Extending Wireless Powered Communication Networks for Future Internet of Things

by

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A thesis submitted in fulfilment of the requirements for the degree of Master of Philosophy

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Declaration

This is to certify that to the best of my knowledge and belief, all material presented in this thesis is the original work of the author, unless otherwise stated. The content of this thesis has not been previously submitted as a part of any academic qualification to any other university or institution.

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Parisa Ramezani

February 2017
To my beloved parents and my lovely brother
Acknowledgment

Foremost, I would like to express my deepest gratitude to my supervisor, Professor Abbas Jamalipour for accepting me into the MPhil program and giving me the honor of being one of his research students. Prof. Jamalipour’s guidance, patience, and continuous support were essential to the completion of this thesis and to my formation as a researcher. His unmatched knowledge and invaluable feedback immensely helped me go forward in my research. I am greatly indebted to him for helping me get through the difficult times I had during my MPhil. I feel very lucky to have worked with Prof. Jamalipour without whom this thesis would have only been a dream.

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Abstract

Energy limitation has always been a major concern for long-term operation of wireless networks. Traditionally, this problem has been dealt with by designing energy conservation methods for minimizing energy consumption of devices. Although these energy minimization techniques provide devices and networks with extended lifespans, the original problem of energy scarcity remains unsolved and the network performance is also compromised due to the prudent use of energy. Moreover, devices ultimately end up being battery-depleted because energy-conservative techniques are only able to postpone the unavoidable battery exhaustion. In such a case, battery recharging or replacement is deemed a possible solution, though inconvenient in most situations. With today’s exponential growth of wireless technologies and the rapid movement towards the so-called Internet of Things (IoT), the need for a reliable energy supply is more tangible than ever. Recently, energy collection from the surrounding environment has gained considerable attention in research communities. This technique, which is called energy harvesting, is a sustainable solution for prolonging the lifetime of wireless networks. Besides conventional energy harvesting sources such as solar, wind, vibration, etc. harvesting energy from radio frequency (RF) signals has drawn significant research interest in recent years as a promising way to overcome the energy bottleneck. RF-enabled wireless energy transfer (WET) is a controllable, stable, and low-cost method for charging wireless devices. Lately, the integration of WET with wireless communication networks has led to the emergence of an interesting research area, namely, wireless powered communication network (WPCN), where network users are powered by a hybrid access point (HAP) which transfers wireless energy to the users in addition to serving the functionalities of a conventional access point. During the last couple of years, WPCN has been one of the most attractive topics of research in the field of wireless communications and this newly-
emerged paradigm is anticipated to play a major role in the upcoming IoT. The main contributions of this thesis can be summarized as follows:

- The baseline model of WPCN is extended to a dual-hop WPCN (DH-WPCN) in which a number of energy-limited relays are in charge of assisting the information exchange between energy-stable users and the HAP. The HAP acts as the energy source for the relays who do not have any stable energy supply and obtain their required energy from RF transmissions of the HAP.

- The existing research in the area of WPCN has overlooked the importance of downlink information exchange and has merely focused on designing methods and protocols for uplink communication. However, in any wireless communication network, downlink communication is a necessary part of the network operation, where the access point transmits information to the network users. WPCN is no exception. Considering this fact, this thesis studies both uplink and downlink information transmission in the DH-WPCN. In downlink communication, the concept of simultaneous wireless information and power transfer (SWIPT) is utilized in order to enable energy-constrained relays to take advantage of the HAP’s transmitted information signal for harvesting their needed energy. Sum-throughput maximization problems in both uplink and downlink directions are investigated and algorithms for optimizing the values of the related parameters are proposed.

- The presented sum-throughput maximization schemes ignore the throughput of individual users, focusing on optimizing the total throughput of the DH-WPCN. Specifically, in uplink communication, some of the users experience acute unfairness in terms of throughput because their corresponding relays are located far away from the HAP. This fairness issue in uplink communication is tackled
by devising a fairness enhancement method which ensures equal throughput for all users in the DH-WPCN and at the same time optimizes the uplink sum-throughput.

Extensive simulations endorse the effectiveness of our sum-throughput maximization algorithms for achieving the best possible uplink and downlink throughput. The capability of the presented fairness-improving mechanism in assuring the highest level of fairness is also affirmed through numerical results.
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## Glossary

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<td>AF</td>
<td>Amplify-and-Forward</td>
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<tr>
<td>AP</td>
<td>Access Point</td>
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<td>DH-WPCN</td>
<td>Dual-hop Wireless Powered Communication Network</td>
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<td>CSI</td>
<td>Channel State Information</td>
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<td>EH</td>
<td>Energy Harvesting</td>
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<td>EM</td>
<td>Electromagnetic</td>
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<td>ET</td>
<td>Energy Transmitter</td>
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<td>FD</td>
<td>Full-duplex</td>
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<td>HAP</td>
<td>Hybrid Access Point</td>
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<td>HD</td>
<td>Half-duplex</td>
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<td>ID</td>
<td>Information Decoding</td>
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<tr>
<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>MIMO</td>
<td>multiple-input multiple-output</td>
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<tr>
<td>MISO</td>
<td>multiple-input single-output</td>
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<tr>
<td>PS</td>
<td>Power Splitting</td>
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<td>PR</td>
<td>Primary Receiver</td>
</tr>
<tr>
<td>PT</td>
<td>Primary Transmitter</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<td>SBS</td>
<td>Secondary Base Station</td>
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<tr>
<td>SDMA</td>
<td>Space Division Multiple Access</td>
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<tr>
<td>SI</td>
<td>Self-interference</td>
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<td>SIC</td>
<td>Self-interference Cancellation</td>
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<td>Acronym</td>
<td>Description</td>
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<tr>
<td>SISO</td>
<td>single-input single-output</td>
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<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
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<tr>
<td>SU</td>
<td>Secondary User</td>
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<td>SWIPT</td>
<td>Simultaneous Wireless Information and Power Transfer</td>
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<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<td>TS</td>
<td>Time Switching</td>
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<tr>
<td>WET</td>
<td>Wireless Energy Transfer</td>
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<tr>
<td>WIT</td>
<td>Wireless Information Transmission</td>
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<td>WPCN</td>
<td>Wireless Powered Communication Network</td>
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<td>WPT</td>
<td>Wireless Power Transfer</td>
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<td>WSN</td>
<td>Wireless Sensor Network</td>
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Chapter 1

Introduction

This chapter briefly describes the background of the research and discusses the motivations for conducting this work. Followed by research motivations, the objectives of the research are stated along with a summary of the thesis contributions. Finally, the structure of the thesis is explained at the end of the chapter.

1.1 Internet of Things

With the ever-increasing speed of technological advances, more and more objects are being connected to the internet every day and the world is moving towards the next generation of the Internet: the so-called Internet of Things (IoT).

Different definitions of the IoT exist in the literature [1]. IEEE defines IoT as a “A network of items, each embedded with sensors, which are connected to the Internet.” A more detailed definition of IoT is provided by Uckelmann et al. in the book “Architecting the Internet of Things”:

“The future Internet of Things links uniquely identifiable things to their virtual representations in the Internet containing or linking to additional information on their identity, status, location or any other business, social or privately relevant information.”
tion at a financial or non-financial pay-off that exceeds the efforts of information provisioning and offers information access to non-predefined participants. The provided accurate and appropriate information may be accessed in the right quantity and condition, at the right time and place at the right price. The Internet of Things is not synonymous with ubiquitous/pervasive computing, the Internet Protocol (IP), communication technology, embedded devices, its applications, the Internet of People or the Intranet/Extranet of Things, yet it combines aspects and technologies of all of these approaches.

Although numerous definitions of IoT exist in the literature, there is a common understanding in the research community about this concept and its high potential to change the world. IoT links the objects of the real world with the virtual world, thus enabling anytime, anyplace connectivity for anything and not only for anyone. It refers to a world where physical objects and beings, as well as virtual data and environments, all interact with each other in the same space and time [2]. An IoT object is not an ordinary object, but a smart one capable of more than just its functional specification. It can receive inputs from the world and transform those into data which are sent onto the Internet for collection and processing. It can also produce outputs into the world some of which could be triggered by data that have been collected and processed on the Internet [3]. IoT enables physical objects to see, hear, think and perform jobs by having them “talk” together, to share information and to coordinate decisions [4]. Through the use of intelligent decision-making algorithms in software applications, objects can respond appropriately to physical phenomena, based on the very latest information collected about physical entities and taking into account the patterns in the historical data, either for the same entity or for similar entities [2]. It is worth mentioning that IoT objects must be able to perform all of these tasks autonomously, i.e., without any human involvement. They should be able
IoT opens opportunities for the development of a wide range of application domains which include but are not limited to smart cities, e-health, logistics, and transportation. Figure 1.1 shows some of the application domains of IoT.

With its innumerable application scenarios, IoT is expected to improve the quality of life, create new markets, and bring huge profits for businesses. However, realizing IoT in a large scale is not an easy task and numerous challenges need to be overcome before this concept is widely accepted. Lack of standardization, privacy issues, and security concerns are among the most important challenges IoT needs to deal with. Energy scarcity issue is another challenge that has to be surmounted for an effective
and widespread adoption of the IoT paradigm. During the last two decades, extensive research has been done for designing methods and protocols for conserving as much energy as possible in order to postpone the inevitable battery depletion of wireless devices. Specifically, we have observed the trend of designing energy-efficient MAC and routing protocols for wireless sensor networks (WSNs) - key enablers of IoT - in order to keep the sensors operative for longer periods (refer to [6]-[11] for some well-known MAC and routing protocols of WSNs). However, the energy conservation methods proposed in the literature often trade off performance for lifetime extensions and make a compromise between quality of service and energy consumption. Even if we neglect this performance trade-off, the fact is that batteries will ultimately be depleted no matter how efficient the energy consumption is. As a consequence, battery recharging/ replacement will be required which may not always be a practical solution. For example, take a health-care application scenario where sensors are implemented inside the human body to continuously control and monitor health conditions or a structural monitoring application having sensors deployed inside the building structures. Even in scenarios where battery replacement is not that difficult, involving humans to keep the things operational contradicts one of the main objectives of IoT: operating without any human intervention. Negative environmental impacts caused by improper disposal of a large number of depleted batteries is another detriment which reinforces the tendency towards a greener solution for supplying the energy of future IoT objects.

1.2 RF Energy Harvesting

Recently, energy harvesting has received significant attention as an alternative solution for prolonging the lifetime of wireless devices. Energy harvesting is the process
of collecting energy from external sources and converting it into electricity which provides devices with theoretically perpetual lifespans.

Energy harvesting is not a new technique. Historically, people were interested in harnessing energy from their environment through windmills, waterwheels, and passive solar systems. Nowadays, with the rapid development of technology, the importance of energy harvesting is more obvious than ever and traditional energy conservation methods are losing their credibility because the energy needs are much wider than what energy-conservative techniques can afford.

Energy harvesting resolves the energy scarcity issue since the energy can be replenished whenever a shortage occurs. Besides, the elimination of the energy bottleneck contributes to network performance enhancement because the availability of energy relaxes the need for energy consumption minimization and helps network designers concentrate on improving the quality of service. Further, rechargeable batteries and supercapacitors employed for energy storage in harvesting-capable devices are more environmentally-friendly than disposable batteries. Energy harvesting is also a key step towards self-sustainable IoT networks as devices can manage their own energy replenishment process.

A variety of sources are available for energy harvesting. Solar [12], wind [13] [14], vibration [15], and thermal energy harvesting [16] are among the most popular energy scavenging techniques. Another energy harvesting method is RF energy harvesting in which radio frequency (RF) signals are deemed viable energy sources. RF energy harvesting provides key advantages over other energy collection methods due to its predictable and stable nature, low cost, and small form factor implementation [17][18]. RF energy harvesting is the process where the energy contained in radio frequency waves is collected and converted into usable electrical energy. RF waves are electromagnetic (EM) waves that originate at a transmitter in the form of a photon that
is oscillating within one of the pre-determined transmission frequency bands such as UHF, SHF, or VHF, etc. [19]. RF energy harvesting is one of the wireless charging techniques along with inductive coupling and magnetic resonant coupling. Inductive coupling and magnetic resonant coupling are near-field wireless energy transfer (WET) methods and are not suitable for mobile and remote charging due to their limited power transfer distance and low tolerance of misalignment between the transmitter and the receiver [17]. RF-enabled WET has a wider operating range because it exploits the far-field radiative properties of EM waves. What’s more, the broadcasting nature of EM waves enables RF energy transfer to multiple devices [20]. Due to the severe attenuation of RF power over distance, RF energy harvesting is more suitable for low-power devices, e.g., sensors. However, recent advances in antenna technologies and power electronics have made it possible to transfer significantly increased power to wireless devices, which are themselves getting more energy-efficient [21].

The fact that energy can be carried by the same RF signal that transports information has recently led to the emergence of an attractive research topic, namely, simultaneous wireless information and power transfer (SWIPT). The idea behind SWIPT is to power energy-constrained devices by the energy contained in an information signal. The energy harvester can be either the information receiver who uses the RF signal for the dual purpose of energy harvesting and information decoding or other ambient devices which treat the signal merely as an energy source. However, there exists a limitation for practical implementation of a receiver who intends to use the transmitter’s signal for both energy scavenging and information decoding because in reality, it is not possible to simultaneously harvest energy and decode information using the same signal. In light of this, some practical architectures have been proposed for a SWIPT receiver among which the power splitting (PS) receiver is one of the best-known de-
signs. A PS receiver splits the received signal into two streams; one stream with power ratio $\rho$ is used for energy harvesting and the other stream with power ratio $(1 - \rho)$ is utilized for information decoding. So far, SWIPT has attracted enormous research and been investigated in various channel setups, e.g., narrow-band noisy channel [22], frequency selective channel [23], multiple-access channel [24], multiple-input single-output (MISO) channel [25], multiple-input multiple-output (MIMO) channel [26], relay channel [27], etc.

Wireless powered communication network (WPCN) is another leading research category of RF energy harvesting, where network devices first harvest energy from the signals transmitted by RF energy sources and then utilize this harvested energy for their communication needs. Generally, any network consisting of devices wirelessly powered by RF energy transfer can be a WPCN; however, the focus of the recent research has been on a specific model of WPCN where an integrated energy transmitter (ET) and access point (AP) - called a hybrid access point (HAP) - is deployed which not only has the functionalities of a conventional access point but also serves energy-constrained devices by providing them with wireless energy. This model makes the energy/information transfer coordination easier and saves implementation costs by using communication and signal processing modules for two purposes [28].

SWIPT and WPCN are expected to play major roles in future IoT as they can alleviate the traditional energy scarcity issue and support low-cost and self-sustainable operation of wireless devices.

Figure 1.2 depicts a general schematic of an RF energy harvesting network consisting of HAP, ET, AP, and a number of energy-constrained users. The green lines indicate the RF energy flow from either the HAP or the ET to the energy-limited users, the red lines demonstrate the information flow, and the blue line corresponds to the simultaneous transfer of energy and information from the HAP to the user.
Figure 1.2: Schematic of an RF energy harvesting network

1.3 Research Motivations

WPCN is a newly-emerged area of research in RF energy harvesting domain. Specifically, the first paper considering a WPCN with a HAP responsible for energy and data coordination dates back to 2014 [29]. During the last two years, many researchers focused on improving the performance of these networks and proposing new network setups for WPCNs to make them applicable to future networks including IoT. Adding the full-duplex (FD) functionality to the HAP to support simultaneous energy transfer and information reception [30][31], equipping the HAP with multiple antennas to increase energy transfer efficiency and throughput [32]-[34], integrating WPCN with cognitive radio network [35][36], and extending WPCN to large-scale scenarios with multiple HAPs and a large number of users [37] are some of the outcomes of the substantial research lately conducted in this field.

Despite the works that have been done for enhancing and extending WPCNs, this area of research is still in the infancy stage and calls for more research to cater to the needs of future IoT networks. Particularly, most of the works in this area consider a specific WPCN setup with one or more HAPs transferring energy to a number of users and receiving information back from them. References [38] and [39] are two...
exceptions to this one-hop energy and information transfer model which incorporate a relaying approach, where information transmission of a user is assisted by either another user [38] or a relay [39]. However, these two models limit the network to a HAP and one [39] or two [38] users and do not consider a network with multiple users and relays. The importance of delivering information in multiple hops and lack of suitable solutions in this regard motivated us to propose a dual-hop WPCN formed by a number of users and a set of energy-constrained relays who assist the communication between the HAP and the users.

Furthermore, to the best of our knowledge, all the contributions in the field of WPCN only consider uplink information transmission, where the users transmit data to the access point; however, in practice, downlink communication constitutes a major part of the network operation with users getting data from the access point. This was our second motivation to further extend WPCN. Unlike the existing literature where the information transmission from the HAP to the users is neglected, we investigate both uplink (from users to the HAP) and downlink (from HAP to the users) information transmissions. In this respect, we exploit the concept of SWIPT in WPCN by letting relays use the RF signal of the HAP for both energy harvesting and information relaying in downlink communication.

1.4 Research Objectives and Methodologies

The objective of this research is to develop a dual-hop WPCN (DH-WPCN) by extending the baseline WPCN model [29] from one-hop energy and information transfer to one-hop energy and two-hop information transfer. To achieve this objective, we include cooperative communication within WPCN by adding a number of energy-constrained relays to the network, who are responsible for assisting the uplink and
downlink communication between the HAP and energy-stable users. We aim to maximize the network performance in terms of total uplink and downlink throughput. For this purpose, we formulate uplink and downlink sum-throughput maximization problems and solve them via analytical methods. To corroborate the analysis, the proposed algorithms are numerically evaluated through extensive simulations in MATLAB.

Learning from the behavior of our DH-WPCN model and the unfair nature of resource allocation in the presence of the HAP, especially in uplink communication, our next objective is to improve fairness in our proposed model by redesigning the resource allocation scheme in order to achieve the maximum level of fairness in the DH-WPCN in terms of individual users’ throughputs. To this end, we formulate a minimum throughput maximization problem and propose a framework for obtaining the optimal value of the related parameters. Simulations are conducted for numerical evaluation of the fairness-improving algorithm via which we compare the performance of the minimum throughput maximization approach with the sum-throughput maximization scheme.

It is also worth noting that we have chosen simulation over test-bed experiments for verifying the theoretical analysis because test-bed measurements fail to give us helpful observations about future large-scale deployment of WPCN models. For example, at this stage of time, the power harvesters available in the market have low sensitivities meaning that the power harvester must be very close to the power transmitter to effectively harvest energy. Such short-range experiments will not provide us with useful insights in understanding the behavior of DH-WPCN in future large-scale IoT networks. For this reason, we have resorted to analytical modeling and numerical simulations as our main research methodologies.
1.5 Thesis Contributions

Although RF energy harvesting has gained significant attention from academia and industry during the last few years, investigation in this area is still in the early stage and plentiful opportunities are ahead for future research in this field. In particular, the lately-emerged WPCN requires extensive efforts to seamlessly integrate into the IoT ecosystem. The main contribution of this thesis is to extend the baseline single-hop model of WPCN to a dual-hop scenario, where the cooperation of energy-limited relays enables the communication between energy-stable users and the HAP in both uplink and downlink directions. A brief summary of the contributions of this thesis is listed below.

- With its high potential to be incorporated into future IoT networks, WPCN needs to be extended to different network setups to embrace various IoT demands. Considering the large dimension of IoT, multi-hop communication will definitely be needed in IoT networks. However, the research carried out in the field of WPCN has mostly concentrated on single-hop communication and paid little attention to data transmission via multiple hops. In this thesis, we propose a DH-WPCN composing of a HAP and a number of energy-stable users with a dedicated energy-constrained relay for each user which is responsible for assisting the communication between its corresponding user and the HAP. The relays have no embedded energy supply and rely on the HAP as an energy source for harvesting the energy they need to perform their information forwarding tasks.

- Downlink information exchange between the access point and the users plays a dominant role in the flawless operation of many wireless networks. Specifically, the control messages sent by the access point are vital for proper functioning of the networks as they contain important scheduling, resource allocation,
synchronization, topology maintenance, etc. information. Nevertheless, the existing works have ignored downlink communication in WPCN and have focused their attention on data transmission from the users to the HAP. In light of this, we investigate both uplink and downlink communication in our proposed DH-WPCN. Particularly, we take advantage of the concept of SWIPT in downlink communication, where the relays harvest their required energy from the information signal of the HAP using a PS strategy. The integration of these two currently hot research topics (i.e., WPCN and SWIPT) is a novel approach which has not been studied before.

- We formulate uplink and downlink sum-throughput maximization problems and investigate the optimal time allocation for energy and information transfer in both uplink and downlink communications as well as optimal power splitting ratios for the relays in downlink communication. To elaborate more, we exploit the convexity of the uplink throughput maximization problem and optimize time durations assigned for energy transfer and information transmission. For the non-convex downlink throughput maximization problem, an iterative approach is adopted to find the near-optimal value of the parameters. We iteratively optimize time-slot durations and power splitting ratios until a satisfactory convergence is achieved.

Through numerical analysis, we compare the optimal uplink and downlink throughputs and discuss their behavior. Numerical results also confirm the importance of optimizing time allocations and power splitting ratios for achieving higher uplink and downlink sum-throughputs. Our simulations disclose a severe fairness problem in uplink throughput allocation resulting from unequal distance of the relays from the HAP.

- We propose a fairness enhancement scheme to tackle the aforementioned fairness
issue. We consider the problem of maximizing the minimum throughput among users in order to guarantee throughput fairness for the users and yet maximize the total throughput. Our findings show that there exists a trade-off between sum-throughput and fairness and the improved fairness comes at the expense of a reduction in total throughput. Therefore, the optimal strategy can be chosen based on network requirements. The proposed fairness enhancement method retains the highest fairness level with increasing the number of users which makes it a proper choice for applications that require equal throughput allocation to all users. On the other hand, the sum-throughput maximization approach is inconsiderate of individual users’ throughputs but is an appropriate strategy in scenarios where the total throughput of the network is deemed the most important metric.

We expect this research to be a motive for further WPCN extensions and the establishment of more sophisticated WPCN network models for stepping towards the impeccable operation of WPCN in the IoT environment.

1.6 Thesis Organization

This Thesis is organized as follows:

Chapter 1 introduces the Internet of Things and discusses the necessity of energy harvesting for successful implementation of IoT systems with a focus on RF energy harvesting which has recently attracted the attention of research community due to its clear advantages over other energy harvesting techniques. The main research topics in RF energy harvesting domain are then presented and the motivations behind this research work are also discussed. Finally, the objectives of this work as well as the contributions of the thesis are provided.
Chapter 2 provides a background on WET techniques with a detailed discussion on RF-enabled WET. A comprehensive survey of the recent research in the areas of SWIPT and WPCN is presented. This chapter also identifies some of the limitations of the existing WPCNs which have worked as our main motivations to carry out this work.

Chapter 3 proposes a new WPCN model referred to as DH-WPCN. Frame structures for uplink and downlink communications in the proposed model are presented and sum-throughput maximization problems in both directions are investigated. By finding the optimal parameters in both uplink and downlink communications, the throughput performance of the system is analyzed via numerical simulations. Numerical results of this chapter reveal a fairness problem in the proposed DH-WPCN leading to severely unfair throughput allocation among network users.

Chapter 4 deals with the above-mentioned fairness problem and proposes a fairness enhancement algorithm for equal throughput allocation in the network. The trade-off between sum-throughput and fairness in the DH-WPCN is investigated through simulations.

Chapter 5 summarizes the findings of this thesis and outlines some potential research directions for future advancements of WPCNs. This chapter also inspects WPCN from the IoT perspective and introduces some of the issues that need to be considered for the wide adoption of WPCN into IoT.

1.7 Chapter Summary

This chapter has reviewed the background of the research by presenting the concept of IoT and the critical need for green and sustainable solutions for powering IoT devices. Followed by this, RF energy harvesting is introduced as a conceivable option for
supplying the required energy of wireless devices and the recent research contributions in this area are briefly discussed. The motivations for conducting this research work are pointed out and the research goals and outcomes are also presented. A chapter-wise outline of the thesis is provided at the end of the chapter.
Chapter 2

Background and Research Trends

This chapter begins with introducing the concept of wireless energy (or power) transfer with a discussion on the historical breakthroughs in this field and the technologies used for charging devices wirelessly, especially the RF energy transfer technique which has been identified as a viable energy replenishment method for controllable and predictable energy transfer to remote areas. Followed by this, a detailed summary of the research conducted in the fields of SWIPT and WPCN - two popular research topics in the RF energy harvesting domain - is presented. We close this chapter by introducing some of the gaps that need to be filled for enabling practical implementation of WPCNs.

2.1 Wireless Energy Transfer

The initial work on wireless power transfer (WPT) dates back to more than a century ago [40][41], when Nikola Tesla used the microwave technology to do experiments on WPT and demonstrated the transmission of wireless power over a distance of 48 km. He then lit up a bank of 200 light bulbs and ran one electric motor by transmitting 100 million volts of electric power wirelessly over a distance of 26 miles. He also
achieved another breakthrough by inventing the “Tesla coil” which produces high-frequency and high-voltage alternating currents and constructing the “Tesla tower” as a wireless transmission station for electrical energy transfer through the Ionosphere. After Tesla, the contributions in the WPT field were limited until William C. Brown successfully converted microwave energy to DC power via a rectenna in 1960s and powered a model helicopter completely through microwave power transfer [42]. In 1975, he beamed 30 kW microwave power over a distance of 1 mile, achieving an efficiency of 84% [43].

Despite the early efforts on wireless power transmission, serious steps toward the widespread realization of this technique were not taken until recently when the rapid advances of electronic devices and the need for on-demand and cable-free energy transmission motivated the research community and the industry to pay earnest attention to the development and commercialization of wireless energy transfer techniques. Generally, WET can be in the form of inductive coupling [44], magnetic resonant coupling [45], or RF-enabled WET. The former two are near-field wireless charging technologies, where the generated electromagnetic field dominates the region close to the transmitter or scattering object and the power is attenuated according to the cube of the reciprocal of the charging distance [46]. In contrast, RF-enabled WET is a far-field charging technology used for transferring wireless energy over long ranges, in which the power decreases with the square of the reciprocal of the charging distance. Inductive coupling refers to the energy transfer from one coil to another as a result of the mutual inductance between the two coils. It occurs when an alternating current in the transmitter coil generates a magnetic field across the terminals of the receiver coil. This magnetic field induces voltage in the receiver coil which can be used for powering devices. This technique is very efficient when the magnetic coupling between the two coils is large enough, i.e., when the transmitter and the receiver coils
are close to each other. Magnetic resonant coupling uses the principle of resonance for increasing the energy transfer range and efficiency. Indeed, if the two coils are tuned at the same resonant frequency, they can exchange energy with greater efficiency at a longer operating distance compared to inductive coupling [47]. However, charging distance with magnetic resonant coupling is still limited to a few meters which makes it inapplicable for mobile and remote charging.

In RF energy transfer, radio signals with frequency range from 3 kHz to 300 GHz are used as a medium to carry energy in the form of electromagnetic radiation [48]. Compared to inductive coupling and magnetic resonant coupling, RF-enabled WET can operate in longer ranges thanks to radiative properties of EM waves. The harvested RF power in the free space can be calculated using the Friis equation [49] as follows:

\[ P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi d)^2}, \]

where \( P_R \) is the received power, \( P_T \) is the transmitted power, \( G_T \) is the transmit antenna gain, \( G_R \) is the receive antenna gain, \( \lambda \) is the wavelength used, and \( d \) is the distance between the transmit antenna and the receive antenna.

Figure 2.1 shows the block diagram of an RF energy harvesting system. The antenna collects RF signals from available RF sources. The matching circuit is used to ensure that the maximum RF power is delivered to the rectifier. The rectifier converts RF power to DC power and finally the DC power is stored in the energy storage which can be either a rechargeable battery or a supercapacitor. The efficiency of the RF energy harvester depends on the efficiency of the antenna, the accuracy of the matching circuit between the antenna and the rectifier, and the efficiency of the rectifier that converts the received RF signals to DC voltage [17].

RF energy harvesting sources can be classified into two categories [50]: ambient RF sources and dedicated RF sources. Ambient RF sources are not intended for RF
energy transfer and are freely available in the environment [51][52]. TV and radio towers, Wifi access points, mobile phones, and mobile base stations are some of the ambient RF energy sources available around us. As another example, in a cognitive radio network, secondary users (SUs) can take advantage of the primary users’ transmissions as an ambient RF source to harvest their required energy [53][54]. On the other hand, dedicated RF sources are specifically intended for on-demand RF energy transfer and are more suitable for applications with quality of service (QoS) constraints due to their high power density and controllable behavior. The TX91501 Powercaster transmitter is an example of a dedicated RF energy source which broadcasts radio waves in the unlicensed 915 MHz ISM band [55].

With this brief background on WET techniques, we are now ready to review two prominent topics of research in this area which constitute the basis of our work.
2.2 Simultaneous Wireless Information and Power Transfer

Simultaneous wireless information and power transfer (SWIPT) is a spectrum-efficient method for powering energy-constrained devices, where instead of occupying the spectrum for separate energy and information transfer, the same radio frequency signal is utilized for both energy harvesting (EH) and information decoding (ID). This objective is achievable because any information-carrying signal also contains energy which can be harvested by either the information receiver who exploits the received RF signal for both EH and ID or ambient devices who use the RF signal only for collecting their needed energy. However, a practical limitation exists for implementing a SWIPT receiver who wants to utilize the same RF signal for both purposes because the energy harvesting operation performed in the RF domain destroys the information content [56]. For this reason, some practical SWIPT receiver architectures have been proposed in the literature which will be reviewed later in this section.

The idea of transmitting energy and information simultaneously was first introduced in [22] for noisy single-input single-output (SISO) channels. The author proposed a capacity-energy function to characterize the trade-off between energy and information transmission rates. This work has been extended to frequency-selective channels and multiple-access channels in [23] and [24], respectively. These early studies have assumed an ideal SWIPT receiver implementation in which both information and energy can be extracted from the same radio frequency signal at the same time.

Reference [26] addressed the practical constraint of a SWIPT receiver for simultaneous EH and ID from the same RF signal. Indeed, any information embedded in the received signals sent to the EH circuit is lost during the EH process. Accordingly, two practical receiver implementations have been proposed in [26], namely, time switching
Figure 2.2: Practical receiver designs for energy harvesting and information decoding [26] (TS) receiver and power splitting (PS) receiver depicted in Figure 2.2(a) and Figure 2.2(b), respectively.

In a TS receiver, time is divided into two orthogonal time-slots and the receiver periodically switches between EH and ID. In this receiver setup, the transmitter can optimize the waveforms for EH and ID in the corresponding time-slots because there is a fundamental difference in the optimal waveforms for information and energy transmissions [20]. A PS receiver differs from a TS one in that both EH and ID are performed at the same time. To achieve this, the received signal power is split into two streams with power ratios $\rho$ and $1 - \rho$ to be fed into the energy harvester and the information decoder, respectively. Different rate-energy trade-offs can be obtained by changing the time-slot durations in the TS architecture and the power splitting ratio in the PS receiver.

In [57], the SWIPT receiver setups proposed in [26] have been generalized to a dynamic power splitting design in which the received signal is dynamically split into two streams with adjustable power ratio for energy harvesting and information decoding. The authors also proposed two receiver architectures, namely, separated and integrated information and energy receivers. A separated receiver splits the received signal in the RF band and transfers the two streams to the conventional energy receiver and information receiver for harvesting energy and decoding information, re-
spectively. In the integrated architecture, the RF-to-baseband converter is replaced by a passive rectifier. Here, the signal is split after being converted to the DC current. The authors characterized rate-energy (R-E) trade-offs for both receivers taking into account the circuit power consumption.

Xiang and Tao considered a three node MISO system in [25] with one multi-antenna transmitter, one single-antenna energy receiver, and one single-antenna information receiver. Assuming that the transmitter only has imperfect knowledge of the channels, they studied the robust beamforming problem for maximizing the harvested energy of the energy receiver while guaranteeing a specific target rate for the information receiver.

Reference [27] integrated SWIPT with relaying networks and proposed two relaying protocols based on TS and PS receiver architectures. The authors considered a three-node amplify-and-forward (AF) relaying network with a source-destination pair and a relay in between, assuming that there is no direct link between the source and the destination. The energy-constrained relay node uses the signal transmitted by the source node for both energy harvesting and information relaying. The relay applies either the TS or the PS approach in order to harvest energy from the source’s RF signal and forward the contained information to the destination using its harvested energy. The throughput performance of the proposed protocols has been analyzed in both delay-limited and delay-tolerant transmission modes. Their study revealed that in such a cooperative setup, locating the relay node closer to the source results in higher throughput.

Lee et al. extended the work in [27] by considering the presence of a direct link between the source and the destination [58]. The outage probability of the system and the power-splitting factor at the relay have been found in closed form. According to their results, the cooperative scheme with direct link shows superior performance to
both the non-cooperative approach (i.e., absence of the relay) and the cooperative approach without a direct link between the source and the destination.

In [59], a framework was developed for realizing SWIPT in broadband wireless systems. Utilizing OFDM, the broadband channel has been divided into orthogonal sub-channels with all sub-channels assigned to one user in a single-user system and a single sub-channel assigned to each of the users in a multi-user setup. This frequency diversity is shown to help improve the efficiency of SWIPT.

Reference [60] considered a large-scale network with multiple transmitter-receiver pairs. The author studied non-cooperative and cooperative schemes where the former consists of a random number of energy-stable transmitters and energy-constrained receivers and the latter also includes a random number of energy-stable relays which assist the energy and information transfer. The receivers employ the PS technique for collecting their needed energy. The fundamental trade-off between the outage probability and the harvested energy has been investigated in both scenarios.

Reference [61] pointed out the disadvantages of TS and PS methods and proposed an antenna switching (AS) technique for SWIPT. According to [61], the main drawback of TS is that dedicated time slots should be used for energy harvesting which leads to a non-continuous transmission of data. What’s more, TS techniques require strict synchronization as any timing inaccuracy may result in loss of information. On the other hand, PS suffers from additional complexity and cost since it requires ideal power splitting circuits. For these reasons, a low-complexity AS SWIPT protocol has been proposed for MIMO relay channels based on the principles of generalized selection combiner.

A practical scenario for SWIPT has been presented in [62], where a multi-antenna AP transmits information and energy to a single-antenna user. To model a realistic system, the authors assume imperfect channel state information (CSI) at the AP,
presence of penalties in CSI acquisition, and non-zero power consumption for the receiver in CSI estimation and signal decoding procedures. Three cases have been studied and analyzed: a) no CSI at the AP, b) imperfect CSI obtained by means of pilot estimation, and c) imperfect CSI obtained by means of analog symbols feedback. Their findings revealed that availability of CSI knowledge at the AP is always helpful although some resources are used in the channel estimation procedure and the resulting information is not perfect.

Reference [63] investigated SWIPT in a cognitive radio network, where a number of energy-limited SUs receive both energy and information from a secondary base station (SBS). The objective is to minimize the transmit power of the SBS by joint optimization of the transmit beamforming vector at the SBS and power-splitting ratios at the SUs such that EH and QoS constraints of each SU are met while the interference level to the primary network is also kept below a threshold.

### 2.3 Wireless Powered Communication Network

A wireless powered communication network (WPCN) basically consists of a hybrid access point (HAP) and a number of energy harvesting users which rely on RF energy transmission of the HAP to scavenge the needed energy for their communication. An example model is depicted in Figure 2.3, where the HAP and the users are equipped with a single antenna each and operate in the half-duplex (HD) mode meaning that they cannot perform transmission and reception at the same time. A harvest-then-transmit protocol has been proposed in [29] which divides the frame into a wireless energy transfer (WET) and a wireless information transmission (WIT) phase as plotted in Figure 2.4. In the first $\tau_0$ fraction of time, the HAP broadcasts an energy signal to the users in the downlink. The users store the energy harvested during the
Figure 2.3: A wireless powered communication network [29]

WET phase in a rechargeable battery and transmit their information to the HAP in the uplink by time division multiple access (TDMA) utilizing their harvested energy.

The time duration allocated for WET and WIT play an important part in the overall network performance. A greater $\tau_0$ results in more harvested energy for the users leading to a higher throughput accordingly; however, as more time is dedicated for energy transfer, less time will be remained for information transmission of the users which subsequently degrades the throughput. Hence, there should be an optimal $\tau_0$ which maximizes the uplink throughput. This optimal value depends on the channel conditions between the HAP and the users. According to [29], as uplink and downlink channel power gains become larger, the optimal policy is to allot more time for WIT instead of WET. That’s because when the downlink channel gets better, users can
harvest sufficient energy in shorter times while in good uplink channel conditions, the users need less power to achieve the same throughput performance, both of which help reduce the energy transfer duration and save time for information transmission. Furthermore, the allocated information transmission time to each user also affects the sum-throughput. Generally, the users who can contribute to the total throughput of the network more than the others get a larger transmission time. As a consequence, the time assigned for each user’s data transmission is coupled with its uplink and downlink channel power gains which results in unbalanced time allocation among the users due to the so-called doubly near-far problem.

The doubly near-far problem stems from unequal distance of different users from the HAP. In a WPCN, users far away from the HAP receive less amount of wireless energy than near users in the WET phase, but need to transmit with greater power in the WIT phase. To achieve the best possible throughput performance for the entire network, the optimal design is to allocate a small amount of time to the far users and leave more transmission time for the users with better channel conditions. Such a strategy sacrifices the far users’ throughputs for the sake of total throughput maximization and induces serious unfairness among WPCN users. To tackle the doubly near-far problem, the authors of [29] solved a common-throughput maximization problem which provides all users with equal throughput by allotting more data trans-
mission time to further users.

The work in [29] was extended in [30] for improving energy harvesting of the users. In this work, employing an FD HAP has been proposed which is able to perform energy transfer and data reception simultaneously on the same frequency, allowing time and spectrum resources to be used more efficiently as compared to the HD scenario. The FD HAP transfers energy signals in all time-slots of the frame and at the same time, receives information from the users who transmit to the HAP by TDMA. In [30], each user can harvest energy in all the time-slots other than the one in which it is transmitting information to the HAP, so, the amount of the harvested energy of the users is substantially increased. Another pioneering work in using FD HAP is [31] which takes energy causality into account by letting users harvest energy only until their allocated information transmission slot.

The performance gain achieved by FD operation mode relies heavily on the ability of the HAP to perform self-interference cancellation (SIC), because the transmitted energy signal can severely affect the information signal of the users received by the HAP as the power of the energy signal overrides that of the attenuated information signal. The achievable throughput thus depends on the extent to which the self-interference (SI) can be cancelled. Reliable SIC techniques are needed to ensure the effect of the SI is significantly reduced. So far, a number of methods for self-interference cancellation have been proposed which can be classified into propagation-domain, analog-circuit-domain and digital-domain approaches [64]. A combination of the aforementioned techniques can considerably reduce the amount of SI; though at the expense of increased complexity. As reported in [30], FD WPCN outperforms the HD counterpart in terms of the overall throughput when SI can be effectively cancelled.

FD operation is also possible at the user side [65]. FD users can transmit information and harvest energy at the same time which results in increased harvested energy for
them. Here, there is no need for SIC and the user can treat its own transmitted signal as a viable source for energy harvesting.

When a single-antenna HAP transmits energy in an omnidirectional manner, the severe signal power loss over distance leaves only a limited amount of harvestable energy for the users. For this reason, exploiting multi-antenna HAP has been proposed to improve the RF energy transfer efficiency [32]-[34]. When the HAP is equipped with multiple antennas, energy beamforming can be employed to design the phase and amplitude of the energy signal at each antenna in a way that the combined energy transfer performance is optimized. Not only the harvested energy of the users would be increased by this technique, but the higher efficiency of energy transfer also enables faster charging of devices [50], leaving more time for data transmission. What’s more, multi-antenna HAP makes it possible for multiple users to transmit information in the uplink simultaneously using space division multiple access (SDMA) which substantially increases the throughput. [34] studied the sum-throughput maximization problem in the multi-antenna WPCN and found optimal energy beamforming, receive beamforming, and time-slot allocations. Similar to the baseline single-antenna WPCN, the sum-throughput maximization problem sacrifices some of the users’ throughputs, so, the total throughput of the network is maximized at the cost of low fairness arising from the doubly near-far problem. To overcome this problem and ensure fairness, references [32] and [33] optimized time and energy allocations plus beamforming vectors to maximize the minimum throughput among users under the perfect and imperfect CSI assumptions, respectively.

A large-scale WPCN has been studied in [37] in which multiple HAPs are responsible for energy/information transmission coordination to/from a large number of users. The large-scale WPCN is modeled based on homogeneous Poisson Point Processes and a scalable energy/information transfer scheme is devised to serve the large num-
ber of network users. The harvest-then-transmit protocol proposed in this work is slightly different from the one in [29] with $T$ being the total number of time-slots for energy and information transmission and $N$ ($1 \leq N \leq T - 1$) slots devoted to energy transfer from the HAPs to the users. Each user randomly picks a slot from the $T - N$ time-slots dedicated for information transfer and transmits its data to the nearest HAP. The objective is to find the optimal transmit power of the users plus the optimal number of energy transfer slots ($N$) using stochastic geometry tools in order to maximize the spatial throughput defined as sum of the throughputs of all users normalized by the network area. As reported in [37], increasing the number of users per network area results in greater maximum achievable spatial throughput; however, more HAPs are needed to be deployed to achieve the maximum throughput due to the increased interference level caused by the dense deployment of the users.

References [35] and [36] investigated the integration of WPCN with cognitive radio networks and presented cooperation strategies such that WPCN as the secondary network helps the primary network by relaying the primary transmitter (PT)’s data to the primary receiver (PR). Assuming that PT’s message is made known to the HAP, [35] proposed to incorporate the cooperation in the WET phase. The HAP cooperatively sends PT’s data to the PR using its WET signal. Higher transmit power is a bonus given to the HAP for this cooperation. Optimal time and power allocations for WET and WIT phases have been found for maximizing the WPCN sum-throughput under a primary rate constraint. Non-cooperative cognitive WPCN has also been studied in [35] in which the secondary network does not assist the primary communication, but keeps the interference level at the primary side below a certain threshold. The cooperative scheme is shown to outperform the non-cooperative approach in terms of both the primary achievable rate and the secondary sum-throughput. [36] proposed another cooperation strategy, where the WPCN users are responsible for
relaying PT’s data. As a result of this cooperation, spectrum access is awarded to
the secondary network on the condition that the target primary rate is met. Here,
it is important to find the optimal set of relaying users, the amount of energy they
must allocate for relaying, and the time duration dedicated to each user’s data trans-
mission. In this scheme, the secondary network throughput highly depends on the
target primary rate. A greater target rate makes WPCN users to spend more time
and energy on relaying which leaves shorter time and less energy for their own trans-
missions resulting in secondary throughput reduction.

In [66], Wu et al. studied a different WPCN setup, where instead of a HAP re-
sponsible for both energy and information coordination, ET and AP are used. This
system model can eliminate the doubly near-far problem as a user which is far from
the access point may be near to the energy transmitter (or vice versa), so, the severe
signal attenuation in uplink information transmission can be made up by better har-
esting conditions in the downlink (or less harvested energy in the downlink can be
made up by good uplink channel conditions). However, using separate AP and ET
makes the energy/information transfer coordination more difficult and also adds to
the production and operation costs [28]. Assuming an initial energy for each user and
also the capability of storing the harvested energy for future use, the authors of [66]
jointly optimized time allocation and power to maximize the energy efficiency of the
proposed system.

Despite all the efforts made to enhance and extend the newly-emerged WPCNs, most
of the works in this area are limited to single-hop communication between the HAP
(or AP) and the users. [38] and [39] are two exceptions to this single-hop model
which exploit a relaying approach by letting the information transmission of a user
be assisted by either another user [38] or a relay [39]. In [38], a two-user WPCN
has been considered where the nearer user to the HAP which has better channel
conditions dedicates a portion of its allocated time and harvested energy to relay the other user’s data. [39] presented a wireless powered cooperative communication network consisting of a HAP, a source, and a relay which operate under the proposed harvest-then-cooperate protocol. The source and the relay harvest energy from the HAP during the downlink energy transfer phase and cooperatively transmit the source’s data to the HAP in the uplink. Although these two network models can provide insights for implementing cooperative communication in WPCNs, they limit the network to a HAP and one [39] or two [38] users and do not consider a network where multiple users need to communicate with the HAP. Considering the increasing number of network users and the large dimension of IoT, WPCN with only one or two users is an over-simplified and unrealistic scenario. Hence, cooperative and multi-hop communication in WPCN need much more investigation to satisfy practical implementation needs.

Moreover, even though remarkable research has been conducted in the fields of SWIPT and WPCN during the last few years (as reviewed in the previous section and this section, respectively), integrating these two interesting research topics has not yet been considered, mainly because the downlink communication (information transmission from the HAP to the users) in WPCN has been overlooked so far. However, downlink communication is an inevitable part of wireless communication networks and the information transmission from the HAP to the users is worthy of investigation.

2.4 Chapter Summary

This chapter has provided a survey on WET by looking into the history of the research in this area and presenting the different techniques used for transferring wireless energy. The two most active research topics in this area, namely, SWIPT and WPCN
are introduced and the recent attempts and contributions made in these two newly-emerged fields are also discussed. The chapter ends with a brief discussion on some of the shortcomings in the existing literature on WPCNs addressing which will be our main objective in the following chapters.
Chapter 3

Dual-hop Wireless Powered Communication Network

This chapter studies a dual-hop wireless powered communication network (DH-WPCN), where the communication between a HAP and a number of users is assisted by energy-constrained relays who need to harvest energy from radio frequency signals broadcast by the HAP. Before uplink (UL) information transmission, the HAP broadcasts a downlink (DL) energy signal to all relays. Each relay harvests energy from this signal and utilizes the harvested energy in forwarding its corresponding user’s data to the HAP. A time slot is allocated to each user-relay pair half of which is dedicated to user-to-relay information transmission and the other half is used by the relay to forward the user’s data to the HAP with an AF relaying approach. In downlink communication, the relays take advantage of SWIPT to harvest their required energy from the information signal broadcast by the HAP. Each relay employs a power splitting method such that a proportion of the received signal power is utilized for energy harvesting and the signal with the remaining amount of the initial power is amplified and forwarded to the corresponding user in the allocated time slot. Under this setup,
we are interested in maximizing the total uplink and downlink throughput. First, an algorithm is proposed for solving the uplink throughput maximization problem which exploits the convexity of the problem to optimize time allocations for energy and information transfer. For the non-convex downlink throughput maximization problem, a near-optimal solution is obtained by optimizing time allocations and power splitting ratios iteratively. Finally, numerical simulations are conducted to evaluate the performance of the proposed DH-WPCN. The contribution of this chapter has been presented in [67].

3.1 System Model

As shown in Figure 3.1, we consider a DH-WPCN with one HAP, $K$ users, and $K$ energy-constrained relays. HAP and users are assumed to have stable energy sources. There is no direct link between the HAP and the users and the $i$th relay is responsible for forwarding the $i$th user’s data to the HAP and vice versa\(^1\), but it needs to harvest energy before assisting the communication. HAP, users, and relays are all equipped with one single antenna each.

Without loss of generality, we assume that channel reciprocity holds for all channels. The channel coefficients between the HAP and the relay $R_i$ and between $R_i$ and the user $U_i$ are denoted by $h_i$ and $g_i$, respectively. All channels are quasi-static flat fading and remain constant over a transmission block, but can change independently from one block to another. It is further assumed that $h_i$ and $g_i$ are perfectly known at the

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\(^1\)The relays can also cooperatively serve the scheduled users, however, we assume a single relay responsible for each user because it reduces the complexity of coordination and implementation [68]. Furthermore, the number of relays can be different from the number of users, but if there are less relays in the network than users, some relays will have to serve more than one user which reduces the energy allocated for information transmission from/to each user and consequently the throughput will be degraded. It is also obvious that if the number of relays is greater than the number of users, some of the relays will remain idle during a whole transmission block which is not efficient. For these reasons, we assume a dedicated relay for each user.
HAP and $U_i$.

The frame structures for uplink and downlink communications are illustrated in Figure 3.2(a) and Figure 3.2(b), respectively. For convenience, normalized transmission blocks are used throughout this thesis. Also, superscripts $u$ and $d$ are used to differentiate between uplink and downlink communications.

### 3.1.1 Uplink Communication Model

In the first $\tau_0$ amount of time ($0 < \tau_0 < 1$), the HAP broadcasts an energizing signal with a constant transmit power $P_A$ to all relays to power them for their upcoming forwarding tasks. Uplink information transmission from $U_i$ to the HAP takes place in the $i$th time slot ($i = 1, ..., K$) with $\tau_i/2$ amount of time given to $U_i$ to transmit its information to $R_i$ and the remaining $\tau_i/2$ devoted to $R_i$ to forward $U_i$'s data to the
Figure 3.2: Frame structures for dual-hop wireless powered communication network

HAP. The energy harvested by $R_i$ during $\tau_0$ can be obtained as

$$E_{r,i}^u = \eta_i P_A |h_i|^2 \tau_0,$$

(3.1)

where $0 < \eta_i < 1$ ($i = 1, \ldots, K$) is the energy harvesting efficiency at $R_i$. Assuming all this energy is used up for forwarding $U_i$’s data during the second half of the $i$th time slot, the average transmit power of $R_i$ is given by

$$P_{r,i}^u = \frac{E_{r,i}^u}{\tau_i} = 2\eta_i P_A |h_i|^2 \frac{\tau_0}{\tau_i}.$$ 

(3.2)

We denote $x_i^u \sim \mathcal{CN}(0,1)$ as the signal transmitted by $U_i$ during the first half of the $i$th time slot, where $\mathcal{CN}(\mu, \sigma^2)$ stands for a circularly symmetric complex Gaussian random variable with mean $\mu$ and variance $\sigma^2$. The sampled baseband signal at $R_i$
can be written as
\[
y_{r,i}^{u} = g_i \sqrt{P_{U,i}} x_i^{u} + z_{r,i},
\] (3.3)
where \( P_{U,i} \) represents the transmit power of \( U_i \) and \( z_{r,i} \sim \mathcal{C}\mathcal{N}(0, \sigma_{r,i}^2) \) indicates the overall additive Gaussian noise at \( R_i \) due to the receiving antenna and RF band to baseband signal conversion. \( R_i \) amplifies the received signal and forwards it to the HAP. The signal received at the HAP in the \( i \)th slot is thus given by
\[
y_{H,i}^{u} = \frac{h_i \sqrt{P_{r,i}^{u}} (g_i \sqrt{P_{U,i}} x_i^{u} + z_{r,i})}{\sqrt{|g_i|^2 P_{U,i} + \sigma_{r,i}^2}} + z_H,
\] (3.4)
where the factor \( \sqrt{|g_i|^2 P_{U,i} + \sigma_{r,i}^2} \) in the denominator is the power constraint factor at \( R_i \) [27] and \( z_H \sim \mathcal{C}\mathcal{N}(0, \sigma_H^2) \) is the additive Gaussian noise at the HAP. Replacing (3.2) into (3.4), we will have
\[
y_{H,i}^{u} = \left( \frac{h_i g_i \sqrt{P_{U,i}}}{\sqrt{|g_i|^2 P_{U,i} + \sigma_{r,i}^2}} \right) \sqrt{2 \eta_i P_{A} |h_i|^2 \frac{\tau_0}{\tau_i}} x_i^{u} + \frac{h_i \sqrt{2 \eta_i P_{A} |h_i|^2 \frac{\tau_0}{\tau_i}}}{\sqrt{|g_i|^2 P_{U,i} + \sigma_{r,i}^2}} z_{r,i} + z_H,
\] (3.5)
where the expression within the first parentheses indicates the signal part and the second parentheses include the noise part. Therefore, signal-to-noise ratio (SNR) can be expressed as
\[
\gamma_i^{u} = \frac{2 \eta_i P_{A} |h_i|^4 |g_i|^2 \frac{\tau_0}{\tau_i}}{|g_i|^2 P_{U,i} + \sigma_{r,i}^2} \approx \frac{2 \eta_i P_{A} |h_i|^4 |g_i|^2 \frac{\tau_0}{\tau_i}}{2 \eta_i P_{A} |h_i|^4 \sigma_{r,i}^2 \frac{\tau_0}{\tau_i} + P_{U,i} |g_i|^2 \sigma_H^2}.
\] (3.6)
Note that we have neglected the term $\sigma_{r,j}^2 \sigma_r^2 \sigma_{H}^2$ in the denominator as its amount is insignificant compared to $P_{U,i} |g_i|^2 \sigma_{H}^2$. Finally, the achievable uplink throughput from $U_i$ to the HAP is given by

$$T_i^u = \frac{\tau_i}{2} \log(1 + \gamma_i) \simeq \frac{\tau_i}{2} \log(1 + \frac{A_{i,i}^{u} \tau_0}{B_i \tau_i + C_i})$$

(3.7)

where

$$A_{i,i}^{u} = 2 \eta_i P_A P_{U,i} |h_i|^4 |g_i|^2$$

(3.8)

$$B_i^{u} = 2 \eta_i P_A |h_i|^4 \sigma_{r,j}^2$$

(3.9)

$$C_i = P_{U,i} |g_i|^2 \sigma_{H}^2$$

(3.10)

### 3.1.2 Downlink Communication Model

In the $0$th slot (with duration $\tau_0$), the HAP broadcasts a signal to all relays which carries both information and energy. Exploiting a power splitting method, $R_i$ uses the proportion $\rho_i$ of the received signal power for harvesting energy which will be used in the $i$th time slot (with duration $\tau_i$) for forwarding HAP’s information to $U_i$. Therefore, the harvested energy and the average transmit power of $R_i$ are expressed as

$$E_{r,j}^d = \eta_i \rho_i P_A |h_i|^2 \tau_0$$

(3.11)

$$P_{r,j}^d = \eta_i \rho_i P_A |h_i|^2 \frac{\tau_0}{\tau_i}$$

(3.12)

respectively. The signal with the remaining $(1 - \rho_i)$ proportion of the initial power will be amplified and forwarded to $U_i$. Denoting $x_H \sim \mathcal{CN}(0,1)$ as the signal transmitted
by the HAP during $\tau_0$, the sampled baseband signal at $R_i$ is given by

$$y_{r,i}^d = h_i \sqrt{(1 - \rho_i)} P_A x_H + z_{r,i}. \quad (3.13)$$

After the AF process, the received signal at $U_i$ is expressed as

$$y_{U,i}^d = g_i \sqrt{P_{r,i}^d (h_i \sqrt{(1 - \rho_i)} P_A x_H + z_{r,i})} \sqrt{|h_i|^2 (1 - \rho_i) P_A + \sigma_{r,i}^2} + z_{U,i}, \quad (3.14)$$

where $z_{U,i} \sim \mathcal{CN}(0, \sigma_{U,i}^2)$ is the additive Gaussian noise at $U_i$. Following the same steps as in uplink communication, SNR at $U_i$ is obtained as

$$\gamma_i^d \approx \frac{\eta_i P_A^2 |h_i|^4 |g_i|^2 \rho_i (1 - \rho_i) \frac{\tau_0}{\tau_i}}{\eta_i P_A |h_i|^2 |g_i|^2 \sigma_{r,i}^2 \rho_i \frac{\tau_0}{\tau_i} + P_A |h_i|^2 \sigma_{U,i}^2 (1 - \rho_i)}, \quad (3.15)$$

and the achievable downlink throughput from the HAP to $U_i$ is given by

$$\tau_i^d = \tau_i \log(1 + \gamma_i^d) \approx \tau_i \log(1 + \frac{A_i^d \rho_i (1 - \rho_i) \frac{\tau_0}{\tau_i}}{B_i^d \rho_i \frac{\tau_0}{\tau_i} + C_i^d (1 - \rho_i)}), \quad (3.16)$$

where

$$A_i^d = \eta_i P_A^2 |h_i|^4 |g_i|^2, \quad (3.17)$$

$$B_i^d = \eta_i P_A |h_i|^2 |g_i|^2 \sigma_{r,i}^2, \quad (3.18)$$

$$C_i^d = P_A |h_i|^2 \sigma_{U,i}^2. \quad (3.19)$$

---

\textsuperscript{2}It is assumed that the information forwarded by the $i$th relay to the $i$th user cannot be properly decoded at the $j$th user ($j \neq i$); so, each user only decodes the information received from its dedicated relay.
3.2 Uplink Throughput Maximization

In this section, we are interested in finding optimal time allocations for energy transfer and information transmission in uplink communication in order to maximize the total uplink throughput. According to (3.7), uplink throughput maximization problem is formulated as

\[ \text{(P1)} : \max_{\tau_0, \tau_i} \sum_{i=1}^{K} \mathcal{T}_i^u(\tau_0, \tau_i) = \]

\[ \max_{\tau_0, \tau_i} \frac{1}{2} \sum_{i=1}^{K} \tau_i \log(1 + \frac{A_i^u \tau_i}{B_i^u \tau_i + C_i^u}), \quad (3.20) \]

s.t. \[ \sum_{i=0}^{K} \tau_i \leq 1, \quad (3.21) \]

\[ 0 \leq \tau_i \leq 1, \quad i = 0, ..., K. \quad (3.22) \]

The constraint in (3.21) is the time constraint implying that sum of time durations for energy and information transfer must not exceed the length of the transmission block which is assumed to be 1.

**Lemma 3.1:** \( \mathcal{T}_i^u(\tau_0, \tau_i) \) is concave for \( 0 \leq \frac{\tau_0}{\tau_i} \leq \infty. \)

**Proof:** \( \mathcal{T}_i^u(\tau_0, \tau_i) = \frac{\tau_i}{2} \log(1 + \frac{A_i^u \tau_0 / \tau_i}{B_i^u \tau_0 / \tau_i + C_i^u}) \) is a perspective function of \( f(\tau_0) = \frac{1}{2} \log(1 + \frac{A_i^u \tau_0}{B_i^u \tau_0 + C_i^u}) \) and \( f(\tau_0) \) is concave over \( \tau_0 \geq 0. \) Since the perspective operation preserves concavity, \( \mathcal{T}_i^u(\tau_0, \tau_i) \) is a jointly concave function of \((\tau_0, \tau_i). \) This completes the proof of Lemma 3.1. □

A non-negative weighted summation of concave functions is also concave. Hence, the objective function of \( \text{P1} \) is a concave function of \( \tau = [\tau_0, \tau_1, ..., \tau_K]. \) Moreover, the constraints of \( \text{P1} \) are affine. Therefore, \( \text{P1} \) is convex and can be solved using convex
optimization techniques [69]. Applying Lagrange duality method, we have

\[ L(\tau, \lambda) = \frac{1}{2} \sum_{i=1}^{K} \tau_i \log(1 + \frac{A_i \tau_0}{B_i \tau_i + C_i}) - \lambda \left( \sum_{i=0}^{K} \tau_i - 1 \right), \tag{3.23} \]

where \( \lambda \geq 0 \) is the Lagrangian multiplier associated with the constraint in (3.21). Then, the dual function is written as

\[ G(\lambda) = \max_{D} L(\tau, \lambda), \tag{3.24} \]

where \( D \) is the feasible set of \( \tau \) determined by (3.21) and (3.22). The optimal solution of \( P1 \) can be obtained from the following theorem.

**Theorem 3.1:** Optimal time allocations of \( P1 \) are given by

\[ \tau_0^* = \frac{1}{1 + \sum_{j=1}^{K} \frac{1}{\zeta_j^*}}, \tag{3.25} \]

\[ \tau_i^* = \frac{1}{\zeta_i^* (1 + \sum_{j=1}^{K} \frac{1}{\zeta_j^*})}, \tag{3.26} \]

where \( \zeta_i^*, i = 1, ..., K \) is the solution of

\[ \frac{1}{2} \left[ \log(1 + \frac{A_i^u \zeta_i}{B_i^u \zeta_i + C_i^u}) - \frac{A_i^u C_i^u \zeta_i}{(B_i^u \zeta_i + C_i^u)(A_i^u \zeta_i + B_i^u \zeta_i + C_i^u)} \right] = \lambda^*, \tag{3.27} \]

and \( \lambda^* \) is the optimal dual solution.

**Proof:** As we can find a \( \tau \in D \) such that \( \tau_i > 0 \) \( i = 0, 1, ..., K \) and \( \sum_{i=0}^{K} \tau_i < 1 \), \( P1 \) satisfies Slater’s condition and the duality gap is zero [69]. As a result, \( P1 \) can be
solved by applying Karush-Kuhn-Tucker (KKT) conditions:

$$\frac{\partial L(\tau^*, \lambda^*)}{\partial \tau_{0}} = 0,$$

(3.28)

$$\frac{\partial L(\tau^*, \lambda^*)}{\partial \tau_i} = 0,$$

(3.29)

$$\sum_{i=0}^{K} \tau_i^* \leq 1,$$

(3.30)

$$\lambda^* \left( \sum_{i=0}^{K} \tau_i^* - 1 \right) = 0.$$

(3.31)

From (3.28) and (3.29) it follows that

$$\frac{1}{2} \sum_{i=1}^{K} \frac{A_i^u C_i^u}{(B_i^u \tau_i^0 + C_i^u)(A_i^u \tau_i^0 + B_i^u \tau_i^0 + C_i^u)} = \lambda^*,$$

(3.32)

$$\frac{1}{2} \left[ \log(1 + \frac{A_i^u \tau_i^0}{B_i^u \tau_i^0 + C_i^u}) - \frac{A_i^u C_i^u \tau_i^0}{(B_i^u \tau_i^0 + C_i^u)(A_i^u \tau_i^0 + B_i^u \tau_i^0 + C_i^u)} \right] = \lambda^*. $$

(3.33)

Setting $\zeta_i = \frac{\tau_i^0}{\tau_i^*}$, it is easy to show that the left hand side of (3.33) is a monotonically increasing function of $\zeta_i$ for $\zeta_i \geq 0$ and we have

$$\lim_{\zeta_i \to +\infty} \frac{1}{2} \left[ \log(1 + \frac{A_i^u \zeta_i}{B_i^u \zeta_i + C_i^u}) - \frac{A_i^u C_i^u \zeta_i}{(B_i^u \zeta_i + C_i^u)(A_i^u \zeta_i + B_i^u \zeta_i + C_i^u)} \right] = \frac{1}{2} \log(1 + \frac{A_i^u}{B_i^u}).$$

(3.34)
Hence, $\lambda^*$ is upper-bounded by $\frac{1}{2} \log(1 + \frac{A_i^u}{B_i^u})$ and there exists a unique $\zeta_i^*$ satisfying (3.33) for $0 \leq \lambda^* < \frac{1}{2} \log(1 + \frac{A_i^u}{B_i^u})$. Now, using bisection method, we can find $\lambda^*$ such that

$$\frac{1}{2} \log(1 + \frac{A_i^u \zeta_i^*}{B_i^u \zeta_i^* + C_i^u}) = \frac{A_i^u C_i^u \zeta_i^*}{(B_i^u \zeta_i^* + C_i^u)(A_i^u \zeta_i^* + B_i^u \zeta_i^* + C_i^u)} = \lambda^*$$

for all $i \in \{1, ..., K\}$

(3.35)

and

$$\frac{1}{2} \sum_{i=1}^{K} \frac{A_i^u C_i^u}{(B_i^u \zeta_i^* + C_i^u)(A_i^u \zeta_i^* + B_i^u \zeta_i^* + C_i^u)} = \lambda^*.$$  

(3.36)

Then, from (3.31) we have

$$\tau_0^* + \frac{\tau_0^*}{\zeta_1^*} + ... + \frac{\tau_0^*}{\zeta_K^*} = 1.$$  

(3.37)

Therefore

$$\tau_0^* = \frac{1}{1 + \sum_{j=1}^{K} \frac{1}{\zeta_j^*}},$$  

(3.38)

and

$$\tau_i^* = \frac{1}{\zeta_i^*(1 + \sum_{j=1}^{K} \frac{1}{\zeta_j^*})}.$$  

(3.39)

This completes the proof of Theorem 3.1.

3.3 Downlink Throughput Maximization

In this section, we want to maximize the total downlink throughput by finding the optimal time allocations and power splitting ratios. From (3.16), we have the following
optimization problem:

\[(P2) : \max_{\tau_0, \tau_i, \rho_i} \sum_{i=1}^{K} T_i^d(\tau_0, \tau_i, \rho_i) =\]

\[
\max_{\tau_0, \tau_i, \rho_i} \sum_{i=1}^{K} \tau_i \log(1 + \frac{A_i^d \rho_i (1 - \rho_i) \frac{\tau_0}{\tau_i}}{B_i^d \rho_i \frac{\tau_0}{\tau_i} + C_i^d (1 - \rho_i)}),
\]

\[s.t. \sum_{i=0}^{K} \tau_i \leq 1,\]

\[0 \leq \tau_i \leq 1, \quad i = 0, 1, ..., K,\]  

\[0 \leq \rho_i \leq 1, \quad i = 1, ..., K.\]

The above problem is in general non-convex due to the coupled optimization variables of time allocations and PS ratios and thus cannot be solved optimally. However, we can obtain a near-optimal solution by optimizing \(\rho = [\rho_1, \rho_2, ..., \rho_K]\) and \(\tau = [\tau_0, \tau_1, ..., \tau_K]\) iteratively.

Initializing \(\rho\), \(P2\) will be equal to finding the optimal value of \(\tau\) which can be solved following the same steps as in uplink throughput maximization problem in the previous section. In the \(k\)th iteration, we first find \(\tau^{(k)}\) given \(\rho^{(k-1)}\). Having \(\tau^{(k)}\), we can then update power splitting ratios by simply taking the derivative of the objective function with respect to \(\rho\). In this case, maximizing the objective function is equivalent to maximizing \(\gamma_i^d\) (\(i = 1, ..., K\)). Hence, we will have

\[
\frac{\partial \gamma_i^d}{\partial \rho_i} = \frac{A_i^d \frac{\tau_0^{(k)}}{\tau_i^{(k)}} [(C_i^d - B_i^d \frac{\tau_0^{(k)}}{\tau_i^{(k)}}) \rho_i^{(k)}]^2 - 2C_i^d \rho_i^{(k)} + C_i^d]}{[B_i^d \frac{\tau_0^{(k)}}{\tau_i^{(k)}} \rho_i^{(k)} + C_i^d (1 - \rho_i^{(k)})]^2} = 0,
\]

(3.44)
thus,

\[(C_i^d - B_i^d \tau_0^{(k)}) \rho_i^{(k)} - 2C_i^d \rho_i^{(k)} + C_i^d = 0, \quad (3.45)\]

which results in

\[\rho_i^{(k)} = \frac{C_i^d - \sqrt{B_i^d C_i^d \tau_0^{(k)} / \tau_i^{(k)}}}{C_i^d - B_i^d \tau_0^{(k)} / \tau_i^{(k)}}, \quad (3.46)\]

Note that \(\rho_i^{(k)} = \frac{C_i^d + \sqrt{B_i^d C_i^d \tau_0^{(k)} / \tau_i^{(k)}}}{C_i^d - B_i^d \tau_0^{(k)} / \tau_i^{(k)}}\) is infeasible because we will have \(\rho_i^{(k)} > 1\) for \(C_i^d > B_i^d \tau_0^{(k)} / \tau_i^{(k)}\) and \(\rho_i^{(k)} < 0\) for \(C_i^d < B_i^d \tau_0^{(k)} / \tau_i^{(k)}\) none of which is a feasible value for \(\rho_i^{(k)}\).

Repeating the above process, we update \(\tau\) and \(\rho\) in each iteration until both converge to a predefined accuracy.

### 3.4 Performance Evaluation

In this section, we evaluate the performance of our proposed DH-WPCN through numerical simulations. Channel power gains are modeled as \(|h_i|^2 = \theta_1 D_{1,i}^{-\alpha_1}\) and \(|g_i|^2 = \theta_2 D_{2,i}^{-\alpha_2}\) with \(D_{1,i}\) representing the distance between the HAP and the \(i\)th relay and \(D_{2,i}\) referring to the distance between the \(i\)th relay and the \(i\)th user. \(\theta_1\) and \(\theta_2\) indicate the short-term fading which are assumed to be Rayleigh distributed, i.e., \(\theta_1\) and \(\theta_2\) are independent exponential random variables with mean unity. \(\alpha_1\) and \(\alpha_2\) are path-loss exponents. For simplicity, We assume that \(\alpha_1 = \alpha_2 = \alpha\), and \(\alpha = 2\) unless otherwise specified. Other parameters are set as follows: \(\eta_i = 1\), \(P_{U,j} = 20\text{dBm}\), and \(\sigma_h^2 = \sigma_r^2 = \sigma_{U,i}^2 = -70\text{dBm}/\text{Hz}, \forall i \in \{1, \ldots, K\}\). The results have been averaged over 1000 simulation runs and the 95% confidence intervals are also shown.

Figure 3.3 shows the effect of the HAP’s transmit power on uplink and downlink sum-
throughput. It is assumed that there are two users in the network with $D_{1i} = D_{2i} = 10m \ (i = 1, 2)$. As we can see in Figure 3.3, both uplink and downlink throughput increase when the HAP’s transmit power increases. With higher HAP’s transmit power, the relays can harvest more energy and the power of the amplified signal is increased accordingly; therefore, the throughput gets better with increasing HAP’s power. Another important observation is that downlink throughput increases faster than uplink throughput. That’s because in downlink communication, increasing HAP’s transmit power not only results in more harvested energy at the relays but also boosts the power of the HAP’s transmitted information signal which also improves SNR and throughput.

In Figure 3.4, we investigate the effect of the number of users on total uplink and downlink throughput. Here, the transmit power of the HAP is fixed at $P_A = 30dBm$. It is observed that both uplink and downlink sum-throughput are non-decreasing with
the number of users in the network\textsuperscript{3}. This can be clarified as follows: Suppose that there are $K$ users in the network and the optimal time allocation and the maximum sum-throughput are denoted as $\tau^*$ and $T^*$, respectively. Now, we add one more user to the network and recalculate the optimal time allocation and sum-throughput. Suppose that $\tau'$ and $T'$ are the new calculated time allocation and sum-throughput, respectively. Now, if $T' < T^*$, we can set the time duration of the newly-added user to 0 and allocate time-slots to other users according to $\tau^*$. In this case, the sum-throughput of the DH-WPCN will be equal to $T^*$. This contradicts our assumption that $\tau'$ is the optimal time allocation which results in maximum possible throughput. Hence, $T' \geq T^*$.

However, Figure 3.4 shows that the rate at which uplink and downlink total throughput increase becomes lower when we continue adding new users to the network. Ac-

\textsuperscript{3}Increasing the number of users means that the number of relays is also increased because we assume a dedicated relay for each user.
Figure 3.5: Energy transfer time vs. number of users

According to Figure 3.5, adding new users reduces the optimal time for energy transfer ($\tau_0$) because increasing the number of users implies that more data transmission time is needed which in consequence decreases the energy transfer duration. As energy transfer time gets shorter, users harvest less amount of energy in the first phase which leads to throughput reduction. Therefore, the throughput boost offered by incrementing the number of users is being neutralized by the shortened energy harvesting time of the users. Nevertheless, as explained earlier, both uplink and downlink throughputs are non-decreasing with the number of network users.

What’s more, Figures 3.3 and 3.4 demonstrate that the downlink sum-throughput is greater than the uplink sum-throughput. The main reason behind this observation is that in downlink communication, the effective transmission time of $R_i$ is $\tau_i$ while only half of the $i$th time slot is dedicated to $R_i$’s transmission in uplink communication which makes the effective transmission time of $R_i$ equal to $\tau_i/2$. This less effective
transmission time results in lower throughput in uplink communication. Next, we want to investigate the doubly near-far problem in our proposed model. To this end, we consider a two-user DH-WPCN, in which the users are 10 meters away from their corresponding relays (i.e., $D_{2,1} = D_{2,2} = 10m$). We also fix the location of $R_1$ at 10 meters from the HAP (i.e., $D_{1,1} = 10m$). Now we vary the location of the second relay ($R_2$) from $D_{1,2} = 10m$ to $D_{1,2} = 20m$\(^4\). $P_A = 30dBm$ and other simulation parameters are the same as before.

Figure 3.6 shows the throughput ratio $T_2/T_1$ as a function of $D_{1,2}/D_{1,1}$ in both uplink and downlink directions. It is observed that increasing the distance between $R_2$ and the HAP drastically decreases both uplink and downlink throughput ratio, however, we can see that uplink throughput ratio decreases at a faster rate than downlink.

\(^4\)Here, changing the location of $R_2$ does not alter the distance between $U_2$ and $R_2$, i.e., $D_{2,2} = 10m$ regardless of the value of $D_{1,2}$ because the objective of this simulation (Figure 3.6) is merely to observe the doubly near-far problem by examining $R_2$ in different locations.
throughput ratio. This arises from the doubly near-far-problem which appears only in uplink communication. Indeed, in uplink communication, the relay which is located further from the HAP harvests less energy than the other relay, but has to transmit with more power. As a result of this, less time is allocated for information transmission of the user whose relay is far from the HAP leading to a lower throughput for this user. In other words, the throughput of the second user is sacrificed for the sake of maximizing the total throughput.

If we assume that the distance between the HAP and the users is fixed and the relays are flexibly positioned between the HAP and the users, we can mitigate unfairness by adjusting relay locations for a more even allocation of throughput among different users. For example, the relay whose corresponding user is further away from the HAP can be placed nearer to the HAP in order to alleviate the doubly near-far problem. Indeed, such a user still suffers from its long first-hop (user-to-relay) distance; however, as the second-hop (relay-to-HAP) plays a more important role in individual

Figure 3.7: A two-user DH-WPCN
users’ throughputs, it is more desirable to decrease the distance between the relay and the HAP for the users who are more prone to getting unfair throughput share (i.e., further users).

An example is plotted in Figure 3.7, where $D_{1,1} = 10m$, $D_{2,1} = 10m$, and $D_{1,2} + D_{2,2} = 30m$. Other simulation parameters are the same as before. We vary the location of $R_2$ between $U_2$ and the HAP from $D_{1,2} = 10m$ to $D_{1,2} = 20m$. Figure 3.8 shows that when $R_2$ is nearer to the HAP, throughput unfairness between the users is less extreme. In fact, as the doubly near-far problem is related to the second-hop of uplink communication, the location of the relay nodes is very important in determining the fairness level in the network.

![Figure 3.8: Uplink throughput ratio vs. $D_{1,2}$ when $D_{1,2} + D_{2,2} = 30m$](image)

Next, we want to demonstrate the importance of optimizing time allocations in uplink and downlink communications. For this purpose, we propose suboptimal time allocations and investigate the performance enhancement that our optimal solution
yields compared to the proposed suboptimal ones. The objective of the suboptimal schemes is to allocate equal transmission time to all users. It is easy to show that the objective functions in (3.20) and (3.40) are monotonically increasing functions of \( \tau_0 \). This indicates that the time constraints in (3.21) and (3.41) must be met with equality. Otherwise, we can always increase \( \tau_0 \) to achieve a higher throughput. Therefore, for the suboptimal solutions we will have

\[
\tau_i = \frac{1 - \tau_0}{K} \quad i = 1, \ldots, K. \tag{3.47}
\]

Replacing (3.47) into (3.20) and (3.40), the uplink throughput maximization problem will turn to a one-variable optimization problem which can be easily solved. For the downlink throughput maximization problem, \( \tau_0 \) and \( \rho = [\rho_1, \rho_2, \ldots, \rho_K] \) are optimization variables. Similar to what we did in the previous section, we iteratively update \( \tau_0 \) and \( \rho \) until satisfactory convergence is obtained.

Figure 3.9 and Figure 3.10 show uplink and downlink sumthroughput, respectively, as a function of the HAPs transmit power for optimal and suboptimal time allocations. In this simulation, there are two users in the DH-WPCN with \( D_{1,1} = D_{2,1} = D_{2,2} = 10m \) and \( D_{1,2} = 20m \). \( \alpha = 3 \) and other simulation parameters are the same as in previous simulations.

We can see that using optimal time allocations always results in higher uplink and downlink throughputs. The figures also illustrate that the throughput gap between optimal and suboptimal solutions increases with increasing \( P_A \). In other words, the importance of using optimized time allocations becomes more perceptible in larger values of the HAP’s transmit power.

Finally, we investigate the performance gain achieved by using optimal power splitting ratios in downlink communication. Again, \( \alpha = 3 \) and there are two users in the network with \( D_{1,1} = D_{2,1} = D_{2,2} = 10m \) and \( D_{1,2} = 20m \). Figure 3.11 depicts downlink
Figure 3.9: Uplink throughput performance with optimal and suboptimal time allocations

Throughput performance with and without using optimal power splitting ratios. We can see that fixed power splitting ratios (i.e., $\rho_i = \rho, \forall i \in \{1, \ldots, K\}$) always offer a lower throughput than the optimized ones. This clarifies that beside optimizing time durations, using optimal ratios for power splitting is also of paramount importance for downlink throughput enhancement.

3.5 Conclusion

In this chapter, we studied a DH-WPCN, where energy-limited relays assist the communication between energy-stable users and the HAP using an amplify-and-forward strategy. The relays scavenge their required energy from the signal broadcast by the HAP which is either a dedicated energy signal with no useful information (as in uplink communication) or an information signal also carrying energy (as in downlink
communication). In the latter case, a power splitting method is employed to divide the signal into two streams one of which is used for energy harvesting and the other for information relaying. We investigated uplink and downlink sum-throughput maximization problems by finding optimal time allocations in uplink communication and near-optimal time allocations and power splitting ratios in downlink communication, respectively. According to the simulation results, downlink communication shows a better throughput performance than uplink communication thanks to a greater effective transmission time. Simulation results also revealed that downlink throughput is more sensitive to the HAP’s transmit power than uplink throughput. Doubly near-far problem was explored in a two-user network showing that in uplink communication, the unfairness between network users in terms of throughput is more severe than in downlink communication due to the doubly near-far problem. We then proposed a
solution for easing this problem and verified our solution through simulation. Finally, the importance of using optimal time durations and power splitting ratios was demonstrated via numerical results.
Chapter 4

Fairness Enhancement in Dual-hop Wireless Powered Communication Network

In Chapter 3, we studied a dual-hop wireless powered communication network (DH-WPCN) and investigated throughput maximization in both uplink and downlink directions. The simulations conducted at the end of Chapter 3 revealed a severe fairness problem in terms of individual users’ throughput in uplink communication. The user whose relay is located far from the HAP suffers from the so-called doubly near-far problem and is assigned a small transmission time which leads to a significantly low throughput for this user. We proposed to flexibly position the relays between the users and the HAP so as to control the doubly near-far problem in the network. However, it is not always possible to change the location of the relays. Hence, a more robust solution is needed to ensure throughput fairness among network users. The aim of this chapter is to tackle the doubly near-far problem in our proposed DH-WPCN by optimizing time allocations for energy and information transfer. We
consider the problem of maximizing the minimum throughput among users in order to guarantee throughput fairness for the users and yet maximize the total throughput. Our findings show that there exists a trade-off between sum-throughput and fairness. While the sum-throughput maximization scheme proposed in the previous chapter demonstrates a better performance in terms of the total uplink throughput, it experiences a low fairness level and the fairness deteriorates with increasing the number of users. On the other hand, the minimum throughput maximization (MTM) approach presented in this chapter preserves fairness regardless of the number of users. The content of this chapter has appeared in [70].

4.1 Minimum Throughput Maximization

Similar to the previous chapter, the system model consists of a HAP, $K$ users, and $K$ energy-constrained relays (Figure 3.1). HAP and users are assumed to have fixed energy supplies, while the relays rely on harvesting energy from downlink energy signals broadcast by the HAP. As discussed in Chapter 3, the achievable uplink throughput from $U_i$ ($i$th user) to the HAP is expressed as

$$T_i = \frac{\tau_i}{2} \log(1 + \gamma_i) \simeq \frac{\tau_i}{2} \log(1 + \frac{A_i \tau_0}{B_i \tau_i + C_i}),$$

(4.1)

where

$$A_i = 2\eta_i P_A P_{U_i} |h_i|^4 |g_i|^2,$$

(4.2)

$$B_i = 2\eta_i P_A |h_i|^4 \sigma_r^2,$$

(4.3)

$$C_i = P_{U,i} |g_i|^2 \sigma_H^2.$$  

(4.4)

1We omit superscript $u$ because only uplink communication is investigated here and we do not study downlink communication in this chapter.
We want to guarantee a minimum throughput for each user, and yet maximize their sum-throughput. According to (4.1), minimum throughput maximization problem is formulated as follows:

\[(P3) : \max R\]

subject to

\[
\frac{\tau_i}{2} \log(1 + \frac{A_i \tau_0}{B_i \tau_i + C_i}) \geq R \quad (4.5)
\]

\[
\sum_{i=0}^{K} \tau_i \leq 1, \quad (4.6)
\]

\[0 \leq \tau_i \leq 1, \quad i = 0, 1, ..., K, \quad R \geq 0,
\]

where the constraint in (4.5) is to ensure a minimum throughput for all users and (4.6) is the time constraint, meaning that the time portions for downlink energy transfer and uplink information transmission must be no greater than the length of the transmission block.

Lemma 4.1: For the optimal solution of the above minimum throughput maximization problem, the constraints in (4.5) and (4.6) must be met with equality.

Proof: Suppose that \(\tau_x = [\tau_{0x}, \tau_{1x}, ..., \tau_{Kx}]\) is the optimal solution of \(P3\) such that \(\sum_{i=0}^{K} \tau_{ix} < 1\). Now, we can form another solution with \(\tau_y = [\tau_{0y} + (1 - \sum_{i=0}^{K} \tau_{ix}), \tau_{1y}, ..., \tau_{Ky}]\). Since \(T_i(\tau) = \frac{\tau_i}{2} \log(1 + \frac{A_i \tau_0}{B_i \tau_i + C_i})\) is a monotonically increasing function of \(\tau_0\) for \(\tau_0 \geq 0\), \(T_i(\tau_y) > T_i(\tau_x)\). This contradicts our assumption that \(\tau_x\) is the optimal solution. Therefore, the optimal solution of \(P3\) satisfies (4.6) with equality. Similarly, as \(T_i\) is a monotonically increasing function of \(\tau_i\) for \(\tau_i > 0\), maximum \(R\) is achieved when all users get equal throughput. Suppose that \(U = [U_1, ..., U_K]\) is the set of network users
and $U_n$ has the minimum throughput among all users, i.e., $T_i > T_n$, $\forall i \in \{1, ..., K\} \neq n$. Now we can decrease $\tau_i$'s and increase $\tau_n$ to have a higher minimum throughput.

This demonstrates that the optimal solution is obtained when equality holds for the constraint in (4.5).

From Lemma 4.1, we know that the optimal solution of $P3$ must satisfy the following equation:

$$R^* = \frac{\tau_i^*}{2} \log \left(1 + \frac{A_i \tau_0^*}{B_i \tau_0^* + C_i} \right), \forall i \in \{1, ..., K\}. \quad (4.7)$$

For a given $R$ and $\tau_0$, $\tau_i$'s are the solution of

$$g(\tau, R) = \tau_0, \quad (4.8)$$

where

$$g(\tau, R) = \frac{C_i \tau_i (e^{2R/\tau_i} - 1)}{A_i - (e^{2R/\tau_i} - 1) B_i}. \quad (4.9)$$

Given $R$, $P3$ is feasible if we can find $\tau = [\tau_0, \tau_1, ..., \tau_K]$ such that $\sum_{i=0}^{K} \tau_i \leq 1$. In the following, we illustrate the feasibility of this problem with an example.

Consider a DH-WPCN consisting of two users as shown in Figure 4.1 with $D_{1,1} = 10m$, $D_{1,2} = 20m$ and $D_{2,1} = D_{2,2} = 10m$, where as explained in the previous chapter, $D_{1,i}$ represents the distance between the HAP and the $i$th relay and $D_{2,i}$ refers to the distance between the $i$th relay and the $i$th user. Rayleigh fading channels are modeled as $|h_i|^2 = \theta_{1,i} D_{1,i}^{-\alpha_1}$ and $|g_i|^2 = \theta_{2,i} D_{2,i}^{-\alpha_2}$, where $\theta_{1,i}$ and $\theta_{2,i}$ are independent exponential random variables with mean unity. Throughout this chapter, $\alpha_1 = \alpha_2 = 2$, unless otherwise stated. Other parameters are as follows: $P_A = 20dBm$, $\eta_i = 1$, $P_{U,i} = 20dBm$, $\ldots$
and $\sigma_H^2 = \sigma_{r,i}^2 = \sigma_{U,i}^2 = -70\text{dBm}/\text{Hz}$, $\forall i \in \{1, ..., K\}$.

Figure 4.2 shows $\sum_{i=0}^{2} \tau_i$ versus $\tau_0$ for different values of $R$. It can be observed that $R = 2.5 \text{ Nats/s/Hz}$ is not feasible for the network setup described above because its corresponding $\sum_{i=0}^{2} \tau_i$ graph never meets the line $\sum_{i=0}^{2} \tau_i = 1$. On the other hand, $R = 2 \text{ Nats/s/Hz}$ and $R = 1.5 \text{ Nats/s/Hz}$ are feasible solutions as we can find $\tau = [\tau_0, \tau_1, \tau_2]$ such that the total time duration is less than or equal to 1. Figure 4.2 also illustrates that the total time duration is shifted upward as we increase $R$. Using bisection method, $R^*$ is achieved when the corresponding $\sum_{i=0}^{K} \tau_i$ graph is tangent to the line $\sum_{i=0}^{K} \tau_i = 1$ and the point of intersection determines the optimal value of $\tau_0$ for which $\tau_i$'s can be found using (4.8).

Algorithm 1 summarizes the process of finding $\tau^*$ and $R^*$.

Figure 4.3 plots time allocation ratio ($\tau_2/\tau_1$) versus $\alpha_1$ for the two-user DH-WPCN.
of Figure 4.1. Throughout this chapter, “STM” refers to the sum-throughput maximization scheme presented in Chapter 3, while “MTM” represents the minimum throughput maximization approach proposed in this chapter. We can see that the time allocation ratio decreases in STM and increases in MTM with increasing $\alpha_1$. As $\alpha_1$ increases, the channels between the HAP and the relays start to degrade, however, $R_2$ experiences a more severe degradation due to its longer distance to the HAP. STM allocates more time to the user whose relay has better channel conditions in order to maximize the total uplink throughput. This unfairness in time allocation intensifies with increasing $\alpha_1$ and results in throughput unfairness. According to Figure 4.4, the throughput ratio between the two users ($T_2/T_1$) drastically decreases in STM when $\alpha_1$ is increased and we can see that $U_2$ gets negligible throughput when $\alpha = 3$. MTM keeps users’ throughputs at the same level by assigning $U_2$ a greater transmission time.

Figure 4.2: Total time duration versus $\tau_0$ for the network setup of Figure 4.1
Algorithm 1 Minimum Throughput Maximization

Initialize $R_{min} = 0$, $R_{max}$.

repeat
    $R = 0.5(R_{min} + R_{max}).$
    $\tau_0 = 0.$
    while $\tau_0 \in [0, 1]$ do
        Compute $\tau_i$'s using (4.8).
        Compute $\sum_{i=0}^K \tau_i$.
        if $0 \leq 1 - \sum_{i=0}^K \tau_i < \epsilon$ then
            $\tau_0^* = \tau_0.$
            $\tau_i^* = \tau_i.$
        end if
        $\tau_0 \leftarrow \tau_0 + \Delta.$
    end while
    if no $\tau = [\tau_0, \tau_1, ..., \tau_K]$ was found such that $\sum_{i=0}^K \tau_i < 1$ then
        $R_{max} \leftarrow R.$
    else
        $R_{min} \leftarrow R.$
    end if
until $R_{max} - R_{min} < \delta$.

$R^* = R.$

4.2 Performance Evaluation

In this section, we present simulation results to evaluate the performance of our minimum throughput maximization algorithm in terms of throughput and fairness. To this end, we compare the proposed scheme with the STM approach discussed in Chapter 3 which aimed to maximize the sum-throughput of DH-WPCN. Channel models and simulation parameters are the same as those used in section 4.1 unless otherwise specified. Simulation results have been averaged over 1000 runs and the 95% confidence intervals are also shown.

Figure 4.5 shows the throughput performance of STM and MTM schemes versus HAP’s transmit power when we have two users in the network with the setup depicted in Figure 4.1. It can be observed that the normalized throughput of STM is higher than $R^*$ which is the normalized throughput of the MTM scheme. That’s because the
STM method sacrifices the second user’s throughput for the sake of sum-throughput maximization. As we can see in the figure, the main part of the maximum sum-throughput belongs to the first user and the second user gets only a small share of the total throughput. MTM provides all users with equal throughput in order to realize throughput fairness.

Figures 4.6 and 4.7 plot normalized throughput and fairness index versus number of users \((K)\), where \(D_{1,i} = \frac{20m}{K} \times i\) and \(D_{2,i} = 10m\), \(\forall i \in \{1, ..., K\}\). \(P_A = 20dBm\) and other simulation parameters are the same as before. Fairness index is calculated as
\[
F = \frac{(\sum_{i=1}^{K} x_i)^2}{K \sum_{i=1}^{K} x_i^2} \quad [71],
\]
where \(x_i\) is the throughput of the \(i\)th user. Figure 4.6 shows that in both schemes, normalized throughput decreases with increasing \(K\) and STM outperforms MTM in terms of throughput. However, the lower throughput of the MTM approach is made up by its higher fairness level as illustrated in Figure 4.7.

According to Figure 4.7, STM suffers from unfair throughput allocation and this gets
worse when $K$ is increased. On the other hand, MTM always maintains fairness as all users achieve the same throughput.

### 4.3 Conclusion

In this chapter, we investigated fairness enhancement in a dual-hop WPCN (DH-WPCN), where energy-constrained relays assist the communication between energy-stable users and the HAP using an amplify-and-forward strategy. To overcome the doubly near-far problem which occurs due to unequal distance of the relays from the HAP, we studied the minimum throughput maximization problem and optimized time allocations to achieve throughput fairness among users. According to the numerical results, there is a trade-off between throughput and fairness in the DH-WPCN and the improved fairness is achieved at the expense of a reduction in throughput. The
Figure 4.5: Throughput vs. HAP’s transmit power in STM and MTM schemes

proposed fairness-enhancing algorithm retains the highest fairness level with increasing the number of users and in different channel conditions which makes it suitable for applications that require equal throughput allocation for all users.
Figure 4.6: Effect of the number of users on throughput

Figure 4.7: Effect of the number of users on fairness index
Chapter 5

Conclusions and Future Works

5.1 Conclusions

In this thesis, we studied the newly-emerged research areas in RF energy harvesting domain focusing on the recent research in the fields of SWIPT and WPCN. We proposed new network models and protocols, designed resource allocation strategies for different scenarios and analyzed the performance of the presented approaches. Particularly, we considered extending the baseline WPCN model to a dual-hop setup and investigated the optimal energy and information transfer strategy from either the whole network perspective or individual users’ point of view. We also studied the integration of SWIPT and WPCN by allowing simultaneous energy and information transfer in our proposed DH-WPCN model, where energy is harvested from an information signal using a power splitting method. To elaborate more, the results and findings of this thesis are as follows:

In Chapter 3, we proposed a DH-WPCN with one HAP and a number of relays and users. Assuming that the users have fixed energy supplies and the relays need to harvest energy from RF transmission of the HAP, we presented uplink and down-
link communication protocols. Optimal values of parameters for maximizing the total throughput of the network in both directions were found. Specifically, we formulated uplink and downlink sum-throughput maximization problems to find optimal time allocation in both uplink and downlink communications as well as optimal power splitting factors in downlink communication. The convex structure of the uplink throughput maximization problem allowed us to obtain the optimal value of the time-slot durations for energy and information transfer in closed form, while in downlink throughput maximization, we used iterations for finding a near-optimal solution due to the non-convexity of the problem. We evaluated the uplink and downlink throughput performance of our proposed schemes via simulations and identified the existence of the doubly near-far problem in uplink communication which results in extremely unfair throughput distribution among the users. Due to the dependence of each user’s achievable throughput on its corresponding relay’s distance from the HAP, we proposed to dynamically adjust the location of the relays to attain a more balanced throughput allocation in the network. Numerical results confirmed that the position of the relays has a major impact on users’ throughputs and the severity of the throughput unfairness can be controlled by changing relays’ placements.

In Chapter 4, we investigated a more robust solution for tackling the aforementioned fairness issue and developed a fairness enhancement scheme to provide all users with equal throughput. We formulated a minimum throughput maximization problem and proposed a novel algorithm for finding the maximum common throughput of the users plus the optimal time allocation for achieving the maximum level of fairness. We also conducted simulations to compare the performance of the proposed fairness-improving scheme with the strategy presented in Chapter 3. Simulation results revealed a throughput-fairness trade-off in our DH-WPCN implying that the fairness is achieved at the cost of total throughput reduction. Therefore, depend-
ing on the network requirements in terms of sum-throughput and fairness, either the strategy proposed in Chapter 3 or the scheme presented in Chapter 4 can be chosen as the optimal policy.

5.2 The Way Forward

5.2.1 Future Research Directions

Although there have been some developments in the field of WPCNs in recent years, there is still much room for further improvements and extensions in this area. Here, we outline some future directions for enhancing the DH-WPCN presented in this thesis.

- In Chapter 3, we proposed adjustment of the relays’ locations in order to alleviate the doubly near-far problem in uplink communication. As discussed earlier, for the users who are placed further away from the HAP, it is more desirable to locate their corresponding relays closer to the HAP so that the allocated throughput for these users would be comparable to the ones nearer to the HAP. Nevertheless, it is obvious that a relay cannot be very distant from its corresponding user because it must be able to successfully receive the information signal of the user. In light of this, optimizing the location of the relay nodes can be an interesting problem for future research. For instance, the optimal location of the relays can be determined for maximizing the throughput fairness under the first- and the second-hop outage constraints.

- In the uplink communication of the proposed DH-WPCN, the first half of each transmission time-slot is dedicated to one of the users to send information to its relay. During this time, the HAP and the other $K - 1$ relays and users re-
main idle. As an enhancement to our proposed uplink communication protocol, the HAP can continue transferring wireless energy in the beginning half of all transmission slots so that the relays which are not receiving information from their corresponding users can add to their harvested energy.

- In our DH-WPCN, we assumed that there is no direct link between the users and the HAP. The proposed schemes can be extended by considering the presence of a link between each user and the HAP to achieve diversity and multiplexing gains [72][73].

- The proposed DH-WPCN can be enhanced to FD scenarios, where the HAP is able to simultaneously transfer energy and receive information on the same frequency band. This strategy can boost the harvestable energy of the relays which consequently improves the throughput. Also, activating FD operation at the relays will enable them to harvest energy from the HAP’s transmitted signals while they are receiving information from their users.

- The proposed model assumes that the HAP is equipped with one single antenna. By applying a multi-antenna HAP and taking advantage of the beamforming technique, the energy transfer efficiency can be improved. In this case, doubly near-far problem can also be mitigated because the beamforming vector plays an important role in the amount of available energy at each relay. As such, designing beamforming weights in the favor of further relays can offset their harsh channel conditions and bring a more balanced throughput distribution.

- The DH-WPCN presented in this thesis can be extended to more complicated network setups. For instance, it would be interesting to consider a large-scale network similar to the one proposed in [37], where multiple HAPs and a large number of users and relays are present. In this setup, cooperative energy beam-
forming can be used to improve the energy transfer efficiency at the target relays by jointly optimizing the energy signal waveforms of the HAPs, thus forming a virtual antenna array. Integrating DH-WPCN with cognitive radio network can be another possible direction for future research.

- This research extended the baseline one-hop energy and information transfer model to a scenario in which information transmission is carried out in two hops. This model can be further extended to include two-hop energy transfer as well. Assuming that both the relays and the users are energy-constrained, dual-hop energy transfer may be utilized such that the relays transfer a portion of their harvested energy to their corresponding users. Studying the resource allocation problem in this new DH-WPCN setup can be considered for future works.

- In reality, the number of relays may be different from the number of users. This can be taken into consideration in future research. Relay selection mechanisms can be implemented to determine which relay should be in charge of data forwarding for each user. Also, if more than one user is assigned to a relay, it is important to specify how much time and energy must be allocated for information transmission/reception of each of them.

5.2.2 A Closer Look into WPCN from the IoT Point of View

IoT consists of heterogeneous devices with different constraints, requirements, and capabilities which makes it impossible to apply one strategy to all scenarios. For example, the required energy for the operation of a low-power sensor node is not comparable to the amount needed for powering a mobile phone. Moreover, different IoT devices may be in different conditions in terms of the volume of data to be trans-
mitted, delay constraints, QoS requirements, etc. One device may experience long
delay (e.g., several weeks) between two transmission cycles while the other has to
transmit once every second. Also, some devices may have critical data (e.g., urgent
medical information) which need to be prioritized for timely transmission. These
dissimilarities between different IoT components have to be taken into account in
designing resource allocation schemes.

Further, information exchange between network devices should also be considered in
IoT. Allocation of time and energy resources in this case may be more complicated
than the scenario in which devices only communicate with the HAP. The communica-
tion between devices also provides them with an extra energy harvesting source. The
receiver can use the transmitter’s signal for the dual purpose of information decoding
and energy harvesting, while other devices treat this signal as an ambient RF energy
source; even the transmitter itself can collect energy from its own RF signal when
operating in the full-duplex mode. In a WPCN having multiple transmitter-receiver
pairs, interference management methods [74] will be helpful for minimizing the effect
of interference at the receivers.

Multi-hop communication is also necessary in future scalable IoT networks, where a
number of nodes cooperate with each other to deliver data to the designated node
(e.g., the HAP). Although our dual-hop WPCN protocol can provide insights for
extending the baseline WPCN to multi-hop networks, extensive research has still to
be done in this area for developing multi-hop WPCNs which perfectly fit into IoT.

In such a multi-hop WPCN setup, in addition to the information routing in conven-
tional multi-hop networks, energy routing can also be exploited to transfer energy
in multiple hops. In this regard, multi-path energy routing is useful for increasing
RF energy harvesting efficiency and extending the network size [50]. Coexistence of
energy-constrained and energy-stable devices is also imaginable in IoT in which case
energy-stable ones can participate in energy transfer process to help feeding energy-limited devices, thus, mitigating the need for deploying additional energy sources and saving on the related costs.

To sum up, seamless integration of WPCN into IoT calls for more intelligent solutions. These solutions can be a combination of the strategies reviewed and proposed in this thesis as well as new techniques which cater to the needs of future IoT networks.
Bibliography


