommunikationssystemet som inte har starkt begränsad energianvändning.

Denna avhandling studerar och föreslår lösningar till problem som uppstår då man vill kommunicera med flera bakspridnings-taggar.

I Papper I och Papper II fokuserar vi på att integrera bakspridningenheter i existerande nätverk och protokoll. I Papper I presenterar vi ett verktyg som stöder uppbyggnad av nät som innehåller bakspridande enheter som saknar batteri. Det möjliggör kommunikation mellan sådana taggar och andra enheter med IEEE 802.15.4-protokollet. Det föreslagna verktyget är användbart för att

förstå skillnaderna mellan ett bakspridnings-nät och ett nät som bara består av konventionella radioenheter.

Vi modifierar och använder sedan verktyget från Papper I för tag-till-tag-kommunikaton i det följande Papper II. Papper II använder experiment med hårdvara för att undersökea prestanda hos multi-hopp tag-till-tag-kommunikation. Det presenterar dessutom en simuleringsstudie av ett skalbart tag-till-tag bakspridningsnätverk. Taggarna i detta nätverk kan demodulera, avkoda och vidarebefordra datapaket via olika vägar i nätverket. Detta kräver att den externa radiosändaren genererar en tillräckligt kraftig bärvåg som når alla taggar. Vi utvärderar hur bärvågseffekten och bärvågssändarens position påverkar funktionen hos denna nya typ av tag-till-tag-nätverk. Baserat på verktyget från Papper I så undersöker Papper II även tag-till-tag nät med ett stort antal noder genom simulering. Resultaten indikerar att samtidig sändning av datapaket via flera vägar (flooding) utgör en pålitlig metod för dataöverföring i sådana täta nät med många noder. Detta arbete byggde upp och studerade det första protokoll-baserade tag-till-tag bakspridnings-nätverket vid tidpunkten då det publicerades.

För att minska energiförbrukningen ytterligare så kan man sträva efter att konstruera bakspridnings-taggar så att de utnyttjar minimal eller ingen digital logik, teknik och processorer. Med sådana analoga bakspridnings-taggar försöker man så långt som möjligt lägga all overhead pga digitalisering och beräkningar i noder som inte är energibegränsade. Sådana analoga bakspridningstaggar kommer dock inte att kunna generera en digital ramstruktur som specificerar kontrollinformation, t.ex adresser.

I Papper III, Papper IV och Papper V undersöker vi de tre viktigaste problemen som begränsar användningen av analoga bakspridnings-taggar. 1) De saknar en tag-identifieringsmekanism. 2) De reagerar på samma sätt för olika bärvågsfrekvenser från den externa radiosändaren, vilket försvårar adressering av dem individuellt. 3) Om sensorn som är kopplad till taggen genererar en hög datatakt så kan deras energiförbrukningen bli hög.

I Papper III föreslår vi en lösning på problemet att analoga bakspridningstaggar saknar en identifieringsmekanism eftersom de saknar de digitala komponenter som skulle behövas för att generera en datapaket-struktur. Med inspiration från hur man kan höra skillnaden mellan olika musikinstrument så föreslår vi en att olika taggar genererar olika mönster av övertoner. Deras identitet avslöjas då av mönstret av övertoner. På så sätt elimineras behovet av energikrävande digitala komponenter. Detta arbete kan integreras med arbetet som presenteras i Papper V.

Huvudidén i Papper V är att lösa problemet med hur man ska fråga en analog bakspridnings-tag om den har någonting att sända, genom att belysa den med energi från radio-bärvågssändaren (querying). Dessutom vill man kunna ställa denna fråga till ett stort antal taggar som befinner sig i ett begränsat geografiskt område. Om man kan konstruera taggarna så att de enbart reagerar på bärvågsfrekvenser i ett smalt frekvensband, så skulle man kunna göra dessa

frekvensband olika för olika taggar. Det är dock inte enkelt att konstruera smala bandpassfilter för kraftigt effektbegränsade analoga taggar. Vårt förslag till lösning av detta problem använder ett passivt bandpassfilter och en kapacitans för att generera en smal frekvensrespons. Metoden möjliggör samtidig tag-identifiering och querying för flera analoga bakspridnings-taggar.

Analoga bakspridnings-taggar erbjuder en enkel design som är väl lämpad för mobila sensorer. Papper IV presenterar en metod för att sända sensordata med hög datatakt via analoga taggar, trots att frekvensen hos switchningarna hos strömbrytar-elementet i taggen kan hållas låg. Vår föreslagna lösning utnyttjar den ökade frekvensspridningen hos de högre övertoner som taggen genererar genom att switchat ändra den reflekterade bärvågens egenskaper. Tidigare föreslagna metoder har utnyttjat större frekvensskift. Detta har krävt snabbare switchning och resulterat i högre effektförbrukning. Vår metod kräver endast en låg switchfrekvens, eftersom den bygger på att övertonernas egenskaper utnyttjas.

Det överordnade bidraget hos min avhandling är att identifiera och föreslå lösningar på problem som uppstår då bakspridnings-taggar ska komma till praktisk användning. Jag tror att dessa bidrag kommer att underlätta och möjliggöra deras användning för mätning och kommunikation.

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