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Wirelessly Powered Communications: From Signal Optimization to Antenna Design

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To my lovely wife, my son Carl, and my parents

Abstract

Future internet-of-things (IoT) and beyond 5G communication systems are envisioned to offer large-scale wireless connectivity where the different components of life, society and industry are connected in a smart yet sustainable way. The need for continuous battery charging and/or replacement is a bottleneck for sustainability in these systems. As the number of battery-powered wireless devices grows, it is associated with an increase in both the maintenance costs and the impact on the environment. Wireless power transfer (WPT) is a promising solution to enable self-sustainable operation and limit battery usage in the enormous amount of devices that the future wireless systems will bring.

WPT co-exists by nature with other well-established communication systems. However, WPT signals are usually transmitted at a higher power level than information signals to overcome propagation losses and provide sufficient power to the receiver. Therefore, when designing a WPT system, it is essential to consider and minimize its impact on the co-existing and co-located communication systems. Moreover, in order to enable wirelessly powered communication (WPC) nodes, efficient WPT is not enough on its own but it is also important to minimize the power consumption of the node and optimize its energy usage. This thesis investigates the above described issues from both a theoretical and an implementation perspectives. It is divided into two parts; the first part focuses on signals and system level optimization with the goal of achieving wirelessly powered sensing nodes, the second part concerns enabling simultaneous wireless information and power transfer (SWIPT) by exploring novel designs of antennas and microwave components.

In the first part of the thesis, we first study the optimization of multi-tone signals to maximize the efficiency of WPT. We discuss and consider different practical non-linear energy harvester models in the problem formulation. Taking into account the in-band co-existing communication links, we provide the optimal weights for the multi-tone signals that maximizes the efficiency of WPT while minimizing the interference. The performance gains obtained using our optimization methods are highlighted through comparisons with other solutions existing in the literature. Furthermore, we present a low-complexity algorithm for designing the multi-tone signal in order to enable practical implementation. Secondly, we study the use of analog joint source-channel coding (AJSCC) in low-power sensing schemes. We propose a novel low-complexity dimension reduction mapping that is used to compress multiple sensor readings into one signal, and thus, limits the power consumption at the sensing node. We provide a comprehensive analysis of the distortion performance of our proposed mapping. We also show that energy scheduling can be utilized to improve the distortion performance of the compression mapping. Moreover, we discuss the practical circuit implementation of our proposed mapping and explain that it provides a very good distortion performance compared to the other AJSCC benchmarks despite having a much lower complexity circuit implementation. The findings of the first part of the thesis are valuable within the context of efficient and practical usage of WPT to energize a low-power IoT sensing node.

Motivated by the need for high isolation between co-located SWIPT antennas, the second part of the thesis first presents a SWIPT antenna design utilizing differential feeding in addition to an electromagnetic bandgap (EBG) structure to minimize mutual coupling between the antennas dedicated for power transmission and information exchange. Second, it investigates exploiting glide symmetry in designing EBG structures and microwave filters. We demonstrate that glide symmetry can increase the operational bandwidth of mushroom-type EBG structures without any additional manufacturing costs. A detailed equivalent circuit model is derived in order to explain this bandwidth increment. Full-wave simulations as well as experimental results are presented to verify the benefits of the glide-symmetric versions compared to the conventional structures without glide symmetry. As an alternative to the use of mushroom-type EBGs, a detailed study on the application of glide symmetry to defected ground structures (DGSs) is also conducted. We show that glide-symmetric DGSs can provide a higher rejection level as well as a higher rejection bandwidth compared to their conventional versions without symmetry. The improvement in the rejection level and bandwidth of both mushroom-type EBGs and DGSs is also explained to be useful in common-mode rejection filters. Finally, we show that fully planar EBG structures can utilize glide symmetry for size reduction and providing an increased level of isolation between microstrip patch antennas. The results of the second part of the thesis enable a new class of hardware designs that are useful for the practical realization of SWIPT systems.

Keywords: Wireless power transfer, multi-tone signals, non-linear energy harvester, wirelessly powered sensors, joint source-channel coding, analog mappings, energy scheduling, mutual coupling reduction, electromagnetic bandgap, glide symmetry.

Sammanfattning

Framtida sakernas internet, internet-of-things (IoT), och kommunikationssystem bortom 5G är tänkta att erbjuda storskalig trådlös uppkoppling där olika komponenter av livet, samhället och industrin är sammankopplade på ett smart men ändå hållbart sätt. Behovet av kontinuerlig laddning och/eller utbyte av batterier är en flaskhals för hållbarheten i dessa system. I takt med att antalet batteridrivna trådlösa enheter växer är det förknippat med en ökning av både underhållskostnader och miljöpåverkan. Trådlös effekttöverföring är en lovande lösning för att möjliggöra självförsörjande drift och begränsa batterianvändningen i den enorma mängd enheter som framtidens trådlösa system kommer att ge upphov till.

Trådlös effekttöverföring samexisterar till sin natur med andra väletablerade kommunikationssystem. Vanligtvis sänds emellertid trådlösa effekttöverföringssignaler med en högre effektnivå än kommunikationssignaler för att övervinna utbredningsförlusterna och ge tillräcklig effekt till mottagaren. När man utformar ett trådlöst effektöverföringssystem är det därför viktigt att överväga och minimera dess inverkan på de samexisterande och samlokaliserade kommunikationssystemen. Dessutom, för att möjliggöra trådlöst drivna kommunikationsnoder, är det inte tillräckligt med effektiv trådlös effektöverföring, utan det är också viktigt att minimera nodens strömförbrukning och optimera dess energianvändning. Denna doktorsavhandling undersöker de ovan beskrivna frågeställningarna ur både teoretiska och implementeringsaspekter. Den är uppdelad i två delar; den första delen fokuserar på signal- och systemnivåoptimering med målet att uppnå trådlöst drivna sensornoder. Den andra delen handlar om att möjliggöra simultan trådlös kommunikation- och effektöverföring (SWIPT-simultaneous wireless information and power transfer), genom att utforska nya konstruktioner av antenner och mikrovågskomponenter.

I den första delen av avhandlingen studerar vi först optimering av flertonssignaler för att maximera effektiviteten hos den trådlösa effektöverföringen. Vi diskuterar och överväger olika praktiska icke-linjära energiskördarmodeller i problemformuleringen. Med hänsyn till de samexisterande kommunikationslänkarna tillhandahåller vi de optimala vikterna för flertonssignalerna som maximerar effektiviteten hos den trådlösa effektöverföringen samtidigt som störningarna minimeras. De prestandavinster som erhålls med våra optimeringsmetoder framhävs genom jämförelser med andra lösningar i litteraturen. Dessutom presenterar vi en lågkomplexitetsalgoritm för att designa flertonssignalen som möjliggör en praktisk implementering. För det andra studerar vi användningen av analog gemensam källa-kanal-kodning (AJSCC-analog joint source-channel coding), i avkänningsscheman med låg effekt. Vi föreslår en ny dimensionsreducerande avbildning med låg komplexitet som kan användas för att komprimera ihop flera sensoravläsningar till en signal och därmed begränsa strömförbrukningen vid avkänningsnoden. Vi tillhandahåller en omfattande analys av distorsionsprestandan för vår föreslagna avbildning. Vi visar också att energischemaläggning kan användas för att förbättra distorsionsprestandan för kompressionen. Dessutom diskuterar vi den praktiska kretsimplementeringen av vår föreslagna avbildning och visar att den ger en mycket bra distorsionsprestanda jämfört med andra AJSCC-metoder trots att den har en mycket lägre kretsimplementeringskomplexitet. Resultaten av den första delen av avhandlingen är betydelsefulla inom ramen för effektiv och praktisk användning av trådlös effektöverföring för att aktivera en IoT-avkänningsnod med låg effekt.

Den andra delen av avhandlingen, motiverat av behovet av hög isolering mellan samlokaliserade SWIPT-antenner, presenterar först en design av SWIPT-antenner som använder differentiell överföring utöver en struktur för elektromagnetiskt bandgap (EBG) för att minimera ömsesidig koppling mellan antennerna avsedda för kraftöverföring och informationsutbyte. Sedan undersöks utnyttjandet av glidsymmetri vid design av EBG-strukturer och mikrovågsfilter. Vi visar att glidsymmetri kan öka den operativa bandbredden för svampformade EBG-strukturer utan några ytterligare tillverkningskostnader. En detaljerad ekvivalent kretsmodell härleds för att förklara denna bandbreddsökning. Helvågssimuleringar såväl som experimentella resultat presenteras för att verifiera fördelarna med de glidsymmetriska versionerna jämfört med konventionella strukturer utan glidsymmetri. Som ett alternativ till användningen av svampformad EBG genomförs också en detaljerad studie om tillämpningen av glidsymmetri på defekta markstrukturer (DMS). Vi visar att glidsymmetriska DMS:er kan ge en högre förkastningsnivå såväl som en högre förkastningsbandbredd jämfört med konventionella versioner utan symmetri. Förbättringen av förkastningsnivån och bandbredden för både DMS:er och svampformade EBG:er förklaras också vara användbar i förkastningsfilter baserade på gemensamma typvärden. Slutligen visar vi att helt plana EBG-strukturer kan använda glidsymmetri för storleksminskning och ge en ökad nivå av isolering mellan mikrostrippatchantenner. Resultaten i den andra delen av avhandlingen möjliggör en ny klass av hårdvarudesigner som är användbara för praktisk realisering av SWIPT-system.

Nyckelord: Trådlös effektöverföring, flertonssignaler, icke-linjär energiskördare, trådlöst drivna sensorer, gemensam källa-kanal-kodning, analoga avbildningar, energischemaläggning, ömsesidig kopplingsreduktion, elektromagnetiskt bandgap, glidsymmetri.

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Boules Nessim
Stockholm, April 2022

Contents

Acronyms and Notations

Acronyms

ADC	Analog-to-Digital Converter
AJSCC	Analog Joint Source-Channel Coding
CM	Common Mode
CSI	Channel State Information
DAC	Digital-to-Analog Converter
DC	Direct Current
DGS	Defected Ground Structure
DM	Differential Mode
EBG	Electromagnetic Bandgap
EH	Energy Harvesting
EM	Electromagnetic
FCC	Federal Communications Commission
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IoT	Internet of Things
LNA	Low Noise Amplifier
LO	Local Oscillator
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average Power Ratio

PLL	Phase-Locked Loop
PS	Power Splitting
RF	Radio Frequency
RFID	Radio Frequency Identification
SWIPT	Simultaneous Wireless Information and Power Transfer
TMRT	Truncated Maximum-Ratio Transmission
TS	Time Switching
USRP	Universal Serial Radio Peripheral
Wi-Fi	Wireless Fidelity
WIT	Wireless Information Transfer
WPBC	Wirelessly Powered Backscatter Communication
WPC	Wirelessly Powered Communication
WPT	Wireless Power Transfer
WS	Wireless Sensors

Notations

$\mathcal{N}(\mu, \sigma^2)$	Normal distribution with mean μ and variance σ^2
ω	Angular Frequency
$\mathcal{CN}(\mu, \sigma^2)$	Circularly-symmetric Gaussian distribution with with mean μ and variance σ^2
$\mathbb{E}\{\cdot\}$	Expectation
k	Propagation constant
β	Phase constant
$\Re\{\cdot\}$	Real part of a complex variable/number
ε_r	Relative Permittivity
μ_r	Relative Permeability

Part I

Thesis Overview

Chapter 1

Introduction

Our world is getting smarter and smarter everyday. The number of wireless communication devices such as smart phones, wearable electronics, and wireless sensors have massively increased over the past decade. An exponential growth in the deployment of wireless sensors (WS) is also expected in connection with the effective realization of the internet of things (IoT) and fifth-generation (5G) networks [1]. In IoT, wireless sensors are envisioned to collect information and take actions while minimizing human interaction. Typical applications include smart transportation, smart homes, environmental monitoring, health care and industrial automation [2]. Despite the huge advancements in wireless communication systems, limited battery capacity remains as the major challenge and the last barrier to achieve a truly wireless system [3]. Wireless power transfer (WPT) is widely seen as a promising technology to cross that barrier. Furthermore, the use of WPT is aligned with the global goals for sustainable development [4] for several reasons: (1) WPT limits the number and size of batteries, and thus, it reduces the consumption of raw materials required to manufacture batteries (e.g., Lithium and Cadmium). (2) WPT minimizes the hazards and the impact on the environment in terms of CO_2 emissions resulting from battery disposal. (3) WPT minimizes the need for continuous maintenance. This issue is of particular importance for IoT systems containing billions of sensors, and consequently, billions of batteries requiring huge human efforts and costs for maintenance. (4) Wireless power receivers typically consist of cheap circuit components compared to the cost of batteries and their maintenance.

Energy harvesting (EH) is a term that is usually associated with limiting battery usage in future communication systems. EH is defined as collecting energy from ambient sources in the surrounding environment such as solar, vibration (piezoelectric), thermal, wind and radio frequency (RF). A comparison of the different EH methods and their power supply capabilities is provided in Table 1.1. Different from ambient RF EH, WPT relies on a dedicated RF power transmitter. Depending on the distance between power transmitter node and the receiver node,

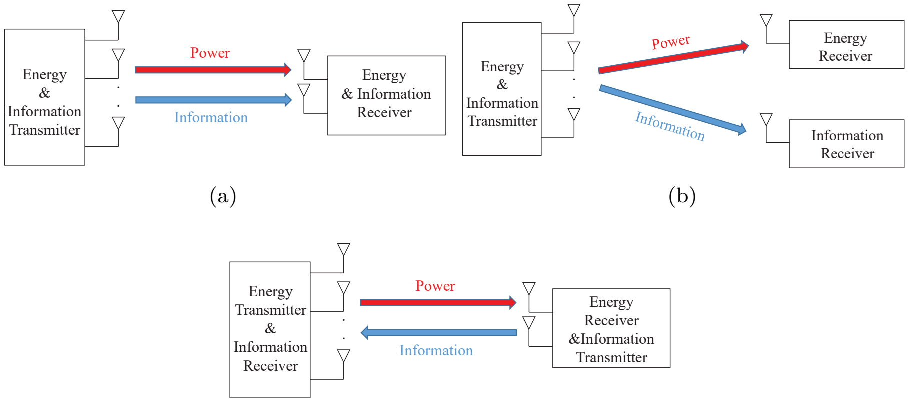
Table 1.1: Comparison of ambient energy harvesting methods [6]

Energy source	Power density	Advantages	Disadvantages
Solar	15 mW/cm^3	sufficient energy at daytime	large area non-continuous availability
Piezoelectric	200 $\mu\text{W/cm}^3$	no voltage source light weight	low conversion efficiency highly variable output difficult to integrate
Thermoelectric	40 $\mu\text{W/cm}^2$	always available low maintenance	low power low conversion efficiency large area
Airflow	1 mW/cm^2	place and time dependent	large size
Ambient RF	up to 1 $\mu\text{W/cm}^2$	widely available easy integration	dependent on the source's available power attenuation due to path loss

WPT can take different forms such as inductive, capacative, magnetic resonance, and radiative (far-field) WPT [5]. In general, radiative WPT has been found more attractive since it provides more freedom without a need to be attached to the transmitter. Nevertheless, the efficiency of radiative WPT is hugely affected by the distance due to attenuation of the RF signals.

One might think that the problem of signal attenuation due to propagation losses could simply be solved by increasing the transmitted power. However, in reality, increasing the radiated power is limited by international safety regulation such as those given by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and Federal Communications Commission (FCC). Consequently, tremendous research has been conducted to improve the efficiency of far-field WPT. Several directions have been considered such as optimizing the transmitter node (e.g., using multi-antennas, distributed antennas, multiple frequency bands), designing the transmitted waveform, and maximizing the RF-to-DC conversion efficiency of the receiver node which is often referred to as the rectenna (rectifying antenna) [1].

In traditional wireless communication systems, RF signals are already used to transmit information. However, wireless information transfer (WIT) and WPT have always been treated as two separate strategies. Recently, different concepts considering the integration of WIT and WPT have been studied such as simultaneous wireless information and power transfer (SWIPT) and wirelessly powered communication (WPC) networks [7]. Block diagrams describing SWIPT and WPC are provided in Fig. 1.1. SWIPT concerns the simultaneous transmission of power and information in the downlink from one or multiple access points (transmitters) to one or multiple receivers. The power receiver (EH) and the information receiver in this case can either be co-located or separated. On the other hand, in WPC, power is transmitted in the downlink to a low-power device. The device uses its harvested energy to send data in the uplink. Different studies on SWIPT and WPC can be found in [8–10]. Since power transfer signals aim at charging or operating a device, they are typically transmitted at a higher power level than information signals within the safety limits. Therefore, WPT signals can significantly impact the performance of the co-existing or co-located communication nodes, and consequently, WPT and WIT components should be



(a) (b)

(c)

Figure 1.1: Wireless Information and Power Transfer (a) SWIPT with co-located receivers, (b) SWIPT with separated receivers, (c) WPC.

jointly designed accounting for the possible interference on both the signal and the electromagnetic level.

In connection with efficient WPT, devices and sensors receiving wireless power should not waste energy. Such devices are required to optimize their performance and efficiently use the received power to transmit or receive data and perform other tasks. One way to minimize power consumption is to limit the use of mixers and local oscillators such as in backscatter communication [11–14]. Limiting the use of power-hungry analog-to-digital converters at the sensing nodes is another approach. This is done by compressing the data of two or more sensors (devices) into one signal and transmitting it through the wireless channel via analog or hybrid analog-digital communication schemes [15, 16].

This thesis combines different studies on SWIPT and WPC systems and is divided into two parts. The first part concerns optimal WPT signals that maximizes the efficiency of WPT while considering possible interference with co-existing communication nodes. Furthermore, it studies the problem of low-power sensing schemes to achieve WPC with a focus on compression mappings and energy scheduling. The second part of the thesis starts by studying different designs of antenna structures to minimize interference between co-located power and information transmission. The largest portion of the second part of the thesis provides an in-depth study on exploiting higher symmetries in electromagnetic bandgap structures and filters with the goal of providing higher rejection bandwidth and higher rejection level compared with conventional designs. These studies are relevant to the practical realization of SWIPT and WPC where high rejection bandwidth and high isolation between information and power signals become essential.

1.1 Motivating Examples

As discussed earlier, WPT signals are usually transmitted at a higher power level than information signals. Nevertheless, WPT could happen to use the same band as WIT due to the scarcity of the available frequency spectrum or in order to minimize the size and the cost of the device (e.g., sharing the same antennas), and thus, creating a high level of interference. The initial goal of this thesis was to study and design different techniques to improve the efficiency of WPT and analyze their impact on co-existing and co-located WIT. Prior to this thesis work, it has been shown in numerous contributions that high peak-to-average power ratio (PAPR) signals such as multisine, chaotic, white noise and OFDM signals can improve the RF-to-DC conversion efficiency of the rectifiers, and consequently, enhances the overall efficiency of WPT [17–20]. However, at that time, the present literature lacked experimental analysis on the impact of using high PAPR signals on the co-existing and co-located information receivers.

For the above mentioned reasons, at the early stages of this PhD work, a simple experiment to evaluate the impact of multisine signals on WPT and co-existing communication networks has been conducted. The experimental setup is shown in Fig. 1.2. It consists of a universal software radio peripheral (USRP) provided by national instruments (NI-USRP 2901), a laptop computer, a 2.4 GHz RF energy harvester (details about the used harvester can be found in [21]). Both the USRP and the energy harvester were connected to a dual-polarized microstrip patch antenna. The Wi-Fi router had two built-in omni-directional monopole antennas. The USRP was programmed to transmit multi-tone signals at 2.4 GHz. A Wi-Fi channel between the router and the computer was established and fixed to channel 7 in IEEE 802.11g protocol (f=2.442 GHz, 52 OFDM, 312.5 kHz spacing). The purpose of fixing the channel was to observe how the interference effect of the multi-tone signal since the router by protocol jumps to another OFDM channel when the Wi-Fi link fails to be established on a certain channel. In the conducted experiment, the number of tones were varied between 1, 2, 4 and 8. The spacing between the tones was chosen in a way to make the tones not interfere with more than one OFDM subcarrier of the Wi-Fi link. The transmitted power was varied along with the number of tones while observing the effect on the data rate. Compared to single-tone WPT, a decrease in the rate of information transfer has been observed when increasing the number of tones for the same transmitted power, even when the multi-tone signals are selected not to interfere with any OFDM subcarrier. This has been attributed to the inter modulation products of the multi-tone signal which may interfere with more than one OFDM subcarrier when the LNA of the information receiver is saturated due to the high received power.

In addition to the above described experiment, another experiment to investigate co-located information reception and power transmission has been conducted. Here, three USRPs each connected to a monopole antenna were used. Two USRPs were co-located in a configuration where one USRP was programmed

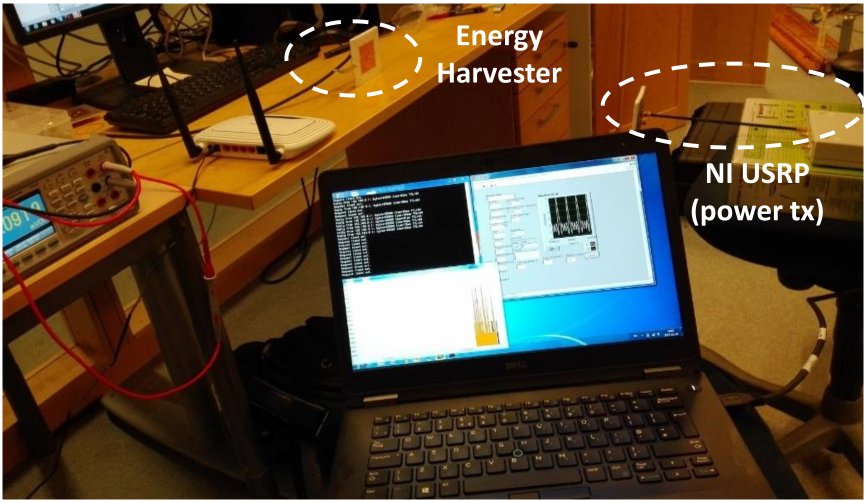


Figure 1.2: Experimental Setup for evaluating the impact of multi-tone signals on WPT and coexisting communication links.

to transmit wireless power using single or multi-tone signals while the other was used to exchange information with the distant third USRP. In this experiment, the distance between the antennas used for WIT and WPT in the co-located USRPs and their orientations were varied as well as adding/removing absorbers in-between. It has been observed that the performance of information transceivers (in terms of data rates and decoding errors) when co-located with WPT is hugely affected by the distance and the isolation between the power and information dedicated antennas. We concluded that, due to the significant difference in the signal strength between the transmitted power and the received information signal, a strong isolation level needs to be present between both links to minimize interference at the EM level.

The above conclusions from our experiments motivated our research on investigating optimal multi-tone signals for maximizing the efficiency of WPT while minimizing their impact on co-existing communication system. To the best of our knowledge, the present literature at the time lacked a global optimal design for the amplitude of multi-tone signals taking into account the RF front ends of co-existing information devices. Another appealing research problem was to explore the possibility to achieve high isolation within a wide band at the EM level between information and power transfer. We investigated this direction through designing a special antenna dedicated for SWIPT and studying whether the operation of conventional electromagnetic bandgap structures could be improved by exploiting higher symmetries. Finally, to provide a complete study of WPC systems in this thesis, we studied low-power sensing schemes from the perspective of using analog signal compression along with energy scheduling.

1.2 Contributions and Scope of the Thesis

This PhD thesis presents a study on WPC systems focusing on both theoretical and implementation aspects. It deals with two parallel lines of research. The first line is concerned with optimizing WPT signals at the transmitter node. In addition, compression of sensor signals at the receiver node with the aim of minimizing their power consumption to enable wirelessly powered operation. The second line of research focuses on investigating and studying electromagnetic design of the different components of a SWIPT system. For example, antenna design for co-located simultaneous transmission of wireless information and power. Moreover, investigating the application of higher symmetries in the design of electromagnetic bandgap structures with the goal of improving their rejection level and bandwidth of operation. High rejection level and wide bandwidth are essential requirements for improving the isolation between information and power signals.

The different aspects considered in this thesis are summarized in Fig. 1.3. At the transmitter side: optimal design of multi-tone signals with the goal of maximizing WPT efficiency while taking into account co-existing communication links. In addition, antenna design for co-located transmission of information and power. At the receiver side: studying the problem of minimizing power consumption and compressing information to enable low-power operation of sensor nodes. The part of the thesis related to electromagnetic design spans both the transmitter node and the receiver node.

Specifically, the following research questions are addressed in this thesis:

1. What are the optimal amplitudes of multi-tone signals to maximize the efficiency of WPT and how to optimize these signals when in-band SWIPT is considered?

2. How to design a multi-antenna structure that allows simultaneous transmission of information and power while minimizing interference?

3. Can the bandwidth and level of isolation between the antennas/devices used for information and power be improved by exploiting higher symmetries in EBG and filter design?

4. What is a suitable low-complexity method to compress two or more sensor readings into one signal to minimize power consumption and enable wirelessly powered operation?

The thesis is presented in the form of seven publications, referred to as paper A-G, with individual contributions summarized in Section 1.3

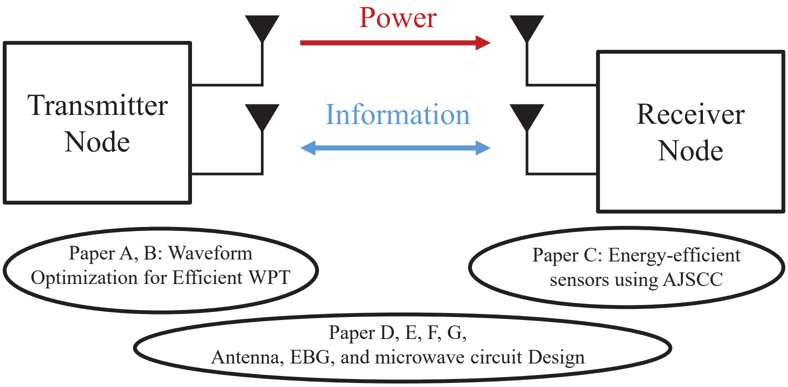


Figure 1.3: Scope of the thesis.

1.3 Outline of Thesis and Included Papers

The rest of this thesis is organized as follows: Chapter 2 provides an introduction to wirelessly powered communication systems and simultaneous wireless information and power transmission. It presents an overview on relevant literature and discusses open problems in the existing research. Chapter 3 introduces higher symmetries and their application to periodic structures. A literature review on the existing work and the reported benefits of exploiting higher symmetries is presented. In addition, Chapter 3 provides preliminary EM concepts that are used in analyzing periodic structures. The final part of the thesis consists of the collection of Papers A-G, each summarized in the following section:

Included Papers

In each of the seven publications Paper A-G included in this thesis, the thesis author contributed with development of concepts and theory, conducting simulations and measurements, evaluation of results, and manuscript writing. All included papers are peer-reviewed and published papers. In the following section, the individual contribution of each paper is summarized. The relevance of each of these publications to each node of the wirelessly powered communication system is illustrated in Fig. 1.3.

Paper A: "Multi-tone signal optimization for wireless power transfer in the presence of wireless communication links"

- Authors: Boules A. Mouris, Hadi Ghauch, Ragnar Thobaben, and B. L. G. Jonsson
- Published: *IEEE Transactions on Wireless Communications*, vol. 19, no. 5, pp. 3575-3590, May 2020

This paper studies optimization of multi-tone signals for WPT systems. Although the problem of multi-tone signal optimization for WPT has been presented earlier in the literature, the obtained amplitudes of the multi-tone signal were not guaranteed to converge to a global optimal solution. This paper can be viewed as the first work to fill this gap by presenting a novel formulation for the multi-tone signal optimization problem and providing globally optimal solution methods. Furthermore, a study of the different non-linear energy harvesting models and their application to waveform optimization for WPT has been presented in the paper. The paper also proposes a method to formulate the multi-tone signal optimization problem using curve fitting models with a focus on a second-order polynomial curve fitting model and comparing it to diode models existing in the literature. Finally, the problem of saturating the RF front end of co-existing in-band information receivers was introduced in this work and considered in signal optimization. The paper concluded that optimized multi-tone signals can significantly enhance the output of a WPT system. However, the multi-tone signal needs to be carefully designed to minimize interference with co-existing information receivers by saturating their RF front ends.

Paper B: "A Novel Low-Complexity Power-Allocation Algorithm for Multi-Tone Signals for Wireless Power Transfer"

- Authors: Boules A. Mouris, Henrik Forssell and Ragnar Thobaben
- Published: *2020 IEEE Wireless Communications and Networking Conference (WCNC)*, 2020, pp. 1-6.

Although Paper A provided a benchmark to assess the best performance for WPT systems with multi-tone signals, the presented solution in Paper A suffered from high computational complexity. This paper addresses this problem by presenting a novel low-complexity algorithm for allocating power to multi-tone signals for WPT. The algorithm, referred to as truncated maximum-ratio transmission (TMRT), performs maximum ratio transmission power allocation on the subset of available tones having the strongest channel coefficients. The paper concludes that the proposed TMRT algorithm achieves a performance very close to the optimal power allocation, despite its very low complexity, and significantly outperforms other low-complexity solutions.

Paper C: "Optimizing Low-Complexity Analog Mappings for Low-Power Sensors with Energy Scheduling Capabilities"

- Authors: Boules A. Mouris, Photios A. Satvrou and Ragnar Thobaben
- Published: *IEEE Intenrnet of Things Journal*, Early access, 2022

This paper investigates the use of analog joint source channel mappings in wirelessly powered sensors. It proposes a novel triangular mapping geometry as a low-complexity dimension reduction mapping. The presented mapping is used to compress the readings of two or more sensors into one signal with the goal of minimizing the power consumption at the sensing nodes. The paper provides theoretical analysis of the mean-squared error (MSE) performance of the proposed mapping in addition to a numerical verification. Methods to improve the MSE performance of the mapping by adapting it to the different distributions of the source signals have been studied. Moreover, the paper considers a WPC scenario in which an energy scheduling problem is formulated. The energy scheduling problem aims at optimizing the parameters of the proposed mapping following the received power profile with the goal of minimizing the sum distortion at the receiver. Finally, for the sake of minimizing the computational complexity at the sensing node, the paper also presents a low-complexity algorithm for optimal energy scheduling.

Paper D: "A Dual-Polarized Multi-Antenna Structure for Simultaneous Transmission of Wireless Information and Power"

- Authors: Boules A. Mouris, Christos I. Kolitsidas, and Ragnar Thobaben
- Published: *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, 2019, pp. 1805-1806.

This paper focuses on the interference issue between WPT and information signals at the electromagnetic level. It serves as the connection between the wireless communication part of thesis and the other part considering EM theory and design. The paper proposes a dual-polarized multi-antenna structure allowing simultaneous transmission of wireless information and power. The proposed antenna structure exploits differential feeding to minimize the mutual coupling between the WPT antennas and information antennas due to radiation leakage. In addition, a mushroom-type EBG was used in combination with the differential feeding to structure for suppressing the coupling due to surface waves. The paper concluded that such combination of differential feeding and EBGs can achieve an isolation level of at least 40 dB between the information transmitting antenna and the power transmitting antennas, and therefore, allowing SWIPT.

Paper E: "On the increment of the bandwidth of mushroom-type EBG structures with glide symmetry"

- Authors: Boules A. Mouris, Armando Fernandez-Prieto, Ragnar Thobaben, Jesus Martel, Francisco Mesa and Oscar Quevedo-Teruel
- Published: *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 4, pp. 1365-1375, April 2020

This paper focuses on investigating and designing novel EBG structures with the goal of suppressing and filtering the surface waves. It provides a comprehensive study on the benefits of exploiting higher symmetries, in particular glide symmetry, in improving the operational bandwidth of mushroom-type EBG structures. A descriptive equivalent circuit model as well as a study on the behaviour of the EM fields inside the structure were presented in the paper. Moreover, full-wave simulations and experimental evaluation were provided. The main finding of the paper is that applying glide symmetry to mushroom-type EBG structures can improve their bandwidth and possibly reduce their size for the same frequency of operation without adding any additional manufacturing costs.

Paper F: "Glide Symmetry Applied to Printed Common-Mode Rejection Filters"

- Authors: Boules A. Mouris, Armando Fernandez-Prieto, Jose L. Medran del Rio, Ragnar Thobaben, Jesus Martel, Francisco Mesa, Francisco Medina and Oscar Quevedo-Teruel

- Published: *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 2, pp. 1198-1210, Feb. 2022

In line with paper E, this paper continues on investigating the applications of glide symmetry in improving the isolation and filtering performance. The paper focuses on presenting defected ground structures (DGSs) as a convenient alternative to mushroom structures eliminating the use of vias. It could be viewed as the extended journal version of Paper I which is excluded from the thesis. The paper provides a complete study on glide-symmetric DGSs in terms of unit-cell study, equivalent circuit models, full-wave simulation and experimental evaluation. A comparison between glide-symmetric DGSs and mushroom-type EBGs is also provied in the paper. Moreover, the paper presents a novel application of glide symmetry to common-mode rejection filters. As will be discussed in Chapter 3, differential and common mode operation have recently been investigated in antenna design for applications that need high isolation between closely packed antenna elements. Our paper is of significant interest for such designs. The paper concludes the common-mode rejection bandwidth is drastically increased when glide symmetry is exploited compared with their corresponding structures without glide symmetry including fully-symmetric structures. Furthermore, it is shown that the use of glide symmetry hardly affects the differential-mode propagation, and thus, ensuring a good integrity of the transmitted information while simultaneously isolating it from the common-mode operation.

Paper G: "Glide-Symmetric Planar EBG Structure for Mutual Coupling Reduction Between Microstrip Patch Antennas"

- Authors: Boules A. Mouris, Ragnar Thobaben and Oscar Quevedo-Teruel

- Published: *2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI)*, 2021, pp. 1155-1156

This paper studies another type of fully planar EBG structures exploiting glide symmetry. Here, the proposed EBG structure consists of planar patches in a high-permittivity substrate without vias or any defected grounds. Such structures are analyzed in the paper and employed for for mutual coupling reduction between microstrip patch antennas. The paper concludes that the proposed structure results in a smaller size as well as an increased level of isolation between the patch antennas compared to the conventional EBG designs.

1.4 Conclusions

WPT is a promising technology to enable self-sustainable devices in a smart connected world. The work included in this thesis attempts to advance WPT and WPC systems by addressing some of the key challenges facing them. Specifically, it studies and presents solutions to the following issues: (1) maximizing the efficiency of WPT while minimizing the impact on the co-existing communication links, (2) minimizing the power consumption of the sensing nodes and optimizing their energy usage to enable wirelessly powered operation, and (3) designing antenna structures and different microwave components to enable SWIPT. This thesis focuses on addressing these challenges from both theoretical and practical perspectives. The most important conclusions of this thesis are summarized below.

Optimal multi-tone signal design for WPT In Paper A and Paper B, we provided methods to find the optimal amplitudes of the multi-tone signals that maximizes the efficiency of WPT according to the available channel state information (CSI) at the power transmitter. In addition, it has been shown that the multi-tone signal needs to be carefully optimized in order to minimize the interference with the co-existing communication nodes. The work in Paper A can be regarded as a benchmark to asses the best performance for WPT systems with multi-tone signals. On the other hand, the work in Paper B proposed a low-complexity sub-optimal algorithm to practically approach this optimal performance in real world implementations. The results of Paper A and B are valuable in the context of improving the efficiency of WPT which is indeed beneficial for achieving wirelessly powered sensing nodes.

Non-linear energy harvester models The work in this thesis emphasized that proper modeling of the energy harvester is essential for exploiting multi-tone signals in increasing the WPT efficiency. Paper A presented a complete overview of non-linear energy harvester model and proposed a method to use curve-fitting models for waveform optimization. Such models are important to decrease the gap between theoretical studies and practical implementation, and thus, allow for maximum utilization of WPT to enable practical realiziation of wirelessly powered communication systems.

Low-power sensors Exploiting analog joint-source channel coding (AJSCC) in compressing two or more sensor readings into one signal has been presented in Paper C. It has been shown that sensors can optimize AJSCC mappings to improve the mean-squared error performance according to the available harvested energy. Besides, Paper C shows that energy scheduling can significantly enhance the performance of the proposed AJSCC schemes. The contributions of Paper C form a base for implementing a real world wirelessly powered sensing node for IoT applications.

Antenna design for SWIPT The problems associated with co-located antennas for in-band SWIPT have been discussed in this thesis and the possible solutions have been presented. In Paper D, a multi-antenna structure providing high isolation between power transfer and information transfer has been presented. This structure can be utilized in SWIPT systems to enable co-located transmission of information and power.

Planar EBGs with glide symmetry In Paper E-G, a complete study on planar EBGs exploiting glide symmetry has been presented. It has been shown that glide symmetry can significantly enhance the performance of electromagnetic bandgap structures by providing a wider bandgap and a higher isolation level. Moreover, the equivalent circuit models described in Paper E and F provide a deep insight into the interesting properties of glide-symmetric periodic structures. The improved bandgap and isolation level resulting from the application of glide symmetry are beneficial for designing antennas and filters which enhances the performance while minimizing the interference level in SWIPT and WPC systems.

1.5 Future Work

Wireless power transfer lies in the intersection area between wireless communication and electromagnetics. In general, this is a very attractive area for future research. There is variety of open research topics in the field of WPC. Specifically, with respect to the work presented in thesis, the following directions are appealing for future exploration:

- Optimizing high PAPR signals other than multi-tone siganls for WPT and analyzing their impact on co-existing communication systems is interesting for future research. Although few existing research attempt to study other high PAPR signals for WPT, they still miss presenting the optimal design for these signals as well as the practical consideration of the co-existing communication nodes. Such studies provide useful input for future standardization processes.

- The performance of a WPT system under multi-tone signal excitation is highly dependent on the quality of CSI. Acquiring CSI in WPT systems is very challenging, especially, when passive receivers are considered. Finding efficient low-complexity techniques to obtain CSI in WPT system is indeed interesting for future investigation. One could also think of methods to increase the robustness of the designed waveforms for WPT to channel estimation errors.

- Low-complexity algorithms for power allocation to multi-tone signals such as the one presented in Paper B could be investigated for the case of multiple receivers. This would contribute to efficient and practical operation of wirelessly powered sensing nodes.

- IoT sensors that are fully-powered by wireless power are required to have an extremely low power consumption. The use of analog compression methods with energy scheduling might not be enough for fully achieving this. It is thus very interesting to investigate the possibility of combining these methods with other low-power communication schemes such as backscatter communications. This could potentially enable a new class of low-power sensors and devices.

- Paper C presented the analog circuit realization of the proposed triangular AJSCC mapping. It is indeed interesting to build such circuit and verify the performance experimentally. For example, by selecting off-the-shelf sensors and connecting them to the proposed AJSCC circuit and analyzing its MSE performance. Experimental validation is an essential step for practical usage and commercialization.

- Finding low-complexity AJSCC mappings that can be implemented using analog circuits remains an attractive area for research. Another direct extension of the work in Paper C is to explore the problem of energy scheduling with stochastic energy arrivals. Such extension is important to increase robustness.

- Fabrication and experimental evaluation of the proposed antennas for SWIPT in Paper D and Paper G are appealing for future work. Furthermore, the work on multi-antenna structures for SWIPT could be extended to include scanning capabilities in both elevation and azimuth planes. Experimental evaluation as well as adding more scanning capabilities would bring the designed antenna structure a step closer to commercial usage for SWIPT.

- Integrating the glide-symmetric EBGs and filters presented in Paper E and Paper F in the practical realizations of the antenna or the RF front end of a WPC system is worth to explore and experiment. Another possibility to extend the work in paper E is to derive an equivalent circuit model for the two-dimensional version of the mushroom-type EBG structure. In general, designing antenna arrays exploiting the methods described in this thesis provide a base for new hardware designs achieving high isolation between co-located information and power signals, and thus, could be utilized for SWIPT and WPC systems.

1.6 Other Contributions

In addition to Paper A-G, during the PhD period, the author has also contributed to the following publications:

Paper H: "Exploiting Glide-Symmetry in planar EBG structures"

- Authors: Boules A. Mouris, Ragnar Thobaben and Oscar Quevedo-Teruel
- Submitted: *IOP Publishing Journal of Physics: Conference Series Journal of Physics: Conference Series* Volume 963, Feb. 2018.

This paper presented the first attempts during the early stages of this PhD work to analyze and study the application of glide symmetry to fully planar EBG structures. The initial simulation results from the paper concluded that glide symmetry can reduce the size of the EBG structure for the same operating frequency compared to the non-glide structure.

Paper I: "Glide Symmetry to Improve the Bandgap Operation of Periodic Microstrip Defected Ground Structures"

- Authors: Boules A. Mouris, Armando Fernandez-Prieto, Ragnar Thobaben, Jesus Martel, Francisco Mesa and Oscar Quevedo-Teruel.
- Published: *2020 50th European Microwave Conference (EuMC)*, 2021, pp. 483-486.

This paper proposes and studies a novel one-dimensional periodic planar defected ground structure exploiting glide symmetry. The purpose of this work was to provide an alternative EBG design eliminating the use of vias which are needed in mushroom-type EBGs. The paper concluded that defected ground structures could also benefit from glide symmetry to improve their rejection properties.

Paper J: "Achieving SWIPT Through Differential Permutation-Based Coding Intelligent Reflecting Surface"

- Authors: Baptiste Cavarec, Boules A. Mouris, Ragnar Thobaben and Mats Bengtsson.
- Submitted: *17th International Symposium on Wireless Communications (ISWCS 2021)*, September 2021.

This paper discusses the utilization of intelligent reflecting surfaces (IRSs) for simultaneous wireless information and power transfer. In the considered setup, the RF power transmitter illuminates the IRS in order to wirelessly power its elements as well as the integrated sensors, and then, the IRS simultaneously uses part of its elements to modulate information by reflecting part of the incoming EM wave. It has been shown in the paper that differential permutation-based coding could be employed by the IRS to eliminate the the need for cabled links or channel state information. A study on the problem of allocating the IRS elements to either information or power transmission has been presented. In addition, a heuristic algorithm to optimize the grouping of the elements was derived. The paper concluded that IRSs could be potentially benefit from differential coding in SWIPT scenarios.

In this work, the author contributed with developing the idea and manuscript writing.

Paper K: "On the Benefits of Cascading Glide-Symmetric Periodic Structures in Bandwidth Improvement"

- Authors: Boules A. Mouris, Armando Fernandez-Prieto, Ragnar Thobaben, Jesus Martel, Francisco Mesa, and Oscar Quevedo-Teruel
- In preparation: *IEEE Microwave and Component Letters.*

This paper is an extension to the work in Paper E. It studies the possibility to combine glide symmetry with other bandwidth improvement methods.

Paper L: Rectenna for Bluetooth Low Energy Applications

- Authors: Boules A. Mouris, Wael Elshennawy, Panagiotis Petridis, Yuan Ding, and Spyridon Nektarios Daskalakis
- Published: *In 2019 IEEE MTT-S Wireless Power Transfer Conference (WPTC)*, pp. 508-511.

This paper focused on designing and testing an efficient rectenna targeting low-input RF power levels. The paper was published as a result of the work conducted in the doctoral course on energy harvesting and wireless power transfer for RFIDs and wireless sensor networks. The doctoral course was organized in the framework of the European School of Antennas (ESoA).

Chapter 2

Techniques for Wirelessly Powered Communications and Sensing

This chapter provides an overview of simultaneous wireless information and power transfer (SWIPT) and wirelessly powered sensing. It outlines the challenges associated with such systems and surveys previous work highlighting the contributions of the thesis.

2.1 SWIPT Overview

Since wireless communication networks are available almost everywhere, WPT appears naturally combined with WIT. However, RF transmitters are typically configured to transmit either information (e.g., base stations, access points, user equipment) or power (e.g., dedicated WPT system). For this reason, various transmitter architectures have been studied to achieve SWIPT such as co-located, hybrid or separated transmitters. A co-located SWIPT transmitter [22] consists of two transmitters; one dedicated for power transmission while the other is dedicated to information transmission. These two co-located transmitters can use independent antennas or share the same antenna structure. A high level of isolation needs to be guaranteed in the first case in order to minimize the interference between power and information links, whereas the latter case employs duplexing schemes such as time division, frequency division or code division [7, 22]. Co-located SWIPT transmitters might also utilize dual-band operation to separate information and power. Hybrid SWIPT transmitters use the same RF signal to transmit both information and power through one or multiple antennas. They usually require complicated transmission strategies. For example, joint beamforming of power and information as in [23]. Another example of hybrid transmission is achieved by modulating information on top of power signals as in [24, 25]. As will be discussed in the next section, signal modulation affects the energy harvester's efficiency. Therefore, it is crucial to carefully design modulation schemes

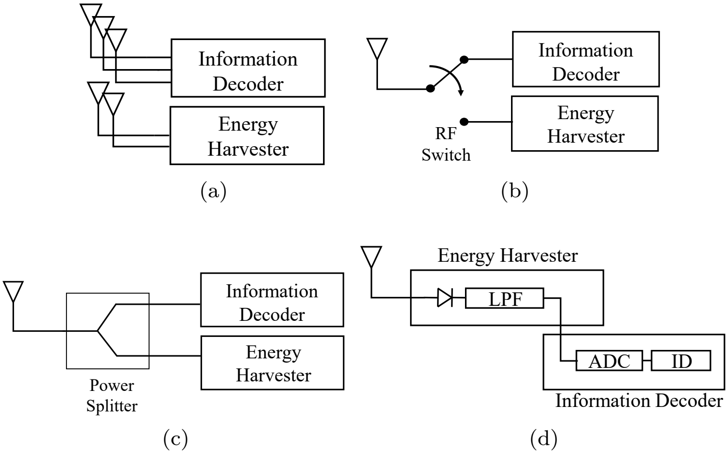


Figure 2.1: SWIPT receiver architectures (a) Antenna splitting (switching), (b) Time switching, (c) Power splitting, and (d) Integrated receiver.

to satisfy both information and energy constraints. Finally, separated transmitters for SWIPT use separate hardware as well as independent RF signals for power and information transmission (i.e., WPT co-exist with WIT). Although separation minimizes the complexity of the transmitter, it may not be optimal in the case of scarce resources.

Similarly, conventional communication receivers are not capable of receiving wireless power. Therefore, different receiver configurations have been investigated for SWIPT. SWIPT receivers may also be classified as separated, co-located and hybrid receivers. A summary of the most widely used receiver configurations in the literature is presented in Fig. 2.1. The antenna splitting (switching) receiver in Fig. 2.1(a) is a generalized model of a separated receiver architecture since each of the energy harvester and the information receiver is equipped with independent antenna(s) and purely perform its function regardless of the presence of the other. In such receiver architecture, beamforming at the transmitter side towards the different receivers becomes an interesting problem [26, 27].

The time switching (TS) and power splitting (PS) receivers in Fig. 2.1(b) and Fig. 2.1(c), respectively can be categorized under co-located receiver architecture. This SWIPT receiver shares one antenna structure (i.e., same channel) between WPT and WIT. It uses either an RF switch or an RF power divider to direct the signal stream to the information decoder and the energy harvester. The main research objectives for these configurations have been to study the rate-energy tradeoff and optimize the ratio of time or power splitting accordingly [26, 28, 29]. The hybrid (integrated) receiver architecture in Fig. 2.1(d) has been first proposed in [30]. It relies on the presence of diodes in the energy harvester circuit (instead of mixers in traditional receivers) to perform the RF-to-baseband conversion for information decoding. The information decoder then receives the output of the

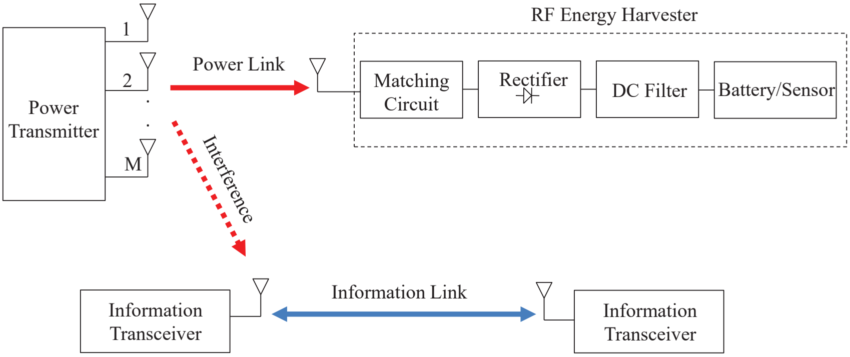


Figure 2.2: SWIPT with separated transmitter and receiver (co-existing WPT and WIT).

energy harvester through an analog-to-digital converter (ADC) and demodulates the encoded information. Integrated receivers reduce size and power consumption. However, information decoding in this type of receivers is not an easy task and requires careful modulation designs to improve the rate-energy trade-off region considering the non-linear nature of the energy harvester [24, 25, 31].

In the first part of this thesis, in particular in Paper A and Paper B, we consider separated hardware for wireless communication and wireless power (i.e., separated architectures for SWIPT) as presented in Fig. 2.2. We aim at maximizing the efficiency of WPT while minimizing the interference with the co-existing information link. Therefore, a summary of the different approaches to improve the efficiency of WPT is presented in the following section.

2.2 Efficient WPT

A typical WPT system consists of an RF power transmitter and an RF energy harvester usually referred to as the rectifying antenna (rectenna). Several factors control the end-to-end efficiency of a WPT system. One can express the end-to-end efficiency of a WPT system as

$$\eta = \frac{P_{\mathrm{DC}}^{\mathrm{Tx}}}{P_{\mathrm{DC}}^{\mathrm{Rx}}} = \underbrace{\frac{P_{\mathrm{RF}}^{\mathrm{Tx}}}{P_{\mathrm{DC}}^{\mathrm{Tx}}}}_{\eta_1} \cdot \underbrace{\frac{P_{\mathrm{RF}}^{\mathrm{Rx}}}{P_{\mathrm{RF}}^{\mathrm{Tx}}}}_{\eta_2} \cdot \underbrace{\frac{P_{\mathrm{DC}}^{\mathrm{Rx}}}{P_{\mathrm{RF}}^{\mathrm{Rx}}}}_{\eta_3} . \tag{2.1}$$

The DC-to-RF conversion efficiency η_1 can be maximized by using efficient mixers and power amplifiers at the transmitter. The RF-to-RF efficiency η_2 is controlled by the Tx and Rx antenna configuration as well as the propagation channel. It can be improved by exploiting directive transmission using multi-antennas and channel-adaptive beamforming [32, 33]. Furthermore, intelligent reflecting surfaces (IRSs) have recently been proposed in order to provide more control of the propagation channel, and thus, improving the efficiency η_2 [34,35]. The rectenna efficiency η_3 which represents the RF-to-DC conversion efficiency is indeed the most crucial factor in an efficient WPT system. The vast majority of the research conducted on efficient WPT is devoted to maximizing the rectenna efficiency. Different blocks forming the rectenna can be viewed in Fig. 2.2. We summarize the various techniques to improve the rectenna efficiency below:

- **Rectifier circuit optimization:** It is necessary to ensure proper matching between the antenna and the rectifier within the operation frequency and input power range. In addition, selecting the diode component as well as the rectifier topology (i.e., using a single diode or multiple diodes) can significantly affect the rectenna efficiency (see [36] and references therein). Usually, a single-diode rectifier is preferred at low-input power levels since it minimizes the power dissipated in the rectification process, and thus, maximizes the efficiency.

- **Multi-band and broadband operation:** In order to increase the amount of the harvested DC power, multi-band rectennas [21, 37] targeting two or more separated frequency bands as well as broadband rectennas covering a continuous wide bandwidth [38] have been investigated.

- **Multiple antenna techniques:** The use of multiple antennas at the energy harvester is beneficial for improving the RF-to-DC conversion efficiency. Three techniques have been introduced in the literature to exploit multiple antennas at the energy harvester [39–41]: 1) DC combining in which each antenna is connected to a separate rectifier and the output powers are combined at the DC level, 2) RF combining where the received power is combined at the RF level and input to a single rectifier (i.e., all antennas are connected to a single rectifier), 3) hybrid combining which makes use of the other two techniques by combining each subset of antennas to one rectifier and then combining the output of the different rectifiers at the DC level.

- **Input signal waveform:** Interestingly, it has been shown that signals having high PAPR such as multi-sine signals, OFDM signals, chaotic signals, and white noise can significantly improve the RF-to-DC conversion efficiency of the rectifier circuit at low input power levels. [17–19, 42–45]. This is mainly due to the non-linear characteristics of the rectifier circuit. In a high PAPR signal, energy is concentrated in a short-duration pulse within the signal's period. The high amplitude of the peak pulse easily overcomes the diode's turn voltage. By properly designing the output DC filter of the rectifier circuit, the output capacitor will hold the output DC voltage during the off period of the diode until the next pulse arrives. Therefore, the output DC voltage is improved by increasing the PAPR in comparison with a single sinusoidal signal having a constant amplitude with the same average power.

2.2.1 Waveform Design for WPT

The impact of signal design on the WPT efficiency has attracted significant attention in the wireless communications society, especially in connection with the evolution of of SWIPT and WPC systems. When the wireless channel is considered, the efficiencies η_1, η_2 and η_3 are coupled due to the rectifier's non-linearity and should be jointly optimized. For example, the efficiency η_3 is function of its input signal shape and power, and consequently, a function of the transmitted signal at the RF transmitter including precoding, beamforming and power allocation as well as the state of the wireless channel.

In general, multi-tone signals are the most popular form of high PAPR signals due to their tractability. The work in [46] was the first work to consider the wireless channel state as well as a non-linear rectifier model when designing multi-tone signals for WPT. The interesting conclusions of [46], in particular, the performance gains when exploiting channel-adaptive signals with a non-linear rectifier model motivated further research in several directions. For example, extension to large-scale WPT systems with large number of tones and antennas and multiple energy receivers [32], accounting for fairness among different energy receivers [47], studying the effect of channel fading and transmit diversity [48], exploring low-complexity methods to design channel-adaptive WPT signals [49,50], optimizing WPT signals according to limited CSI information [51], multi-users with multi-antenna receivers [52]. Using non-linear energy harvesting models with channel adaptive waveforms was further studied in the context of SWIPT in [10,53], [7] and the references therein.

2.2.2 Considered Setup in Paper A

In Paper A, we consider the setup described in Fig. 2.2 with a WPT system consisting of an RF transmitter transmitting power to an RF energy harvester. The WPT system co-exist with a WIT system consisting of two information transceivers communicating with each other using an OFDM-based radio access technology. As described earlier, this setup can be viewed as a SWIPT architecture with separated transmitters and receivers. Assuming that the RF transmitter is equipped with M antennas and transmitting N tones, one can express the multi-tone signal at time t on the mth antenna as

$$x_m(t) = \sum_{n=1}^{N} s_{n,m} \cos\left(2\pi f_n t + \varphi_{n,m}\right) = \Re\left\{\sum_{n=1}^{N} w_{n,m} e^{j2\pi f_n t}\right\}, \tag{2.2}$$

where f_n is the tone frequency such that $f_n = f_o + (n-1)\,\Delta_f$ and $w_{n,m} = s_{n,m} e^{j\varphi_{n,m}}$ with $s_{n,m}$ and $\varphi_{n,m}$ referring to the amplitude and phase of nth tone, respectively. The transmit signal vector can therefore be written as

$$\mathbf{x}\left(t\right) = \Re\left\{\sum_{n=1}^{N} \mathbf{w}_n e^{j2\pi f_n t}\right\}, \tag{2.3}$$

where $\mathbf{w}_n = [w_{n,1}, w_{n,2}, .., w_{n,M}]^T$.

It is assumed that the RF transmitter is capable of acquiring CSI to the energy harvester as well as the information transceivers in its vicinity. Our work in Paper A focused on finding the optimal weights (i.e., $s_{n,m}$ and $\varphi_{n,m}$) for the multi-tone signal given a constraint on transmit power with the goal of maximizing the efficiency of WPT transmission while minimizing the interference with co-existing in-band OFDM-based communication systems. In particular, the interference due to the inter-modulation products resulting from saturation of the low-noise amplifier (LNA) of the nearby communication receivers.

Proper modeling of the rectifier circuit is an essential step in optimizing multi-tone signals. The DC output of the rectifier is a non-linear function of its input signal which can generally be expressed as

$$z_{\mathrm{DC}} = f\left(y\right), \tag{2.4}$$

where $f\left(\cdot\right)$ is a monotonically non-decreasing non-linear function. Many attempts to model the non-linear behaviour of the rectifier exist in the literature. The vast majority of the existing work on waveform optimization for WPT and SWIPT rely on models derived from the diode I-V characteristics. In Paper A, a survey of non-linear rectifier models is provided. Moreover, we introduce a method to use models based on curve-fitting of the input-output power relation of the rectifier in formulating the multi-tone optimization problem.

Optimizing multi-tone signals yields a non-convex optimization problem which is computationally complex to solve, and thus, may not be suitable in real world applications. We address this issue in Paper B by proposing a fast low-complexity methods for optimizing multi-tone signals for WPT.

2.3 Wirelessly Powered Sensing Nodes

As discussed earlier, in a WPC setup, a dedicated RF transmitter firstly sends power to the RF energy harvester attached to the sensor. Secondly, the energy harvested is used partially or completely to transmit information to an information receiver, which is not necessarily the same node that initiated WPT. WPC is envisioned for the wireless powering of low-power WSNs and IoT nodes. However, traditional radio architectures include power-hungry RF chains having local oscillators (LO), mixers, phase-locked loop (PLL), ADCs, and digital-to-analog converters (DAC) which limit the battery life and also minimizes the chances of being wirelessly powered. Although WPC is a broad term which includes many interesting problems (e.g., [9, 54] and the references therein), we here focus on methods that can potentially reduce the power consumption of the sensing nodes, namely backscatter communication and analog compression mappings.

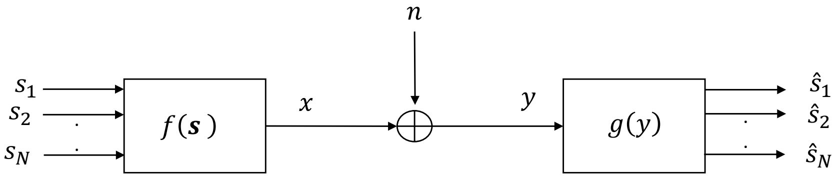


Figure 2.3: Block diagram of $N : 1$ dimension reduction mapping.

2.3.1 Wirelessly Powered Backscatter Communication

Backscatter communication has been explored to minimize the power needed to establish communication with the base station or an access node. In particular, backscattering enables uplink communication through load modulation and reflection of a portion of the incident RF signal on the sensor node. Therefore, backscatter communications avoid the power consumption due the RF front end (LO, mixers and DACs). Over the air carrier generation eliminating the use of LO and mixers could alone save power up to the range of 80 mW [55] in addition to lowering the production costs. Nevertheless, the range of communication might be limited due to weakness of the received backscatter signal at the reader node.

RFID tags are a typical example of wirelessly powered backscatter communication (WPBC). An RFID tag usually uses a passive envelope detector to decode downlink information which it receives along with wireless power (similar to a SWIPT scenario with an integrated receiver). The tag then uses its harvested power to enable load-modulation and transmit its information by reflecting the incident RF signal [56]. Recent works have shown that backscatter modulation can be extended to higher-order modulation schemes [12, 57], and thus, possibly increase data rates. In addition, studies on WPBC were extended to include multi-tone signal excitation with non-linear energy harvesting models in the cases of a single point-to-point link [13] as well as a multi-user backscatter system [58]. These studies focused on characterizing the tradeoff between the harvested energy and the signal-to-intereference-and-noise ratio at the backscatter reader.

2.3.2 Analog Mappings for Low-Power Sensing Schemes

Analog joint source-channel coding (AJSCC) was introduced by Shannon more than seventy years ago [59]. However, applications of AJSCC were limited due to the lack of practical implementations. AJSCC has recently been revisited for limiting the use of power-hungry ADCs at the sensing nodes [60]. Within this context, AJSCC is used to compress the reading of two or more sensors into one signal and transmit it through the wireless channel via analog or hybrid analog-digital communication schemes.

A block diagram describing the idea of analog signal compression is shown in Fig. 2.3. Here, an encoding function $f(\cdot)$ performs $N : 1$ dimension reduction and then the encoded signal is transmitted through the communication channel.

At the receiver side, a decoding function $g(\cdot)$ is applied to decompress and and retrieve the N-dimensional signal. In general, the function $f(\cdot)$ analytically describes the process of projecting the source point into a space-filling curve and using the length from the origin of the curve to the projected point as the encoded signal. Here, the challenge is two-fold because: (1) there is no general method to find mapping geometries that cover the source-space efficiently while being analytically describable and minimizing the distortion; and (2) even if one could find a proper mapping, its corresponding encoding function usually involves a variety of non-linear functions that cannot be implemented using simple analog circuits.

The work in [60] was the first to present a low-complexity all analog implementation of a 2 : 1 dimension reduction mapping, namely the rectangular mapping geometry. Later on, applications of that mapping in wireless monitoring [61] and health care [62] were investigated. In addition, alternative dimension reduction mappings based on MOSFET I-V characteristics were proposed in [61, 63]. In Paper C, we present a novel triangular mapping geometry as a low-complexity dimension reduction mapping. We provide a low-complexity analog circuit of such mapping enabling its use in low-power sensing nodes and evaluate its performance.

In general, the performance of a dimension reduction mapping is characterized by the distortion at the receiver node. This distortion is greatly dependent on the available power for the encoding function (at the sensing node). Therefore, in a wirelessly powered sensors scenario, it is important to optimize the mapping performance according to the received wireless power. Consequently, it is reasonable to schedule the use of energy in order to optimize the average performance of the mapping over time. Our work in Paper C discusses energy scheduling in wirelessly powered sensing nodes exploiting AJSCC with the goal of optimizing their performance.

One might think of a sensing node utilizing both AJSCC and backscatter communication to minimize power consumption. This could be an interesting direction to further research and develop.

Chapter 3

SWIPT Antenna and Glide-Symmmetric Periodic Structures

As discussed in the previous chapter, in case of a multi-antenna transmitter node, in-band SWIPT can be achieved by splitting the antenna elements among wireless information and power transmission. In such scheme, the antenna elements are co-located and mimic a full-duplex antenna system as shown in Fig. 3.1. This results in a high self-interference level between the power link and the information link. This chapter addresses this problem by discussing the reasons for the high interference level and presenting the possible solutions. Moreover, it provides an overview of periodic structures and their electromagnetic bandgap operation as a possible solution for mutual coupling reduction in antenna arrays. Finally, the concept of periodic structures with glide symmetry is explained with a summary of the state-of-the art research in that field highlighting the contribution of the thesis.

3.1 Mutual Coupling in Antennas

Mutual coupling in antenna arrays is usually caused by two paths [64]. The first path is due to radiation leakage from the space between antenna elements and is present in all types of array antennas (see Fig. 3.2(a)). The second path arises from the surface waves along the substrates and becomes of particular significance in microstrip patch antennas. WPT usually uses frequencies in the range of few GHz to minimize the propagation losses. In this frequency range, microstrip technology is preferred for antennas due to the low-complexity and low-cost fabrication process. Moreover, microstrip antennas have a low-profile and can easily be integrated with other circuits.

Mutual coupling due to surface waves is usually suppressed by the use of elec-

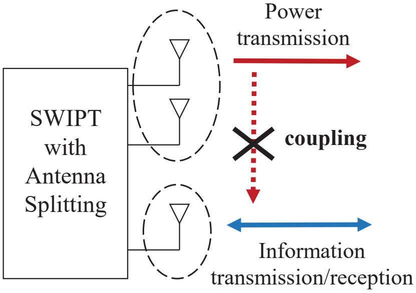
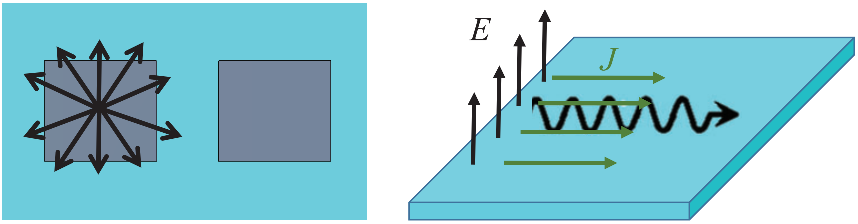


Figure 3.1: SWIPT with co-located transmission of power and information.



(a) (b)

Figure 3.2: Sources of mutual coupling: (a) Radiation leakage. (b) Surface waves.

tromagnetic bandgap (EBG) structures. On the other hand, minimizing radiation leakage requires innovative isolation methods.

Methods to minimizing radiation leakage are widely discussed in the context of in-band full-duplex systems [65]. These methods include:

- **Physical or beam separation:** Separating antennas physically reduces radiation leakage since the path loss of the propagating radio waves increases proportionally to the square of the distance between the transmit and receive antennas. Beam separation could also be used in directional antennas by orienting them in a way that minimizes the overlap between their radiated beams.

- **Cross polarization:** Two antennas operating with orthogonal polarizations (i.e., cross-polarized) provide inherent isolation since different polarizations do not couple into each other. However, maintaining the radiated waves at a certain polarization in a multi-path environment cannot be guaranteed.

- **Phasing methods:** In these methods, multiple Tx (Rx) antennas are utilized to create destructive interference at the Rx (Tx) antennas which are co-located in the same structure [66, 67].

- **Decoupling structures:** Decoupling structures such as absorbers, metasurfaces and metamaterials can be placed between two antenna elements to prevent radiation leakage. However, decoupling structures need to be carefully designed since they are placed in the near-field of the antenna. This means that they can be parasitically excited, and thus, alter the radiation properties of the antenna. An efficient decoupling structure composed of coupled metamaterial slabs was shown to significantly reduce the radiation leakage between two dual-polarized patch antennas in [64].

Paper D proposes a novel dual-polarized multi-antenna structure allowing co-located SWIPT. The proposed antenna structure utilizes phasing methods, in particular differential feeding, to minimize to radiation leakage between the WPT antennas and WIT antennas. In addition, the proposed antenna structure uses an EBG structure in combination with the differential feeding in order to suppress the coupling due to surface waves.

EBG structures are microwave structures that can be used to control the propagation of waves by not allowing the wave propagation at certain frequency bands (i.e., having band gaps or stop-bands). EBG structures are typically realized using periodic structures. For this reason, a summary of the concept of periodic structures and their analysis is presented in the following section.

3.2 Periodic Structures and their Analysis

Periodic structures consist of an infinite repetition of identical components referred to as the unit cell. Repetition can be done in 1D, 2D or 3D. In this section, we provide a brief explanation on analyzing periodic structures and their operation as electromagnetic bandgap structures.

3.2.1 Wave Propagation in a Periodic Structure and Floquet Theorem

Wave propagation is governed by Maxwell's equations. Assuming time dependence of $e^{j\omega t}$ and a periodic lossless medium that is linear, isotropic, and non-dispersive with relative permeability $\mu_r = 1$ and relative permittivity $\varepsilon_r = \varepsilon_r(\mathbf{r})$, one can re-arrange Maxwell's equations into the following equations for the electric field $\mathbf{E}(\mathbf{r})$ and the magnetic field $\mathbf{H}(\mathbf{r})$ [68]:

$$\nabla \times [\nabla \times \mathbf{E}(\mathbf{r})] = \frac{\omega^2}{c^2}\varepsilon_r(\mathbf{r})\mathbf{E}(\mathbf{r}), \tag{3.1}$$

$$\nabla \times \left[\frac{1}{\varepsilon_r(\mathbf{r})}\nabla \times \mathbf{H}(\mathbf{r})\right] = \frac{\omega^2}{c^2}\mathbf{H}(\mathbf{r}). \tag{3.2}$$

Here, $\mathbf{r}$ represents the position vector, ω is the angular frequency of the electromagnetic wave and c is the speed of light in vacuum.

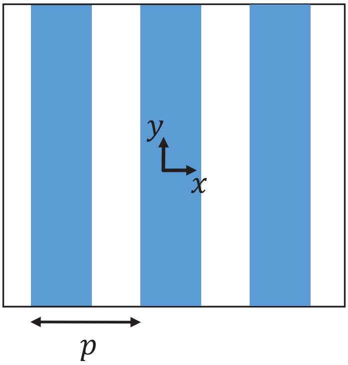


Figure 3.3: An example of a 1D periodic structure.

In practice, only one of the above equations needs to be solved. The other field component can be obtained using Maxwell's equation. However, it is more mathematically convenient to solve (3.2), and thus, we will adopt it as the initial equation for the rest of the discussion.

Let $\mathcal{L}$ be a linear differential operator defined as:

$$\mathcal{L} \equiv \nabla \times \left[\frac{1}{\varepsilon_r(\mathbf{r})} \nabla \times \right]. \tag{3.3}$$

Consequently, one can express (3.2) as the eigenproblem of the operator $\mathcal{L}$ given by

$$\mathcal{L}\mathbf{H}(\mathbf{r}) = \frac{\omega^2}{c^2}\mathbf{H}(\mathbf{r}). \tag{3.4}$$

Here, the spatial patterns of the modes of the magnetic field $\mathbf{H}(\mathbf{r})$ are the eigenvectors, and ω^2/c^2 are their corresponding eigenvalues [68].

Assume a one-dimensional (1-D) periodic structure in the Cartesian coordinates. An example of such structure is shown in Fig. 3.3. This structure is invariant after translation of length p along the x direction. The length p is called the period or the lattice constant. The smallest repeatable section of the structure is called the unit cell. The translation operator $\mathcal{T}$ describing this transformation is defined as

$$\mathcal{T} \equiv \begin{cases} x \to x + p \\ y \to y \\ z \to z \end{cases} \tag{3.5}$$

Floquet's theorem states that applying the translation operator $\mathcal{T}$ to the field $\mathbf{H}$ yields

$$\mathcal{T}\mathbf{H}(x,\, y,\, z) = \mathbf{H}(x + p,\, y,\, z) = e^{-jk_x p}\mathbf{H}(x,\, y,\, z). \tag{3.6}$$

In the above equation, the field **H** is the eigenvector of the translation operator $\mathcal{T}$ with e^{-jk_xp} being the eigenvalues [68]. From (3.4) and (3.6), it can be observed that the field **H** is the eigenvector of both the linear operator $\mathcal{L}$ and the translation operator $\mathcal{T}$. As discussed in [68], it follows that

$$\mathcal{L}\left(\mathcal{T}\mathbf{H}\right)=\mathcal{T}\left(\mathcal{L}\mathbf{H}\right). \tag{3.7}$$

From (3.7), one can deduce that, in a periodic structure, the field distributions (i.e., **E** and **H**) can be obtained by finding out the solutions inside one period and implementing a transformation afterwards. That is to say, the fields at a cross section differs from the fields at a period away only by a factor. Similar results can be formulated for the electric field **E** applying the same analysis procedure to (3.1).The above analysis can be extended to two-dimensional (2D) and three-dimensional (3D) periodic structures.

According to Floquet theorem [68, 69], the solutions to (3.2) which satisfy (3.6) can generally be expressed as

$$\begin{aligned}\mathbf{H}(\mathbf{r})=\sum_m \mathbf{c}_m(y,\,z)e^{-j\left(k_x+\frac{2\pi m}{p}\right)x}&=e^{-jk_xx}\sum_m \mathbf{c}_m(y,\,z)e^{-j\frac{2\pi m}{p}x}\\&=e^{-jk_xx}\mathbf{u}(x,\,y,\,z),\end{aligned} \tag{3.8}$$

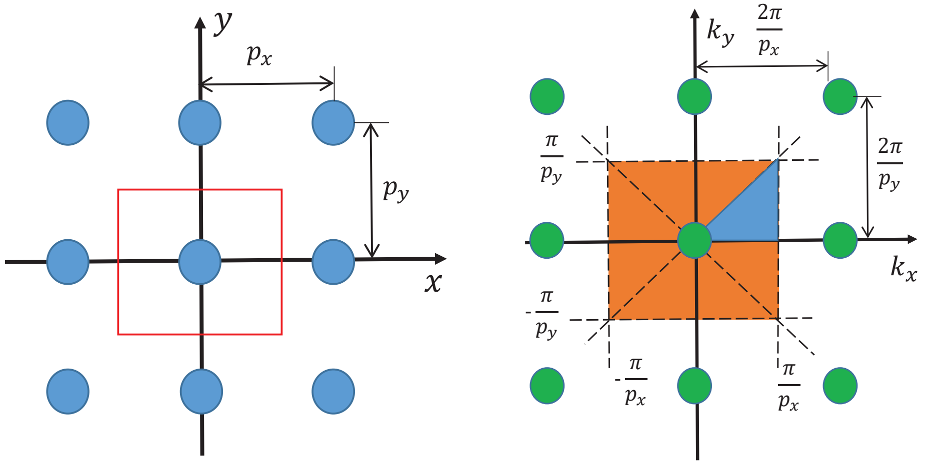
where m is an integer, $\mathbf{c}_m(y,\,z)$ are the expansion coefficients which are determined by the analyzed configuration and $\mathbf{u}(x,\,y,\,z)$ is a periodic function in x with period p.

3.2.2 Dispersion Diagram

Substitution of (3.8) in (3.2) provides a relation between ω and k_x. Such relation is called the dispersion relation and can be used to understand the propagation characteristics in a periodic structure. The dispersion relation is usually visualized in a plot of $\omega(k_x)$ versus k_x called the dispersion diagram. Due to the 2π periodicity of the exponential in (3.6), changing k_x by integral multiples of $q=2\pi/p$ does not change the corresponding frequency. This means that the dispersion relation $\omega(k_x)$ of a periodic structure is also periodic with period q. Therefore, it is sufficient to obtain the dispersion relation within $-\pi/p\le k_x\le \pi/p$. This range of k_x is referred to as the Brillouin zone [70]. The dispersion relation for the other values of k_x are deduced from the periodicity of the result.

It has also been shown that if a periodic structure has an additional symmetry such as rotation, mirror reflection or inversion, its dispersion diagram (ω versus the wave vector $\mathbf{k}$) is also symmetric with the same symmetry [68, 70]. In such case, the Brillouin zone can be further reduced to the smallest region within which $\omega(\mathbf{k})$ is not repeating itself which is called the irreducible Brillouin zone.

From the above discussion, periodic structures have two lattices, one in the physical domain, and the other in the reciprocal wavenumber domain. For example, for the 2D periodic structure in Fig. 3.4, the lattice vectors are $\mathbf{p}_x=p_x\hat{x}$



(a) Physical domain. The unit cell is highlighted with the red rectangle.

(b) Reciprocal domain (wavenumber domain) higlighting the Brillouin zone in orange.

Figure 3.4: Lattice of a 2-D periodic structure with periodicity p_x along the x -axis and p_y along the y -axis and its reciprocal Brillouin zone.

and $\mathbf{p}_y = p_y\hat{y}$ and are shown in Fig. 3.4(a), while the reciprocal lattice vectors (Fig. 3.4(b)) in the (k_x, k_y) plane are $\mathbf{q}_x = (2\pi/p_x)\hat{x}$ and $\mathbf{q}_y = (2\pi/p_y)\hat{y}$. In the physical domain, the unit cell is defined by the red rectangle in Fig. 3.4(a). The corresponding Brillouin zone is defined by the orange area in Fig. 3.4(b) which is bounded by the four black dash lines given by $k_x = \pm\pi/p_x$ and $k_y = \pm\pi/p_y$.

For a periodic structure with a square lattice (i.e., $p_x = p_y = p$), the Brillouin zone is a square defined by $-\pi/p \leq k_x \leq \pi/p$ and $-\pi/p \leq k_y \leq \pi/p$. The Brillouin zone can be divided into eight equal triangles. The field modes inside these eight triangles have the same behavior due to the rotational symmetry. Therefore, the irreducible Brillouin zone in this case is represented by one triangle which is highlighted in blue and magnified in Fig. 3.5. Conventionally, the vertices of the irreducible Brillouin zone are referred to as as Γ, X and M. Since all the limiting cases occur on the boundary of the irreducible Brillouin zone, it is common to obtain the dispersion diagrams over the edges of the irreducible Brillouin zone, which are the lines connecting the path $\Gamma - \mathrm{X} - \mathrm{M}$.

It is worth mentioning that nowadays dispersion diagrams can easily be calculated using commercial EM solvers such as *CST Microwave Studio* [71]. Using a unit cell of the periodic structure under study and setting the proper periodic boundaries in the simulator, the eigenmode solver calculates the eigenfrequencies and the associated fields. The dispersion diagram is then obtained directly from CST eigenmode solver as a plot of the propagation constant (i.e., $\Re\{k\}$) vs. frequency.

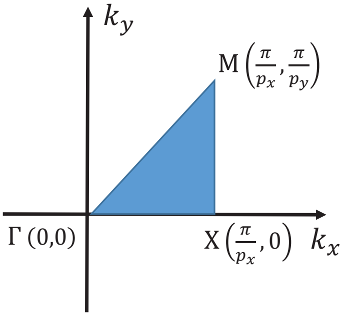


Figure 3.5: Irreducible Brillouin zone.

3.3 Glide Symmetry Applied to Periodic Structures

Glide symmetry is one type of higher symmetries. In general, higher symmetries are described by a translation and a second geometrical operation such as reflection or rotation [72, 73]. A periodic structure is glide-symmetric if its invariant under translation and reflection operators. As described in Fig. 3.6, to obtain a glide-symmetric structure, the unit cell is mirrored with respect to the glide plane and translated by half of the unit cell periodicity.

The first studies of higher symmetries for electromagnetic purposes date back to the 60's and 70's [72–74] focusing on 1-D periodic structures possessing higher symmetries. However, their extraordinary properties in 2-D lattices were neither discovered nor exploited until very recently [75]. In [75], glide symmetry was exploited in unit cells of bed-of-nails as well as holey structures in a parallel plate configuration showing interesting properties in increasing the equivalent refractive index of the periodic structure in addition to reducing the dispersion. Since then, the interest in studying the attractive properties of glide-symmetric periodic structures and exploiting it in practical microwave devices has exponentially increased (see [76] and the references therein). To list a few examples, glide-symmetric periodic structures have been applied to realize cost-effective gap-waveguides technology [77–79], filters [80], flanges [81], low-dispersive leaky-wave antennas [82], broadband lens antennas [83–85], mushroom-type EBGs [86](Paper E), defected ground structures [87], impedance matching [88], low-dispersive transmission lines [89], and providing accurate control of the frequency dispersion and the equivalent refractive index [90–92]. The attractive properties of glide-symmetric structures motivated several theoretical and numerical methods to analyze their operation such as mode-matching techniques [93], equivalent circuit models [86, 94, 95] and multi-mode analysis [96].

The work in this thesis aim at studying the applications of glide symmetry in microstrip technology since it is more relevant for the frequencies of interest for WPT.

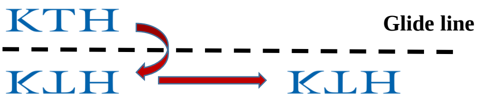


Figure 3.6: Glide symmetry.

3.3.1 Glide-symmetric Mushroom-type EBG Structure

Mushroom surfaces made of metal patches with center vias were first shown to operate as high impedance surfaces in [97]. They are widely used as EBGs to suppress surface waves propagation, especially in the context of mutual coupling reduction in antenna arrays. However, mushroom-type EBGs usually suffer from having a narrow bandwidth and being electrically large. Extensive work can be found in the literature addressing these two problems. However, the presented solutions usually result in either a complicated geometry or a multi-layer design.

Since mushroom-type EBGs are of particular interest for filtering and bandgap operation in SWIPT systems, our work in Paper E investigated the application of glide symmetry to mushroom-type EBG structures with the goal of improving their bandgap properties. Paper E investigates the application of glide symmetry to the mushroom unit cell described in [98]. In [98], it was shown that use of edge-located vias can reduce the size of mushroom-type EBG structures at the cost of reducing the bandgap compared to conventional mushroom structures. However, in Paper E, we demonstrate that glide symmetry significantly improves the bandwidth of mushroom-type EBGs with edge located vias at no additional cost, and thus, benefit from both a reduced size and a wide stopband. Furthermore, Paper E provides a comprehensive study of the presented glide-symmteric structure in terms of dispersion diagrams, a detailed equivalent circuit model, description the field behaviour, simulations and measurements.

3.3.2 Glide-Symmetric Defected Ground Structures with Common-mode Rejection

A microstrip defected ground structure is obtained by etching slots or defected patterns in the metallic ground layer of a microstrip structure. Defected ground structures (DGSs) exhibit bandgaps at certain frequency bands, and thus, they are viewed as a convenient alternative to the use of vias (as in mushroom structures) and drilling in printed technology [99]. DGSs have also been investigated for filtering in efficient WPT [100]. In Paper F, we show that DGSs can benefit from glide symmetry to widen its bandwidth of operation and increase the rejection level. We also provide an equivalent circuit model and present a detailed analysis for such structures.

Another aim for Paper F was to investigate a novel application for glide symmetry, in particular to study differential lines loaded with glide-symmetric periodic structures to enhance their common-mode (CM) rejection properties. Differential structures are very attractive for future wireless devices due to their high robustness to environmental noise, lower electromagnetic interference problems, and lower power consumption. To list a few relevant examples, differential feeding was utilized in improving the RF-to-DC conversion of a rectenna in [101]. In [102], it has been shown that a high isolation between closely packed antenna elements can be obtained by symmetrically placing a differential-mode (DM) antenna and a CM antenna together. The concept of a DM/CM antenna proposed in [102] is interesting for SWIPT with co-located antennas and could potentially be exploited to provide high isolation between antennas dedicated for WIT and WPT. For the above reasons, a detailed study on the application of glide symmetry to CM rejection filters has been conducted in Paper E of this thesis. It concludes that glide symmetry can conveniently improve the bandwidth and the level of CM rejection without affecting the DM operation or adding any extra manufacturing costs.

3.3.3 Fully-Planar Glide-Symmetric EBG Structure

The use of vias in mushrooms increases the manufacturing costs since drilling and conductor-filling is needed in addition to the potential need for a multilayer stack. Although DGSs are easier and cheaper to fabricate, some structures may still require a solid ground plane to avoid external interference.

Another alternative to the use of vias or defected grounds in realizing EBG structures in microstrip technology was presented in [103]. The work in [103] showed that the use of planar metallic patches in a high dielectric constant substrate can provide a bandgap operation and stop the surface wave propagation, and thus, could be used to reduce mutual coupling between patch antennas. Paper G investigates the application of glide symmetry to the structure presented in [103]. It also conducts a study on the different parameters affecting the bandgap properties of the glide-symmetric structure. The proposed fully-planar glide-symmetric EBG structure was shown to have a reduced size in addition to providing an increased level of isolation between the antennas when compared to its corresponding conventional version without glide symmetry. Such structure is indeed interesting for usage in a practical SWIPT antenna.

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Part II

Included Papers