SCHOOL OF ELECTRICAL ENGINEERING AND

TELECOMMUNICATIONS

Maximum Throughput Design for WPCN Systems

By

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Thesis submitted as a requirement for the degree Bachelor of Engineering (Telecommunications)

Date: May 01, 2020

Abstract

In the recent decades, the rapid development of wireless communications with higher bandwidth has triggered the massive growth for the needs of the wireless devices. The new wireless communication technology is widely spread and used in various applications such as environmental monitoring, transportation autonomous vehicle, etc. This thesis study mainly focuses on the beamforming design for the wireless powered communication network (WPCN) system. The system in the thesis design is proposed as a multiuser with multiple antennas and a single relay communication system. The users use the devices that can be charged wirelessly by RF signals, thus the users can harvest energy from the power station and harvest energy or information from it. This paper firstly gives the ideas and the basic background of WPCN, multi-antennas and beamforming technology. Then it discusses the optimization of the system model to maximize the throughput of the WPCN system as well as the energy efficiency. Through the process of the optimization, series of transformations from non-convex to convex problem are proposed in the design in order to obtain the optimized solutions. The formulas and the problem solving process shows the relationships between the users and the average signal received by all users form the replay or the average signal of the noises.

Acknowledgement

I want to thank Dr Derrick Wing Kwan Ng for giving me confidence and supporting during the whole process of thesis study. He is the most reliable and patient supervisor I've ever met. I want to thank him for giving me the opportunity to do this thesis study with all his kind help and his inspiring teaching. It's been a wonderful time to do this project with him in this trimester. I wish nothing but the best to you and your career.

Abbreviations

DC	Direct Current
DL	Down Link
EM	Electromagnetic Wave
HAP	Hybrid Access Point
HTT	Harvest Then Transmit
ICT	Information and Communication Technology
KKT	Karush–Kuhn–Tucker
NOMA	Non Orthogonal Multiple Access
PS	Power Selection
RF	Radio Frequency
SDMA	Space Division Multiple Access
SDP	Semi-Definite Programming
SNR	Signal to Noise Ratio
SWPIT	Simultaneous Wireless Information and Power Transfer
TDMA	Time Division Multiple Access
TS	Time Selection
UL	Up Link
WIT	Wireless Information Transfer
WPCN	Wireless Power Communication Network
WPT	Wireless Power Transfer

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Introduction

Background

[1]Due to the rapid development of the wireless communication, the field for wireless power transfer has been triggered and thus evoke a massive growth in the number of amount of wireless communication devices for virous applications. [2] Including autonomous driving, E-health, safety management, environment management devices.

However, the built-in batteries design which has been conducted for decades, crates the bottleneck for the improvement of wireless communication. [3] Batteries have limited power density, therefore it is impossible to have a life-long device to work 24/7 without any batter replacement or repairing. [4] The frequent battery changing or replacement can be very costly which adds a heavy burden onto the cost of the basic infrastructure.

Therefore, [5]further research and development on WPCN (wireless power communication network) seems to be the promising and effective way to break the bottleneck for the development of the WPCN and prolong the lifetime of the wireless communication system by harvesting energy in the environment by themselves[6]. By realizing this system, the WPCN equipment can be invisibly integrated into the surroundings (walls, clothes, streets etc.).

[7]It is expected that in the next decade, there would be a large amount of needs for the IoT (Internet of Things) devices with around 50 billion wireless communication equipment per square kilometer. It would not be implemented until further development wireless power system be realized. [8] This would also help to reduce the enormous cost for the frequent replacement and repairing for the battery changing and repairing, which can be very time-consuming and cumbersome. During the study of my thesis study, it is found that the limited battery time for the devices has raised huge challenge in the development for the next generation of wireless communication. With more and more devices and wireless sensors nodes are widely deployed in indoors areas, streets and lakes to implement indoor monitoring, like streets, lakes, buildings and other functions. They are usually powered with built-in batteries to do the environmental data collection and information analyzing, and the lifetime of the built-in batteries really limit the service life of the wireless devices. It is possible to replace the batteries regularly in order to extend the lifetime but that would be very costly for the node replacement. Moreover, it is not possible to do the maintenance for the entire system.

[9] Before the idea of WPCN is proposed, it is anticipated that the energy can be harvested from the natural or renewable resources. For example, solar wind, waves and geothermal resources. [10] However, these renewable energy resources are not stable and they are climate and

location dependent, this is pretty difficult to control during some unstable environment. WPCN technology instead, aims to provide a stable energy resource to the system without considering the location nor climate condition. [11]It is estimated that by 2025, the carbon dioxide emissions generated by information and communication industry will be around 2.3% of the total emission of the world. This industry has now become the fifth largest energy-consuming industry in the world since it generates 180 megatons, which is 22% of all the ICT emission and it still continues to grow in the future.

[12] WPCN technology works based on the transmitting and receiving the radio frequency waves (RF) in the radio wave frequency which contains both information and energy to the receiver. [13] More technology related to the wireless communication in the report such as NOMA, WPCN, SWIPT and beamforming work based on the collection RF signals. [14] WPCN is the main technology that is going to be introduced in this report. To solve the problem of short life-time of built-in batteries, WPCN technology has emerged to provide the stable and continuous power supply. By using the far-field radiation features of the electromagnetics wave, the wireless devices used by users receive signal from the single relay, which is powered from the base station. The power and information are transmitted through the electromagnetic wave, this method helps to realize a certain long-distance for the wireless

devices to receive signals remotely from the power station, therefore solving the problem of energy supply. [15]RF is a practical solution with many advantages, it helps to reduce the cost dramatically, it is much more energy efficient and the multicast feature to the nature of electromagnetic waves.

With the help of relay, the power signal can be amplified and transmitted to longer distance user devices. The report discusses the method to maximize power efficiency and data rate, also discuss the way to adjust some parameters to get max power efficiency.

Literature Review

Wireless power transfer (WPT) is firstly proposed by Nikola Tesla back in 1899. [16]The initial purpose of WPT mainly focuses on high power consumption applications in everyday life. Since 1970s, the wireless communication had taken its huge step into people's daily life, its useful functions has been gone deeply into people's work and entertainment. However, there are still many other fields that the wireless communication networks had not been able to provide the needs due to their limited built-batteries. This reality caught the telecommunication engineers' attention and Wireless Power Network Communication (WPCN) technology has emerged, [17]it raised the people's attention who works in the fields and to really study and develop it. WPCN is the technology to realize wireless power transfer (WPT), which is possible for the wireless devices to do the energy harvesting remotely. [18]The wireless communication therefore reduces the times for the people to do the frequency battery replacement, which can be very costly and cumbersome. Compared to the traditional devices powered by the built-in batteries, the WPT dramatically improves the performance for the wireless devices in terms of lifetime and repairing or operation costs. Therefore, it boosts the development of the fields for wireless communications. More people will be interested in working with projects related to WPT.

The history of WPT has never been a smooth drive. [19]The initial propose of WPT raised the public health concerns about the strong electromagnetic radiation which stopped the further development of the projects. The fields for WPT was growing slowly until the booming of the advances in silicon technology. [20] No more health concerns from the people due to strong waves, but a much safer project with the advanced silicon materials. [21] The engineers were attracted by the promising future with changes it might bring to people’s life. The promising WPT technology avoids the high risks for people to do regular replacement, planning and installing. [22] It is expected that would be 10 billion devices at the end of this decade with the potential economic impact of 1.9 trillion per year in the next decade. The continuous study on WPT in both business, industry or academic study would all enable the breakthrough in WPT in the information and communication technology industry sector.

The WPT that is commonly studied and proposed in the industry or academic study is Radio Frequency (RF) based WPT, [23] which is also the type that is discussed in this report. Some other main types for WPT are inductive coupling and magnetic resonant. However, these two types are working based on near-field Electromagnetic (EM) waves which means they do not provide strong mobility to the energy-limited wireless communication devices, thus they need to be charged within a certain charging distances (few meters). The RF based WPT is working on the far-field properties of EM waves, [24] which enables the power and information to be communicated and transmitted within a longer distance, which is around hundreds of meters. RF energy is generated and transmitted everywhere, it can be harvested from the signals radiated by WIFI point, base stations, signal towers and other service stations. The RF is working on a safe frequency and wavelength since it is

by the government policy to ensure safety. [25] WPT is expected to harvest microwatts to milliwatts of power within the range around 10m for the transmitted power of 1W of the carrier frequency less than 1GHz. [26] This amount of power is able to power the small wireless devices like sensors or other little equipment. It is also able to power the big digital electronics, like digital clocks, home use electricity meters, water meters, reducing the incontinence of the regulate battery replacement and repairing.

One main structure for WPT would be Simultaneous Wireless Information and Power Transfer (SWIPT) . [27] It is also the one of the ways to study WPT. SWIPT is able to transmit information and power simultaneously, the Wireless Power Transfer (WPT) and Wireless Information Transfer (WIT) are conducted in one time slot and simultaneously, which means it is transmitting information while the power is also getting transmitted. The SWPIT technology takes

Time-Selection (TS) Signal time slot and Power-Selection (PS) signal time slot separately. [28] It allows the system to switch between PS and TS periodically, the two time slots thus harvest energy and operate information decoding. However in [28] and [29], the existing RF based WPT harvest energy of the incoming signals from its energy-harvesting circuits directly from the RF signal domain. Sometimes, the energy harvesting process would interference with the modulated information, which is the decoded information in the WIT time slot. Therefore, the information decoding would be conducted in the digital baseband, meaning the information decoding and energy harvesting cannot be performed on the same incoming signal. [30] That is to say, for the SWIPT system, the receiver aims to separate the energy harvesting process and information decoding process in order to generate a clearer result for the wireless equipment. The RF waves received by SWPIT receives are containing both energy and information, which defines the rate-energy tradeoff in discrete memoryless channels (DMC), which also defines what is the maximum date transfer rate under the received energy constraints. In the given materials by Doctor Derrick Kwan, it is also proposed that the frequency selective channel would be extended to multi-access or multi-hops characteristics. The channels are also suggested to be bi-directional channels. Thus the channels take TS and PS as separate schemes. This somehow would improve the performances of the entire communication system. There is also another method to do the signals separating, which is to separate signals from radio frequencies, giving another SWIPT receiver to do the front to end decoding and energy receiving. This kind of receiver converts the signals directly to current.

Generally speaking for the SWIPT technology, [31] is more focused on the simultaneous transmitting for both energy and information. It utilizes frequency channels as the media to transmit energy, the information is transmitted along with the orthogonal time. [32] However, for SWIPT technology, the technical requirements for repairing and deployment are considered to be relatively higher than other methods. [33] is not the most suitable solution or the key for the future of the wireless power transfer.

Another direction to study WPT with relatively lower cost or requirements for deployment would be Wireless Powered Communication Networks (WPCN). Its comparatively better simplicity raised engineers' attention and other study era about it. It is also considered that WPCN is going to fit better with the market of WPT and more welcome for other demands in this fields. With different system structure, it's got that better energy efficiency, which helps the development of more low-power wireless devices for IoT fields. WPCN is also the main point in my thesis study and this report.

The bounds for the batter life and lifetime of the wireless powered devices should be broken, wireless devices are not meant to be constrained by the limited power and lifetime due to batteries. The system is designed to look for the balance between energy supply, energy consumption and the data transmitting in order to optimize the maximum throughput for the information and the best power efficiency for the energy transmitting. The wireless powered communication network is composed with three main parts. The sensors from the wireless devices receives the power transmitted from the nearest base stations in the downlink (DL) communication, whereas the uplink (UL) communication indicates the information transmission from the devices to the sink nodes. Once the system structure has been confirmed, the protocol for information transmitting in this new generation is to be confirmed in order to make sure the order, integrity and the sustainability. Harvest Then Transmit Protocol (HTT Protocol) is used in the system. In some paper given, it is said that in WPCN system, there would be interferences within in the signal baseband of the RF. [34] NOMA is proposed by some of the paper and in a few design of WPCN. NOMA is known and proposed to improve the spatial efficiency, as well as for the fairness of the users since all users use one same frequency spectrum simultaneously with successive interference cancellation performing at the receiver. However, its difficulty is beyond my knowledge background and my supervisor cancel this idea. [35] Instead, TDMA is to be used in the WPCN system design with its simplicity and understandability. Later on, during the reading and researching, it is found that by taking into account the circuit energy consumption, spatially efficiency, and energy efficiency, [36] TDMA-WPCN is more considerable with all these parameters and suitable for optimizing the energy efficiency. So from the network perspectives and users' perspectives, TDMA-WPCN would be a better solution. [37] TDMA would efficiently removes shares channel interferences. And based on some math equations, an optimization solutions would be used to maximize the throughput of the data transfer and energy transmission. In [38], based on the examples and calculations, there is possibility of link losses in the system throughput, and the author proposes a method to maximize the throughput. By combining HTT protocol with TDMA technology, the signal inferences among wireless communication equipment is able to be eliminated, therefore increasing the efficient and capacity.

The design for the WPCN system is closely related to its performance and the total power consumption, which results in various optimizations raised by engineers and people who work in the fields. [38] It has attracted many attentions and therefore countless ideas for optimizing the systems are raised in the book and paper. The ideas are mainly based and reflected in two aspects :

(1) The asymmetry between the information transmission in the downlink and in the uplink.

(2) Transmission in the DL and in the UP are coupling with each other.

Due to the special characteristics of WPCN, the power transmission and information transferring are conducted in different time slots due to TDMA. [39] Therefore, it is necessary to optimize the allocation of energy and information and equally consider the energy harvesting and data transferring. In the design proposed in this thesis report, a single-antenna WPCN transmission model is to be optimized with multiple wireless devices. A single antenna wireless access point (HAP) and multiple wireless communication devices to construct the whole WPCN system.

In this WPCN network system, it utilizes energy from base stations in the hybrid network system, which is used as the energy resources. The purpose of this optimization idea is to maximize the energy throughput and the maximum efficiency for data transmission. [40] The different slots for both data transferring need to be allocated reasonably in the DL and UP for WPT as well as WIT under the idea of guaranteeing in the maximum transmission power. It is also proposed that a full-duplex wireless hybrid access point is applied in order to transfer the power to the wireless devices from the users. However, information interferences always occur in a WPCN system structure with hybrid access point caused by its operation model. Since users are transferring information data, information data rate is what most concerned in this process. [41] During transmission, it is inevitable to have noises in the channels. This may be from the ambient signals or EM waves, or the noises from the circuits within themselves. [42] Shannon Theorem is applied here to demonstrate the maximum rate at which the information can be transmitted in the wireless communication channel with the existence of noise and a given bandwidth. The theoretical upper bond of the information transmission data rate at the low error rate with SNR will be calculated with Shannon Theorem.

[43] In future 5G communication, a clean communication environment is very essential. Therefore the main focus of this report is to find the solution to maximize the energy efficiency and consider the power and time slots allocation. The electromagnetic waves have a decline in the process of transmission, therefore multi-antenna technology is introduces in the system WPCN research. This new idea enables the central node to regulate the power beam signal direction through adjusting multiple antennas in a different way of transmitting. It efficiently increase the energy signal received by the wireless devices. In the paper given, it is to be suggested that the single-antenna HAP is extended to multi-antenna HAP. The authors in the paper given applies the idea of SISO wireless energy transmission in a MISO system, the

redesigned energy beam is designed to be Space Division Multiple Access (SDMA), the background knowledge required for SDMA is somehow beyond my boundary. It effectively eliminate the near-far problem by maximizing the throughput in the DL from the wireless devise. The [44] also discusses the difference between the resources allocation in MISO and MIMO, and studied the optimization of power transmission. All the WPCN system in the paper is designed and constructed based large amount of study and research to find the joint optimization of channel length estimation, energy and data transmission. [45] gives the research on the multi users in a relative simpler MIMO systems design based on the wireless energy transmission. It unites the MISO technology with energy beamforming transmitted by multiple antenna ad received by multiple antennas. The authors in [46] discusses the effects from using the energy beamforming technology to realize allocate harvested energy for users. The research from [47] demonstrates the idea of how energy beamforming technology improves the energy efficiency as well as transmission rate.

Generally speaking, with all the research paper given, they all indicate that energy beamforming is the main factor as the key for multi-antennas and multi-users system for the potential development in the future study of WPCN system or for the future development and its wide use in 5G communication.

System Model and Problem Formulation

System Model

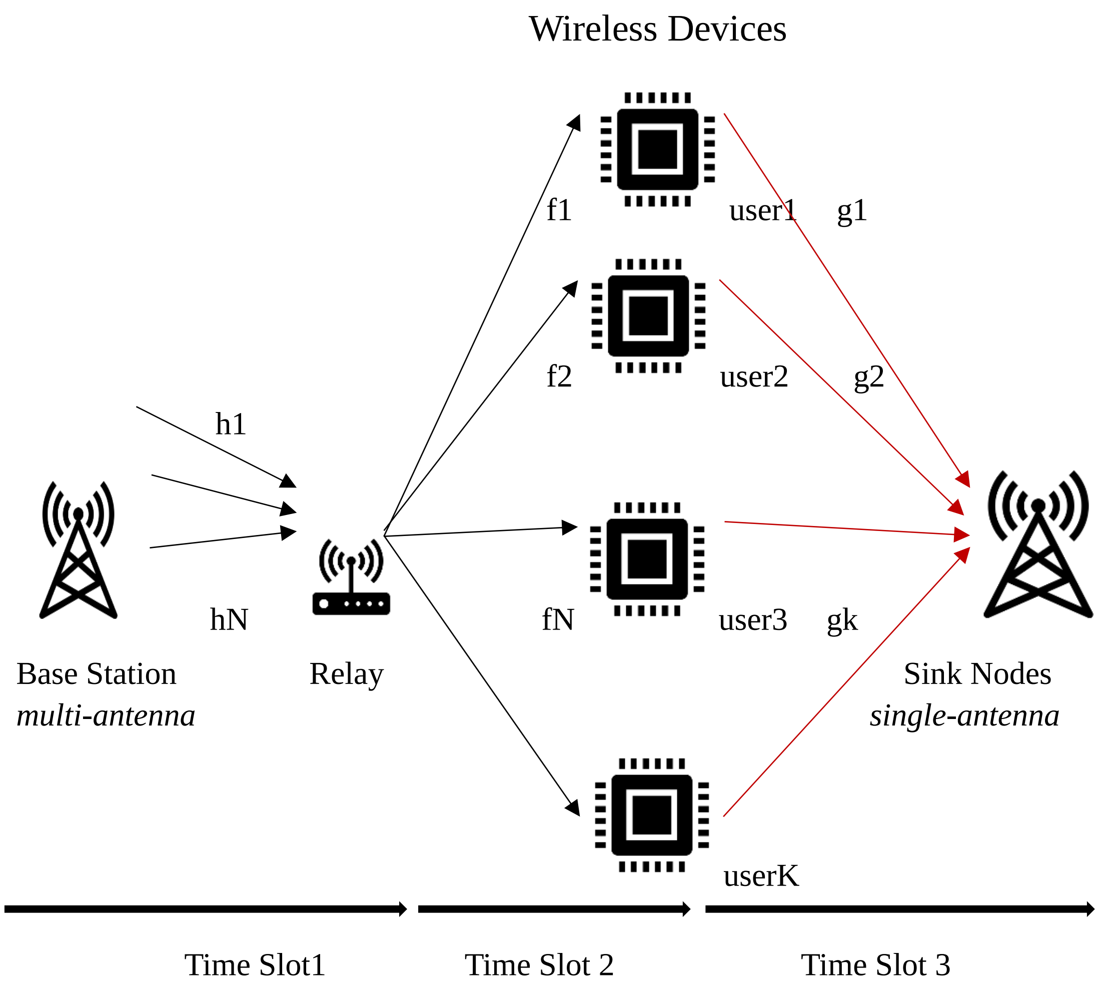

Figure1 System Model of multi-user WPCN

: Energy Transfer

: Information Transfer

The paper considers a WPCN system with multiple users with multiple devices used by multiple users as shown in the figure above. The system is composed with a base station, which can be also seen as a power station to power up all the wireless devices. It is assumed as a multi-antenna power transmitter. It is composed with multiple antennas, the number of antennas is to be defined as N shown in the figure since it is also consumed that there are N number of devices need to be powered up by the base station and then they will transmit the information to the sink nodes, which is considered as the information access point. Each antenna used to process to do energy transferring and information transmitting is marked as hk(h1,h 2…,hk) in the DL, and gk(g1, g2…,gk) in the UL. The relay between the base station and the wireless devices is assumed to have multiple antennas. The relay is designed to retransmit the power from the power station to the devices in order to broad the range of the whole communication system, the sources and the destinations in the system are interconnected by some nodes. Since in some situations, the source and destination cannot be connected due to the long distance or by some other obstacles between the source and the destination.

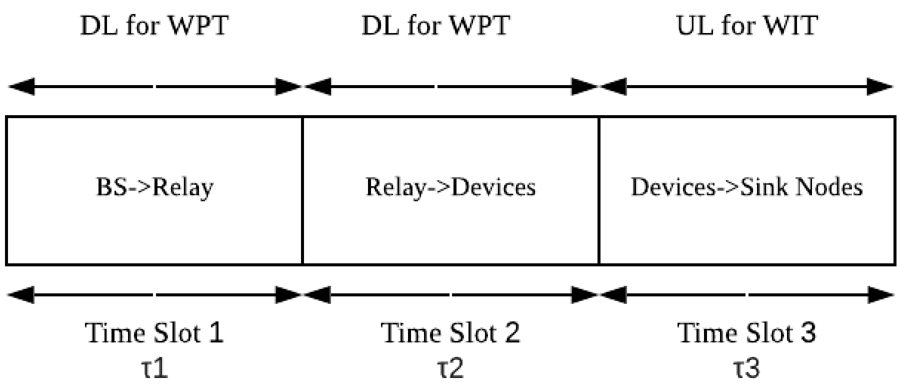

Figure2: TDMA

The WPCN system in the design is assumed to be applied with Time Switching method (TS) which separates the power transferring and information transferring into 2 different time slots. This scheme is more flexible and adjustable to have different performances. The receiver in the WPCN system aims to switch between the co-located energy harvesting circuit and information decoding circuit for harvesting energy and decoding information in successive time slots.

The main idea to this design is to take the time switching method (TS) signal separation scheme and the power switching method (PS) signal separation scheme into consideration and then allow the receivers switch periodically switch between two time slots to harvest energy and operate information decoding. [48] This kind of receiver did improve the performances of the communication system. This report mainly focuses on the last step, which is in the uplink from the devices to the sink nodes. The aim is to maximize the throughput of data and also the power transferring. The frequency band that used to transfer power and information is assumed to work over the same frequency band. Working on same frequency would result in frequency interferences. Therefore, for the intention of eliminating frequency interferences, the energy transferring and information will be conducted based on Time Division Multiple Access method (TDMA) like shown in figure 2, each device will operate WPT and WIT in different time slots in order to be flexible in the system.

The total time for the system to operate is marked as T. It is divided into 3 time slots, the sum of each time duration operated by single time slots is denoted by $\tau_1\,\tau_2\,\tau_3$ as show in figure 2. The restriction for the operation time would have such equation:

$$\tau_1 + \tau_2 + \tau_3 \leq T \;\;,\;\; \tau \geq 0 \qquad (1)$$

τ_1 denotes the first time slot arranged for wireless power transmission. It is radiated from the base station with the media of radio frequency signal to the relay between the power station and the devices. τ_2 shows the time slot where the energy is retransmitted from the relay to the devices since the relay here is to minimize the probability of outage problem. τ_3 denotes the time slot for the information transferring from the devices to the sink nodes, which also can be seen as an information access node. The details of operation of the whole system will be explained in the later part of the report.

Downlink Wireless Energy Transfer

Power Station to Relay

The system model contains a power station as the energy source, a relay aims to minimize the outage probability, since multiple users need to harvest energy and get powered up, and finally to the sink nodes as the information terminal. The power station in the thesis design model is assumed to have multiple antennas for transmitting signal, and marked as number N1. N1 number of antennas transfer their power signal to the relay simultaneously. The channels are described in channel vector between the power station and relay as $\vec{h} \in N1*1$ describing the vector size of N1*1. [49] The channel vectors describe the channel direction from a certain antenna to another antenna, the both ends can be described and expressed as a number in the channel vector. (Eg. h1 would be the first antenna of the power station to the relay, hN1 would be the N1th antenna of the power station to the relay). Each channel information is recorded in the channel vector and further analysis of the channels would be much simpler and easier.

Since we are using the beamforming technology, [49] it makes the use of the difference between the desired signal and the interference signal in terms of spatiality characteristics, such as initial emitting angle, phase, amplitude, approximately weights of the antennas on the power station to make constructive interference for the waves at the receiver. They are represented in complex number that describes the waves' phase and angle in the channel. [50] Therefore beamforming vectors contains a serious of complex number in exponential form. It is expressed as $\vec{w} \in 1*N1$ with the size of 1*N1. N1 waves transmitted with certain angle and amplitude in order to isolate the desired signals and interference signals, thus constructive interference can be made at the receivers. Therefore, beamforming can improve the capacity and the quality of the wireless communication, enhancing the desire signal and the suppression of the interference signal.

The total power transferred from the power station would be:

$$P_{in} = |h^H \vec{w}|^2 \tag{2}$$

Relay to Users

The total power harvested by the relay would be:

$$P_{relay}^{Power\ Harvest} = \eta_r |h^H \vec{w}|^2 \tag{3}$$

The reason why we have a power efficiency η_r here is because the relay consumes part of the energy it harvested to maintain the requirement of the power consumption of itself to do the signal transmission, harvesting efficiency characteristics also plays a role in decreasing the energy received. If the time duration of time slot 1 is taken into account, the total energy harvested by the relay would be:

$$E_{relay}^{Energy\ Harvest} = \tau_r \eta_r |h^H \vec{w}|^2 \quad (4)$$

All the power signals form the power station is conducted in the first downlink between the power station and the relay. [51] The co-located circuits in the relay can perform energy harvesting, information decoding, and energy transferring in successive time slots. Different functions in the relays switch parodically in order to have different performances. Once the relay get powered up, it will transfers the rest of the power signal to all the users and power them up. The math constraint for the power signal transferred from the relay would be

$$Contraint\ \tau_2 P_r \leq\ E_{relay}^{Energy\ Harvest} \quad (5)$$

The total energy the relay transfers must be equal or less than the total energy it harvested from the base power station. Again, different channels between the relay and the users are described in the channel vector f from f1 to fN2 (N2: the number of total users harvest energy from the relay).

Uplink Wireless Information Transfer

Users to Sink Nodes

Self-powered users firstly harvest energy from the relay in the downlink, then transfer information in the uplink to the sink nodes. The total power received by all users would be

$$P_{users}^{Power\ Harvest} = P_r |f_k|^2 \quad (6)$$

(multiplication of the channel vector and the power). If time slot 2 is take into account into the formula, the total energy received by the users would be

$$E_{users}^{Energy\ Harvest} = P_r |f_k|^2 \tau_2 \quad (7)$$

One of the main goal in the design is to maximize the power received by the users in order to prolong the lifetime of the users.[52] Energy normally communicates via electromagnetic wave (EM) in the radio frequency band. The RF signals of the propagating signals transmitted can be recycled and reprocessed at the users or other receivers therefore to extend the lifetime of the self-powered devices, RF signals contain both energy and information, and that energy is sufficient to support the power consumption required for the users to do the information transmission.

The last step would be the information transmission from the users to the sink nodes, which is conducted in time slot 3. During this process, there is no energy nor power signal transmission but information transmission instead. [54]TDMA technology is applied during this step as all the users share one same frequency spectrum channel but in different time slots. The signal is divided into different time slots so that each user will not interference with each other (user1 in time slot $\tau_{3,1}$, user2 in time slot $\tau_{3,2}$, userN2 in time slot $\tau_{3,N2}$). Since users are in successive time slots, individual user communicates in their own time slot in order to avoid the interference in the channels. TDMA has its advantages in spatially efficient and energy efficient. It seems to be a satisfying solution for spatial ad energy-efficient IoT devices (IoT networks with energy constrained devices).

Again, the math constraints for the power transmitted from the users to the sink nodes are expressed as

$$\tau_{3,k} \ P_{users}^{PH} \leq E_{users}^{Energy\ Harvest} \tag{8}$$

which means the total energy transmitted from the users must be equal or less than the total energy received by the users from the relay. Information signal is transferred consecutively in the order of use by different devices. The total sum of the time for each user to transfer information signal must be less than the total time slot 3 in order to finish the process. This constraint can be described in the math formula as

$$\sum_{k=1}^{K} \tau_{3,k} \leq \ \tau_3 \tag{9}$$

However, [62] and [63] the single time slot for individual user may not be equally split, different length time slot can be applied to users based on their needs and throughput of the information signal.

Since users are transferring information data, information data rate is what most concerned in this process. [55] During transmission, it is inevitable to have noises in the channels. This may be from the ambient signals or EM waves, or the noises from the circuits within themselves. Shannon Theorem is applied here to demonstrate the maximum rate at which the information can be transmitted in the wireless communication channel with the existence of noise and a given bandwidth. The Shannon Theorem states that:

$$C=\log_2(1+SNR) \tag{10}$$

[56] where C is the maximum channel capacity, the theoretical tightest upper bond of the information transmission data rate at the low error rate with SNR (signal to noise ratio).

$$SNR_k = \frac{S}{N} = \frac{P_k|g_k|^2}{E^2} \tag{11}$$

[60] SNR is expressed as above, where S is the avenge received signal by the users (all devices) through the channel. [54] N is the average power of the noise in the channel and other interferences over the given bandwidth. S and N are measure in Watts (W).

Maximum data rate from all users to sink nodes can be expressed by summing all individuals users, which can be expressed as:

$$max\colon \sum_{k=1}^{K} \tau_{3,k} \ \log_2(1+\frac{P_k|g_k|^2}{E^2}) \qquad (12)$$

Where $P_k|g_k|^2$ is the average signal received by all users from the relay, E^2 is the average signal of the noise (especially white Gaussian noise and the interference in the channels or from the circuits within).

This is the most important equations in the thesis design which combines all the parameters that show up in all steps of the system. By playing around with all these parameters, we can test and simulate the maximum throughput from users to the sink nodes. Creating constraints is essential in the thesis design as it provides the limitations and direction to the system model, the math formulas make the system model make sense and traceable in every step and process, it is easier to check the logic and function of all the system model. Of course, these formulas may be changed or corrected in the future plan of designing in order to maximize the throughput of the model.

In conclusion, the aim of this WPCN system model design is to maximize the throughput of the users by considering all parameters created by making constraints. Since we apply beamforming technology, beamforming vector is considered in the system model design. All the self-sustained or self-powered devices are designed to have built-in batteries just in case of breakdown of the energy harvesting. TDMA technology is also used in the system model, therefore the total energy from the users should be the sum of all individuals. The optimization problem can be expressed by the summary of following:

Maximizing: $\sum_{k=1}^{K} \tau_{3,k} \;\; \log_2(1 + \frac{P_k |g_k|^2}{E^2})$

(13)

Constraints:

1. $\tau_1 + \tau_2 + \tau_3 \leq T$, $\tau \geq 0$

2. $\tau_2 P_r \leq \; E_{relay}^{Energy\ Harvest}$, $\tau_2 \geq 0$

3. $\tau_{3,k} \;\; P_{users}^{PH} \leq E_{users}^{Energy\ Harvest}$, $\tau_{3,k} \geq 0$

Solution for Optimization Problem

The primary method to get the optimal solution is by solving the convex formulations. However, it is not hard to find that the optimization formulations above are not all convex constraints, meaning the first task to be done is to transform the non-convex constraints to convex constraints through some transformations. It is defined that the general form of the optimization equation is to look for:

$$f(x^*) = \min\{f(x): x \in \chi\} \tag{14}$$

In the above equation, x denotes a n-dimension size vector and it is feasible in the region of x. f(x) is a real-valued function.

A convex function is defined as $f : R^n \rightarrow R$ if the domain of f is a convex set and:

$$f(\theta x + (1 - \theta)y) \leq \theta f(x) + (1 - \theta)f(y) \tag{15}$$

for all $x,y \in$ dom f and $0 \leq \theta \leq 1$. If x in the general expressing of optimization solution is a closed convex set, with f is a convex function on the set of x, then it is considered that the optimization problem is a convex optimization problem. It is not hard to find that my constraints 3 and 4 are non-convex due to the variables

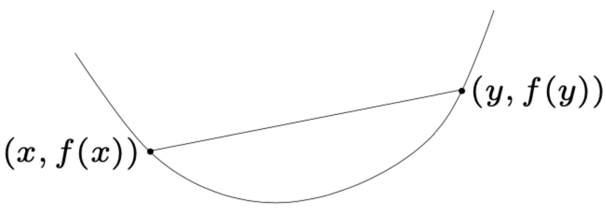

Figure3: Convex Curvature

It is defined that if f is concave, then -f would be convex. f is strictly convex if the domain of f is convex and also

$$f(\theta x + (1 - \theta)y) < \theta f(x) + (1 - \theta)f(y). \qquad (16)$$

for $x,y \in \mathrm{dom} f$, $x \neq y$, $0 < \theta < 1$.

Once it gets to know the basic characteristics of the convex problem or optimal solutions, determining whether the constrains in the optimization problems are convex depends on 3 basic definitions:

1. If the objective optimal function is non-convex, then it would be non-convex.
2. If the primal variable x contains discrete variables (discrete variable means 0-1 variables or integer variables), then it would be a non-convex optimization problem.
3. If the contains for $g(x) \leq 0$ and $g(x)$ is not a convex function, then it would be a non-convex optimization problem.

After the basic ideas of looking at the optimal constrains in terms of convex, it is not hard to find that the constrains 2 and 3 are non-convex. Constrains 1 and 4 would leave as what they are and stay the same for the further calculations. The objective function for the WPCN system is also non-convex due to the variable $P_k|g_k|^2$.

Transformations for the non-convex formulations to convex formulations is essential in this scenario. [57] The key idea to do the transformation is to

1. Converting the objective formula from non-convex to con-vex.
2. Abandoning certain constrains that result in non-convexity.

In this case, I would transform the variable by expressing it in another way with some other equivalent expressions since it causes non-convexity. The reason to transform non-convex into convex is due to that it is impossible to solve the optimal solution with the constraints non-convex. Since for the non-convexity the feasible domain is continuous. Semi-definite is also involved in the process solving. The processes in solving optimal solutions can be demonstrated as:

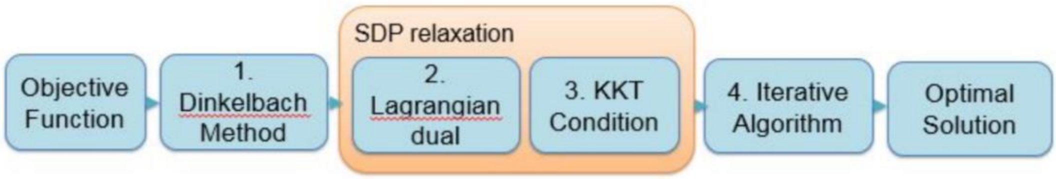

Figure 4:Optimization Formulation Process

SDP relaxation is an effective and efficient way to eliminate the unwanted non-convexity in the formulas. The first step in the project is to transform $\tilde{P}_{3,k} = \tau_{3,k} P_k$, $\tilde{w} = \sqrt{\tau_1}\ \vec{w}$. Thus constraints become:

$$2.\tau_2 P_r \leq E_{relay}^{Energy\ Harvest} \rightarrow \tau_2 P_r \leq \tau_1 \eta_r |h^H \vec{w}|^2 \rightarrow$$

$$\tilde{E}_{2,r} - \eta_r |h^H \vec{w}|^2 \leq 0 \quad (17)$$

$$3.\ \tau_{3,k}\ P_{users}^{PH} \leq E_{users}^{Energy\ Harvest} \rightarrow \tilde{E}_{3,k} - P_r |f_k|^2 \tau_2 \leq 0 \rightarrow$$

$$\tilde{E}_{3,k} - \tau_1 \eta_r |h^H \vec{w}|^2 |f_k|^2 \leq 0 \quad (18)$$

However, it also assumes that $\|\widetilde{w}\|^2 = \eta_r\|w\|^2$ with Rank(w)=1, w≥ 0. Matrix h^H & f_k^h are matrix of dimension 1*N and matrix of dimension of N*1. $h^H * h = H$; $f_k^h * f_k = F_k$ are the power transmitted from the relay or the base station. In constraint C2, we have:

$$|h^H\widetilde{w}|^2 \rightarrow h^H\widetilde{w}^H\widetilde{w}h \rightarrow \mathrm{Tr}(h^H\widetilde{w}^H\widetilde{w}h) \rightarrow Tr(\widetilde{w}h^H h) \quad (19)$$

In constraint C3, we have:

$$|f_k h^H\widetilde{w}|^2 \rightarrow f_k^H f_k h^H\widetilde{w}^H\widetilde{w}h \rightarrow \mathrm{Tr}(h^H\widetilde{w}^H\widetilde{w}h) \rightarrow Tr(\widetilde{w}h^H h) \quad (20)$$

Thus until now, to reorganize the functions. The objective and all the constraints have transformed to convex.

Objective : Maximizing: $\sum_{k=1}^{K}\tau_{3,k}\ \log_2(1 + \frac{\tilde{P}_{3,k}|g_k|^2}{\tau_{3,k}E^2})$

(21)

1. C1: $\tau_1 + \tau_2 + \tau_3 \leq T$, $\tau \geq 0$
2. $\overline{C2}$: $\tilde{E}_{2,r}$ - $\eta_r Tr(\widetilde{w}h^H h) \leq 0$
3. $\overline{C3}$: $\tilde{E}_{3,k} - \eta_r Tr(\widetilde{w}h^H h f_k f_k^h) \leq 0$
4. C4: $\sum_{k=1}^{K}\tau_{3,k} \leq \tau_3$, $\tau_{3,k} \geq 0$

After replacing the constraints with new name and thus they are all transformed into convex formulas. [58] The SDP reformulation helps to reshape the convex optimization problem due to constraints 2 & 3 involves the combinational rank constraint.

The non-convexity is due to constraints 2 and 3 on the information bearing $\tilde{P}_{3,k} = \tau_{3,k}P_k$. In general, there is no standard way to solve non-convex optimization problem. In some extreme cases the way to solve the optimal solution is by brute forces approach and that requires to obtain a global optimal solution which is computationally intractable for a moderate system size. [59] states that in order to derive an efficient resource allocation algorithm for the problem by importing the idea of SDP. And thus in this part, SDP aims to prove that SDP relaxation to the optimal solution will have no effect on the convexity. Due to the duality characteristics of the problem, the maximization and the minimization problem can be seen as dual pair of problems and they can be converted to each other.

The general form for optimization with inequality is expressed as:

$$\begin{aligned} &\underset{x}{\text{minimize}} \quad f(x) \\ &\text{s.t.} \quad g_i(x) \le 0, i = 1, \dots, I \\ &\quad h_j(x) = 0, j = 1, \dots, J \end{aligned} \tag{22}$$

The Lagrangian function can thus be written as：

$$\mathrm{L} = f(x) + \sum_{i=1}^{I} \lambda_i g_i(x) + \sum_{j=1}^{J} \beta_j h_j(x) \tag{23}$$

To facilitate the transformation of SDP relaxation, $\tilde{E}_{3,k}$ is transformed into $\tau_{3,k} p_k$. Upon rearranging terms, the Lagrangian function can be written as:

Objective: $\sum_{k=1}^{K} \tau_{3,k} \ \log_2(1 + \frac{\tilde{E}_{3,k}|g_k|^2}{\tau_{3,k}E^2})$

(24)

2: $\sum_{k=1}^{K} \lambda_k \left(\tilde{E}_{2,r} - \eta_r Tr(\widetilde{w} h^H h)\right)$

3: $\sum_{k=1}^{K} \beta_k (\tilde{E}_{3,k} - \eta_r Tr(\widetilde{w} h^H h f_k f_k^h))$

$$L = \sum_{k=1}^{K} \tau_{3,k} \ \log_2\left(1 + \frac{P_k|g_k|^2}{E^2}\right) - \sum_{k=1}^{K} \lambda_k \left(\tilde{E}_{2,r} - \eta_r Tr(\widetilde{w} h^H h)\right) - \sum_{k=1}^{K} \beta_k (\tilde{E}_{3,k} - \eta_r Tr(\widetilde{w} h^H h f_k f_k^h))$$

$$L = \sum_{k=1}^{K} (\tau_{3,k} \log_2(1 + \frac{\tilde{E}_{3,k}|g_k|^2}{\tau_{3,k}E^2}) - \lambda_k(\tilde{E}_{2,r} - \eta_r Tr(\widetilde{w} h^H h)) - \beta_k(\tilde{E}_{3,k} - \eta_r Tr(\widetilde{w} h^H h f_k f_k^h)))$$

L$(\lambda_k, \beta_k, \tau_{3,k}, k, p_k,)$ where λ_k and β_k are the Lagrangian multipliers associated with the subcarrier usage constraints with elements:

$$\lambda_k, k \in \{1,...,K\} \ \& \ \beta_k, k \in \{1,...,K\} \quad (25)$$

$$\min_{\lambda_k,\beta_k \geq 0} \ \max_{\tau_{3,k},k,p_k} \ L(\lambda_k, \beta_k, \tau_{3,k}, k, p_k) \quad (26)$$

The KKT conditions explains that the optimal values has to meet requirement:

$$\frac{\partial L}{\partial \tilde{E}_{3,k}} = 0 \quad (27)$$

For the duality of the problem, the constraint condition has to be:

$$\lambda_k, \beta_k \geq 0 \quad (28)$$

By dual decomposition, the BS first solves the following layer 1 subproblem:

$$\max_{\tau_{3,k},k,p_k} \ L(\lambda_k, \beta_k, \tau_{3,k}, k, p_k) \quad (29)$$

Once the KKT condition is applied, the complementary slackness should be met in the derivation:

Whenever (30)

$$\lambda > 0 \rightarrow \; g_i(x) = 0$$

$$\lambda \; = 0 \rightarrow \; g_i(x) < 0$$

What it wants is $\lambda_i g_i(x) = 0 \; with \; \frac{\partial L}{\partial x}$ = 0 as shown in formula above. Once KKT condition is applied and Lagrangian equation is written down, four main characteristics of KKT should be met or proved. The KKT conditions mean that the optimal value must satisfy the stability condition:

$$\frac{\partial L}{\partial \tilde{E}_{3,k}} = 0 \; \rightarrow \; \frac{|g_k|^2}{E^2 log2(\frac{|g_k|^2 p_k}{E^2}+1)} = \beta_k \tag{30}$$

The objective is to minimize the noises in the channel due to shadowing, path loss multipath fading or frequency interferences. When the objective is differentiated w.r.t $\tau_{3,k}$:

$$\frac{\partial L}{\partial \tau_{3,k}} = \frac{log(\frac{|g_k|^2 p_k}{E^2})}{log2} - \frac{\tilde{E}_{3,k}|g_k|^2}{E^2 \tau_{3,k} log2(\frac{|g_k|^2 p_k}{E^2}+1)} \tag{31}$$

$$\text{Since :} \frac{|g_k|^2}{E^2 log2(\frac{|g_k|^2 p_k}{E^2}+1)} = \beta_k \tag{32}$$

$$\text{Therefore:} \; \frac{\partial L}{\partial \tau_{3,k}} = \frac{log(\frac{|g_k|^2 p_k}{E^2})}{log2} - \frac{\tilde{E}_{3,k}|g_k|^2}{E^2 \tau_{3,k} log2(\frac{|g_k|^2 p_k}{E^2}+1)} \tag{33}$$

$$\frac{\partial L}{\partial \tau_{3,k}} = \frac{log(\frac{|g_k|^2 p_k}{E^2})}{log2} - \beta_k p_k \tag{34}$$

The problem can be solved by standard solvers.

Due to the duality of the problem the minimization problem can be solved by its dual problem.

By differentiating L w.r.t $\tau_{3,k}$ we get:

$$\frac{\partial L}{\partial \tau_{3,k}} = \frac{log(\frac{|g_k|^2 p_k}{E^2})}{log2} - \beta_k p_k \qquad (35)$$

$$\tau_{3,k}{}^{*} = max_k\{log_2(\frac{|g_k|^2 p_k}{E^2}) \qquad (36)$$

Only one user is selected for maximin the throughput.

Simulation Results

Table 1: Simulation Parameters

BS to Relays	10 meters
Relay to Users	40 meters
Users to Sink Nodes	100 meters
Carrier Frequency	915 MHz

In this simulation results sections, it evaluates the WPCN system performance for the purpose of this system design. The optimized design aims to reduces noises from the users/devices to the sink nodes due to path loss, shadowing or other gaussian noises occurred due to frequency interferences or built-in electronics components in the circuits. The path loss model for indoor or outdoor environment. The results are simulated in MATLAB with the simulation parameters showed in the table. the simulation observes the relationships between the extra equipped antennas versus the throughput of the system. The downlink from the relays to the users can be considered as since all devices are single-antenna structured. For the real situation consideration, the power station should have a budget Pmax to limit the power consumption or the cost for the system.

The first figure below shows the relationship between average throughput versus Pmax due to the number of extra equipped antennas on the base station. It can be observed that in the graph with a fixed Pmax required for the base station, as well as with the fixed distances between base station and users and a fixed distance between users and the sink nodes, the more extra equipped antennas on the base station, the better the system performance will be. On the other hand, it demonstrates that if a fixed system throughput is required, the more antennas on the base station, the less Pmax will be for the base station. Therefore, the number of antennas helps to reduce the power consumption cost for the system.

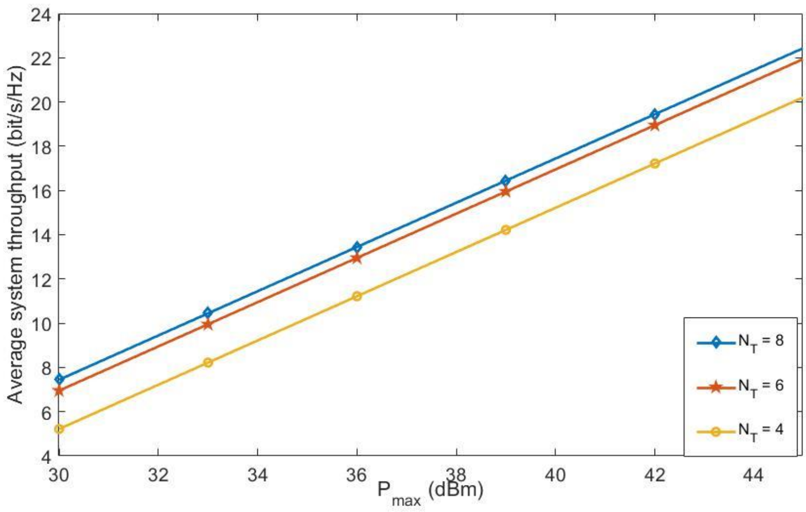

Figure 5: Average Throughput vs Pmax

In the next figure, same amount of extra equipped antennas are examined in the simulation with N=4, N=6 and N=8. In the graph, the results reveal that with the same distance between users and the sink nodes, in order to save more transmitting power, the more antennas should be installed in order to get larger system throughput. It shows a different trade-off in the system under the intention of optimal beamforming vector scheme. It demonstrates the ups and downs between different numbers antennas and different distances from users to the sink nodes. The longer the distances between the user and the sink nodes, the energy will be more relayed to the energy losses due to path loss or other factors.

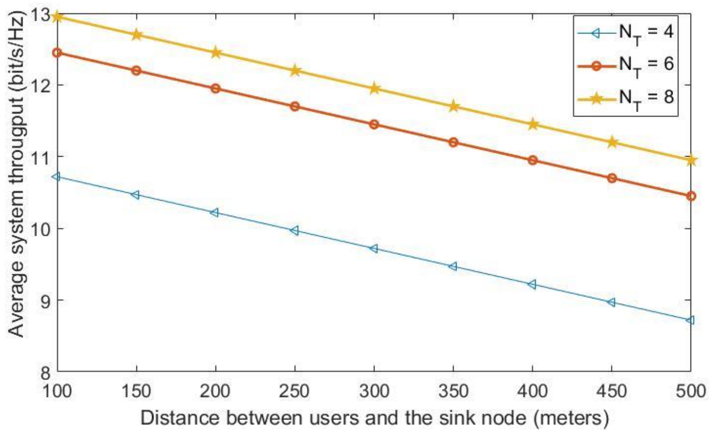

Figure 6: Average System vs Distance Between Users and Sink Nodes

Generally speaking, with some fixed conditions for base station, fixed distances between users and sink nodes, the more the antennas installed on the power station, the better the power efficiency it would be for the system. In realistic condition for the WPCN system, power consumption is always considered in the system. Therefore all aspects should be considered in the simulation.

Conclusion

In this report, I propose a design for a multi-user WPCN system with a multiple-relay relay for a real life use situation. The key technology for the design is beamforming technology, it takes the advantages of the spatial characteristics in order to make an more efficient transmission for the system, and thus better system performance. The very first intention of this design is to make transition for the wireless communication devices from built-in battery powered into wireless powered. It aims to open a greener communication system generation based on wireless power transfer as it is expected that there would 10 trillion wireless powered devices around the world. It is definitely essential and urgent to do the new design for the system.

After, the design discovers the importance of time allocation for both WPT and WIT into different time slots. Based on this design, the system would be more flexible and efficient. The core of this report aims to show the optimal algorithm for the multi-user WPCN to optimize its efficiency. It is done by introducing serious transformation from non-convex to convex. SDP relaxation plays an important role in solving the optimal solution, converting the problems in order to get the ultimate optimal solutions.

It is still going to take a much longer time and further work to study this WPCN design in terms of security, or pursuing even better efficiency. In the future, the system would be widely used for public through microwave frequency channel, a more secure channel and greater transmitting capability.

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