Ph.D. DISSERTATION

# Sum Rate Maximization Using Time Scheduling in Wireless Powered Communication Networks

무선 전력 전달 네트워크에서의 시간 자원 할당을 통한 총 전송률 최대화

BY

YEONG-WOO KO

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지도교수 노 종 선

이 논문을 공학박사 학위논문으로 제출함

2020년 2월


서울대학교 대학원

전기 · 정보 공학부

고 영 우


고영우의 공학박사 학위 논문을 인준함

2020년 2월

위 원 장: ____________________

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# Abstract

In this dissertation, two main contributions are given as;

i) Power level modulation of the downlink signal for uplink time scheduling to maximize sum rate in wireless powered communication networks (WPCNs)

ii) Formulation of sum rate maximization problem to maximize sum rate in WPCN with relay and multi-user pairs.

First, an uplink scheduling scheme is proposed via downlink signal design for WPCN. Although harvest-then-transmit protocols and related optimal resource allocation problems were studied, explicit methods of transmitting the scheduling information have not been considered in prior works. For uplink time scheduling, a design of the downlink energy signal with power level modulation is proposed, which conveys the scheduling information to users. Hybrid-access point (H-AP) allocates different power levels to the subslots of the downlink energy signal and the users recognize their uplink subslot lengths from their corresponding downlink subslots' power levels. The uplink time scheduling can be optimized based on the user channel state with respect to sum rate. The sum throughput maximization problem is formulated for the proposed WPCN scheme using a convex optimization problem. The proposed WPCN scheme in a noisy environment is also considered. The solution to the proposed WPCN scheme provides the optimal downlink and uplink slot lengths. Numerical results confirm that the throughput of the proposed WPCN scheme outperforms that of the conventional schemes. The improvement of performance is shown even in imperfect synchronization scenario.

Second, a special case of WPCN is considered, that is, a WPCN with relay and multi-user pairs, which was not considered in the previous study of WPCN. In the proposed system model, calculate the sum rate of each user pair. The sum throughput maximization problem is formulated in the WPCN using a convex optimization problem. In addition, an opportunistic scheme is considered. Using the proposed scheme, the harvested energy of the users is increased more efficiently, which shows that higher sum rates can be achieved. The simulation results show that the proposed scheme shows better performance than the conventional equal resource allocation scheme.

**keywords**: Energy harvesting, hybrid-access point (H-AP), relay, resource management, wireless powered communication network (WPCN)
**student number**: 2014-21612

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# Chapter 1

# INTRODUCTION

## 1.1 Background

Energy durability has always been an important issue in wireless communicaiton networks. Many researches have proposed energy saving protocols and transmission schemes for longer battery life. As an alternative to conventional energy harvesting techniques such as magnetic induction or other types of wireless power transfer (WPT), application of energy harvesting (EH) using radio-frequency (RF) signal was introduced in [1]. Recently, wireless powered communication networks (WPCNs) have been proposed for wireless communication environment such as sensor networks or internet of things (IoT) [2], [3]. Such radio-frequency energy harvesting (RF-EH) has emerged as an alternative solution for prolonging the lifetime of wireless devices.

There are two main research categories for RF-EH based wireless communication systems, which are simultaneous wireless information and power transfer (SWIPT) and WPCN. In the SWIPT, wireless energy transfer (WET) and wireless information transmission (WIT) are simultaneously accomplished in the downlink [4]-[6]. However, in WPCN, there is no downlink data transmission. A hybrid-access point (H-AP) broadcasts only energy transfer RF signals in the downlink phase and users charge their energy storages such as batteries or supercapacitors from received WET signals. In the uplink phase, users transmit their WIT signals to the H-AP using harvested energy.

A harvest-then-transmit protocol was proposed for an efficient establishment of WPCN in wireless sensor networks [7], where the H-AP broadcasts a WET signal in the downlink phase and recovers user messages from the WIT signals in the uplink phase. Time division multiple access (TDMA) was adopted in the uplink, where time slots are optimally allocated to each user for maximizing the uplink throughput. In [7], a general scheme for wireless powered cellular networks was studied, which incorporates a two-way information transmission together with energy transfer in the downlink from the H-AP to the cellular users. Heterogeneous WPCNs were also studied, where EH nodes and non-EH nodes coexist in [9] and WPCN with full-duplex was considered in [10]. However, the previous works [7, 8, 9, 10] miss the discussion on how to provide the scheduling information to users.

For WPCNs with an energy storage constraint, the optimal downlink power allocation policy was proposed in [11], where the transmitted downlink signals have different power levels in the time slots. The H-AP concentrates all available energy in the first few downlink time slots but the power profile does not carry any scheduling information in [11]. However, we intend to use such a power level variation of the WET signal for information transmission to users.

In this dissertation, we assume a WPCN composed of an H-AP and users without information receiver, which is a feasible assumption in sensor networks. We focus on how to schedule the users' uplink transmission time according to a quasi-static fading channel. We propose a power level modulation of the donwlink WET signal at H-AP so as to provide the uplink time scheduling information to users, where the users extract their uplink time slot information from the received power level modulated WET signal. We formulate the sum-rate maximization problem, where the proposed downlink signaling is incorporated and prove its convexity. Use of reduced dynamic range in the H-AP is applied to alleviate the performance loss due to the peak power constraint. Numerical analysis shows that the throughput of the proposed WPCN with power level modulation scheme outperforms that of the conventional schemes in the quasi-static channel condition. Further, imperfect synchronization scenario is also studied. The packet is in outage if synchronization error occurs. In general, guard time in each subslot mitigates the synchronization error. It is proved that the sum rate maximization problem is still convex and can easily be solved using convex optimization. The outage constrained sum rate of the proposed scheme still outperforms that of the conventional scheme. The optimization of the dynamic range of power level modulation in terms of outage constrained sum rate is also studied. The numerical results show that the proposed power level modulation schemes in WPCN perform better than the conventional equal resource time allocation scheme. In addition, high performance is obtained with guard time even in a noisy environment.

Also, WPCN with relay and multi-user pairs is studied. Wireless power transfer is an effective technology to prolong the lifetime of wireless devices and WPCN is represantative model which received attention from both academic and industrial [17]-[19]. The important restriction of conventional WPCN is the short transmission distance because of the dual path loss and fading for both uplink information transfer and downlink energy transfer [20]. In a WPCN with relay model, communication with the help of relays is performed. The harvest-then-transmit protocol commonly used in WPCN was proposed in [7] and the basic model consists of H-AP and multiple users. Also, the energy efficiency is studied in [27]-[29], since the dissipation of the RF energyh during the energy transfer time decrease the efficienycy of WPCNs. Since then, several modified WPCN models have been proposed including WPCN with relay. In the WPCN with relay model, communication for the help of relay is performed. There are two main streams among the current related works for WPCN with relay. One is source powering relay [30]-[32] and the second one is relay powering source [33], [34].

For the first category, that is, source powering relay in [30], the authors proposed a harvest-then-cooperate protocol. In that protocol, both source and relay can harvest energy from the RF signals from a base-station or an AP. In the two-user WPCN with relay in [31], it was studied that the closer user to H-AP harvests energy sent by H-AP and the users relay the information of distant users. The full duplex relay which is not only powered by the source but also harvests its own energy through energy recycling was proposed in [32].

Next, in the study of relay powering sources, the sum rate maximization problem was studied in [33]. In this study, the source may harvest energy from the AP and relay before transmitting the information. In [34], the authors studied the capacity subject to an additional energy transmission cost at the AP. In [33] and [34], it is considered that there is a single source destination pair.In [38], multiple source-destination pairs and a single hybird relay nodes are considered, where relay has double roles; energy transmission and information forwarding. However, the communication flow is one sided and two-way communication was not considered.

In this dissertaion, it is considered to optimize the performance of a network with multiple peer to peer links over which communication takes place in both ways. Also, it is assumed a WPCN with a relay which operates as a hybrid node. The setting is feasible in sensor networks. We focus on how to maximize the sum throughput in the quasi-static fading channel. It is assumed that each user pair is composed of left and right users, where the relay is located in the middle of each user pairs. Therefore, each user pairs must communicate during the allocated time slots with the help of relays. In order to obtain the optimal time slot of each user pairs, we formulate the sum-rate maximization problem for the given WPCN system model setting and prove its convexity. We also propose an opportunistic scheduling to improve the performance than the general communication model. In that case, users not communicating in the uplink phase harvest energy from the communication signals of other user pairs. The numerical results show that the proposed WPCN schemes perform better than the conventional equal resource time allocation scheme. Numerical analysis shows that the throughput of the proposed WPCN with relay and multi-user pairs is higher than that of the conventional schemes which allocate the time slot equally in the quasi-static channel condition. It is also shown that the opportunistice harvesting improves the performance compared to the basic model of the proposed WPCN.

## 1.2 Overview of Dissertation

This dissertation is organized as follows.

In Chapter 2, the notation and review of WPCN are introduced and the convex optimization theory used to solve the optimization problem is introduced. Section 2.1 presents basic descriptions of WPCN with hybrid access point and multi-users. A harvest-then-transmit, the basic protocol in WPAN, is introduced together with how time subslots are constructed. In Section 2.2, sum rate maximization of WPCN is discussed. The throughput at WPCN is defined and a brief explanation of the optimization problem is formulated. A brief description of convex optimization is given in Section 2.3. Some of the convex optimization properties and perspective functions used in the dissertation are introduced. In Section 2.4, doubly-near-far problem are briefly described. The optimal allocation and throughput of one user and two user cases are illustrated.

In Chapter 3, sum rate maximization of WPCN with power level modulation is proposed. Section 3.1 introduces the system model of WPCN. In Section 3.2, the proposed downlink signal design is introduced and the optimization problem formulation and its convexity proof are given. We apply the proposed WPCN scheme to the noisy environment and analyze it in Section 3.3. Numerical analysis for the proposed WPCN with power level modulation is given in Section 3.4.

In Chapter 4, sum rate maximization of WPCN with relay and multi-user pairs is considered. In Section 4.1, the system model with relay and multi-user pairs is presented. The sum rate maximization problem and proof of convexity are given in Section 4.2. In addition, an opportunistic scheme for energy harvesting using unnecessary other users' information signals as energy sources is proposed in Section 4.3. Further, the conventional and the proposed WPCNs are compared in the sum rate in Section 4.4. Finally the concluding remarks are given in Chapter 5.

# Chapter 2

# Overview of Wireless Powered Communication Networks

In this chapter, some preliminaries of WPCN are introduced. First, the basic concepts of WPCN are described and the sum rate maximization in WPCN is discussed. Next, the convex optimization theory used to solve the optimization problem is introduced, and several definitions are mentioned. Finally, doubly-near-far problem is discussed.

## 2.1 Wireless Powered Communication Networks

Limited battery capacity of wireless devices has always been a important consideration and RF-enabled WET technology was considered as an attractive solution by powering wireless devices with continuous and stable energy. In general, an RF energy harvesting circuit model using WET is depicted at Figure 2.1. In this model, the receiver consists of a diode and a low-pass filter. The amount of energy $E$ harvested from the received signal is proportional to the received RF power $P_r$ as

$$E \propto \eta P_R.$$

The network model using WET is divided into two main streams. The first one is SWIPT as the network model, where information is jointly transmitted along with WET, and the second one is WPCN, which is the network model studied at the dis-

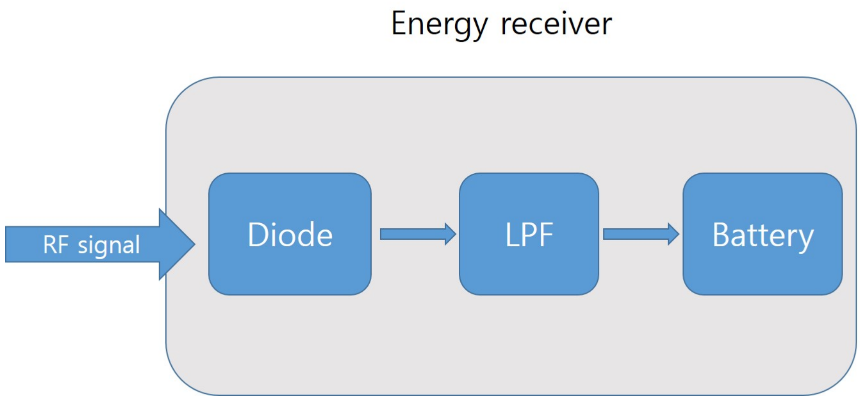


Figure 2.1: Example; Energy receiver.

sertation. WPCN is considered as an important network in many industrial systems, including the Internet of Things, which consists of numerous sensor devices.

In WPCN, an H-AP broadcasts energy to multiple wireless devices in the downlink, while the wireless devices communicate to the H-AP in the uplink using the harvested enrergy as in Figure 2.2. It is considered that H-AP has half-duplex hardware constraint. The network operates under a two-phase harvest-then-transmit protocol within a transmission block of duration $T_{block}$ as Figure 2.3. In general, the block time is assumed to be normalized to one. Then, in the first phase, downlink for WET as in Figure 2.3, $\tau_0$, $0 \leq \tau_0 \leq 1$, the wireless devices harvest energy from downlink wireless energy transfer signal. In the second phase for the rest of the transmission, the wireless devices transmit data to H-AP. Those operation can be achieved from time switching circuit model in H-AP. In this two phase operation, the performance of throughput achieved in the H-AP depends on downlink and uplink time allocation. If there are multi-users, this time resource allocation becomes more important and needs research to optimize it.

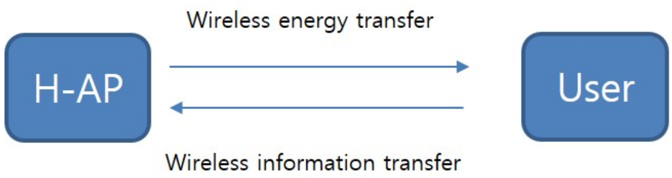


Figure 2.2: Example; Wireless powered communication networks.

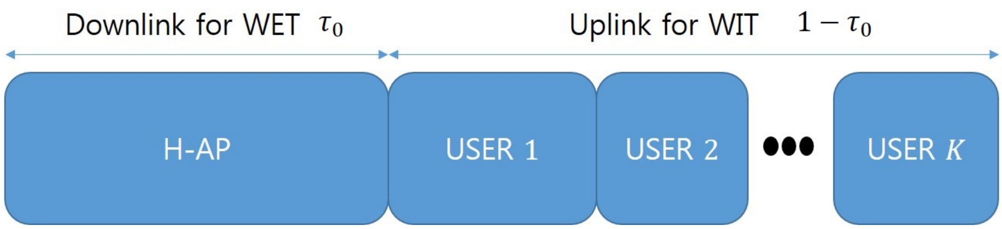


Figure 2.3: Harvest-then-transmit-protocol.

## 2.2 Sum Rate Maximization

In this section, maximization of sum rate used as a representative measure of performance in WPCN is discussed. Intuitively, with a larger downlink time $\tau_0$, the uplink data rate could be improved as the devices could harvest more energy to transmit information. However, large values of $\tau_0$ can also reduce throughput as it leaves a shorter data transmission time.

In general, the optimal time allocation of $\tau_0$ that results in the maximum uplink throughput is related to the user's wireless channel conditions. If the users are all close to the H-AP, the optimal $\tau_0$ becomes small value, each user could still harvest a sufficient amount of harvested energy within the short duration of downlink WET. Otherwise, in the far user case, a larger $\tau_0$ is required to harvest sufficient energy before starting reliable data transmission. In [7], the optimal value $\tau_0$ that maximizes the sum throughput was studied. In the simplest network model, the one-user case, the user achieves the following rate

$$R = (1 - \tau_0) \log(1 + SNR), \tag{2.1}$$

where $SNR$ denotes the signal to noise power ratio. For a $K$-users case, the uplink time allocated to the $i$-th user is $\tau_i$, the rate achieved by the $i$-th user is

$$R_i = \tau_i \log(1 + SNR_i). \tag{2.2}$$

The sum rate can also be expressed as

$$R_{sum} = \sum_{i}^{K} R_i. \tag{2.3}$$

From the above equation, the sum throughput maximization problem is formulated as

$$\begin{aligned} &\max_{\boldsymbol{\tau}} \ R_{sum} \\ &\quad \text{subject to} \\ &\qquad \text{C1: } \tau_0 \geq 0, \quad \tau_i \geq 0 \\ &\qquad \text{C2: } \tau_0 + \tau_1 + ... + \tau_K \leq 1. \end{aligned} \tag{2.4}$$

From the lemma in [7], objective function of the optimization problem is concave function of $\boldsymbol{\tau} = [\tau_0, \tau_1, ..., \tau_K]$. Therefore, the problem is convex optimization problem. Thus, it can be solved by convex optimization techniques. In this dissertation, we apply the newly proposed power level modulation to the WPCN. Then, to maximize sum rate in multi-user WPCN, the optimization problem is formulated and it is proved that the problem is convex optimization problem.

## 2.3 Convex Optimization

Convex optimization is a subfield of mathematical optimization that studies the problem of minimizing convex functions over convex sets. Many classes of convex optimization problems admit polynomial-time algorithms, whereas mathematical optimization is NP-hard [12]. In general, the resource allocation problem in the WPCN is not a straight forward problem but is often bound by multiple variables. To solve this problem, we need to simplify it and use the convex optimization technique and refer to some of the definitions and convex optimization properties studied in [12].

**Definition 2.1.** *A convex optimization problem is one of the form*

$$\begin{aligned} &minimize \;\; f_0(x) \\ &subject\ to \;\; f_i(x) \leq b_i, \;\; i = 1, ..., m, \end{aligned}$$

*where the functions* $f_0, ..., f_m : \boldsymbol{R^n} \rightarrow \boldsymbol{R}$ *are convex, i.e., satisfy*

$$f_i(\alpha x + \beta y) \leq \alpha f_i(x) + \beta f_i(y)$$

*for all* $x, y \in \boldsymbol{R^n}$ *and all* $\alpha, \beta \in \boldsymbol{R}$ *with* $\alpha + \beta = 1, \alpha \geq 0, \beta \geq 0.$

**Definition 2.2.** *Define the perspective function* $P : \boldsymbol{R^{n+1}} \to \boldsymbol{R^n}$*, with domain* $\textbf{dom}\ P = \boldsymbol{R^n} \times \boldsymbol{R_{++}}$*, as* $P(z,t) = z/t$*, where* $\boldsymbol{R_{++}}$ *denotes the set of positive numbers:* $\boldsymbol{R_{++}}\{x \in \boldsymbol{R} | x > 0\}$.

The perspective function scales or normalizes vector so the last component is one, and then drops the last component.

**Definition 2.3.** *If* $f$: $\boldsymbol{R^n} \to \boldsymbol{R}$*, then the perspective of* $f$ *is the function* $g$: $\boldsymbol{R^{n+1}} \to \boldsymbol{R}$ *defined by*

$$g(x,t) = tf(x/t)$$

*with domain*

$$\textbf{dom}\ g = \{(x,t) | x/t \in \textbf{dom}\ f, t > 0\}.$$

**Definition 2.4.** *Let* $f$: $\boldsymbol{R^n} \to \boldsymbol{R}$*. The function* $f^* : \boldsymbol{R^n} \to \boldsymbol{R}$*, defined as*

$$f^*(y) = sup_{x \in \textbf{dom} f}(y^T x - f(x))$$

*is the conjugate of the function* $f$*. The domain of the conjugate function consists of* $y \in \boldsymbol{R^n}$ *for which the supremum is finite.*

**Definition 2.5.** *A function* $f$: $\boldsymbol{R^n} \to \boldsymbol{R}$ *is called quasiconvex if its domain and all its sublevel sets*

$$S_\alpha = \{x \in \textbf{dom} f | f(x) \leq \alpha\}$$

*for* $\alpha \in pmbR$ *are convex. A function is quasiconcave if* $-f$ *is quasiconvex. A function that is both quasiconvex and quasiconcave is called quasilinear. If a function* $f$ *is quasilinear, then its domain, and every level set* $\{x | f(x) = \alpha\}$ *is convex.*

**Definition 2.6.** *Consider the function $f(x) = -log(x)$ on $\boldsymbol{R_{++}}$. Its perspective is*

$$g(x,t) = -tlog(x/t) = tlog(t) - tlog(x)$$

*and is convex on $\boldsymbol{R^2_{++}}$. The function $g$ is called the relative entropy of $t$ and $x$.*

The perspective operation preserves convexity, that is, if $f$ is a convex function, then so is its perspective function $g$. Similarly, if $f$ is concave, then so is $g$.

The properties of convex optimization is as follow. First, every local minimum is global minimum. It means that the complexity of convex problem is significantly lower than nonconvex problem. Next, the optimal set is convex and if the problem is strictly convex, then the problem has at most one optimal point.

Convex optimization is used in a wide range of applications, such as estimation and signal processing, communications and networks, electronic circuit design and statistics, where the approximation has proven to be efficient. Also, with recent advancements in optimization algorithms and computer science, convex programing is nearly as straightforward as linear programming and complexity is relatively low than other optimization methods.

## 2.4 Doubly Near Far Problem

In general, in conventional wireless systems, users far from the base station achieve low throughput. This issue is more critical in WPCN, where uplink and downlink exist. In other words, a user who is far from H-AP has a relatively bad channel gain. In this user, the amount of energy harvested from the H-AP is smaller as well as the attenuation of the signal sent to the H-AP is greater when compared with the close user. This means that in order to maximize the sum rate, it is necessary to allocate more time to close users rather than equal time resource allocation. On the contrary, if user fairness is taken into account, more time resources should be allocated to users

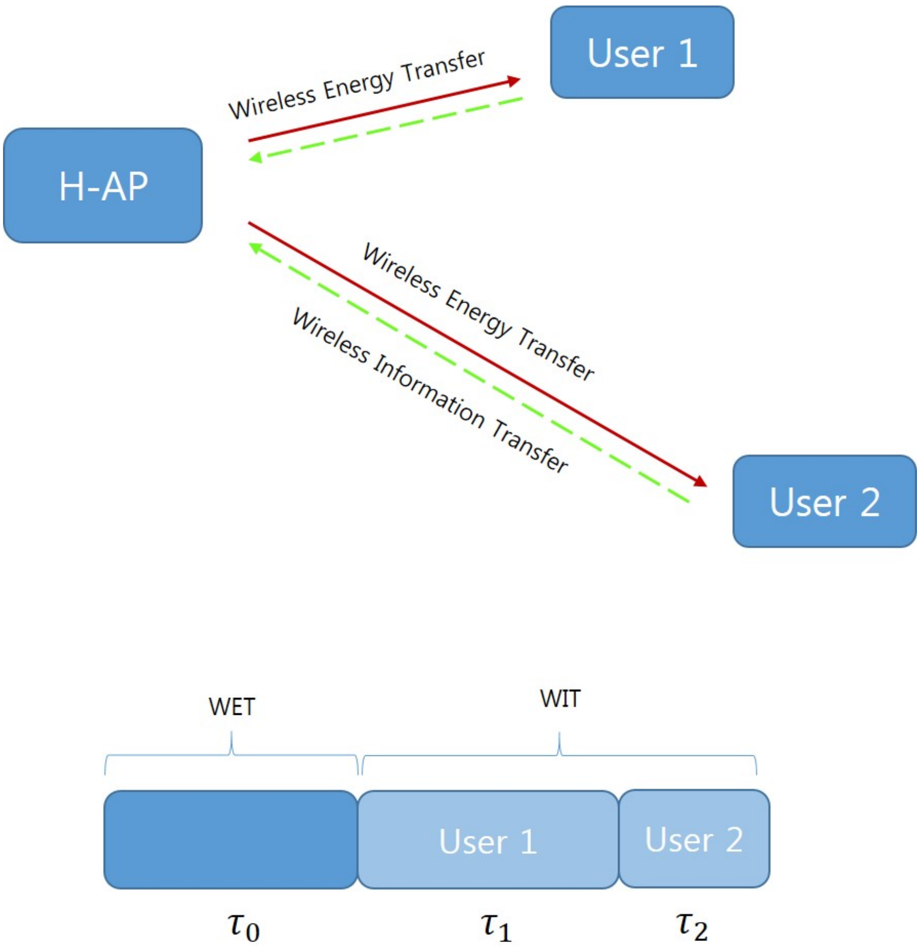


Figure 2.4: Exapmle; WPCN model and time resource allocation with (5, 10) users.

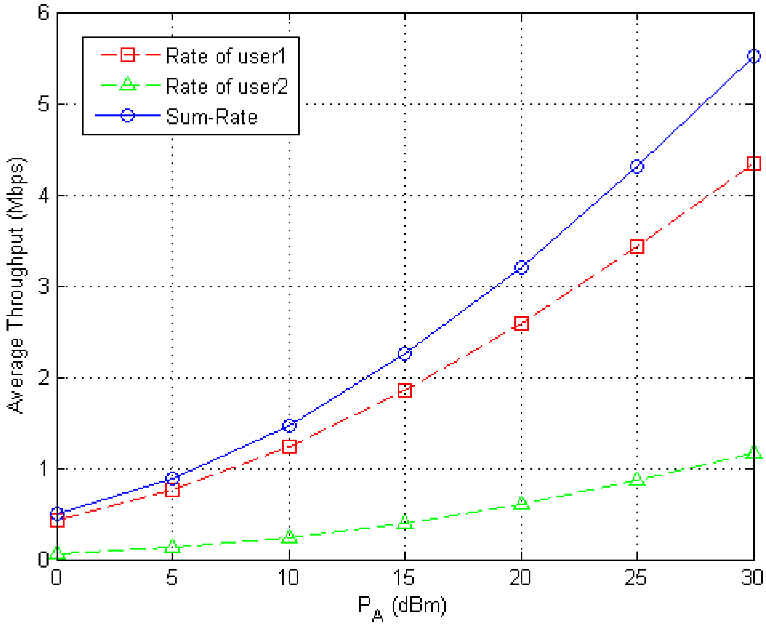


Figure 2.5: Average throughput of 2-user WPCN with (5, 10) users.

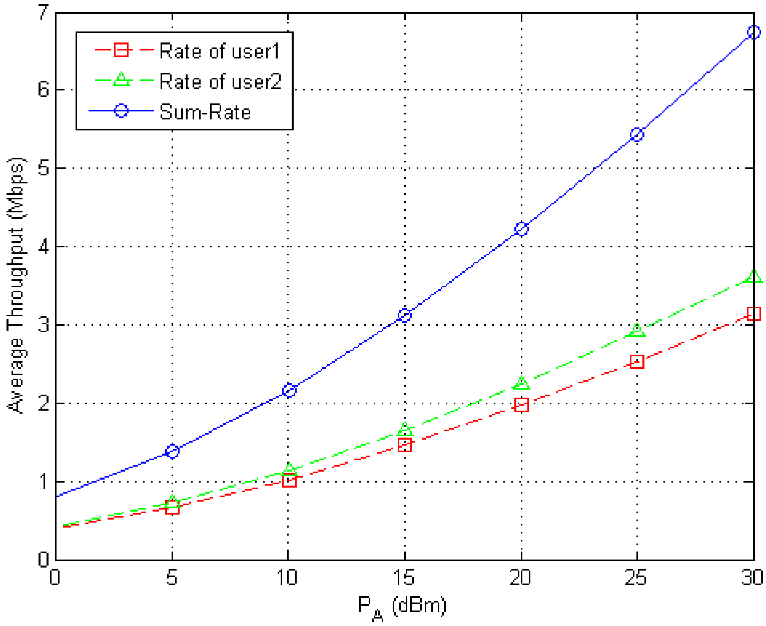


Figure 2.6: Average throughput of 2-user WPCN with (5, 5) users.

who are farther away.

For exmaple of 2-user WPCN, in order to maximize the sum rate, time resources should be allocated according to the distance between the H-AP and two users. The time resource allocation in the case where the distance between the two users and the H-AP is 5 meters and 10 meters respectively is shown in Figure 2.4. Referring to [7], in the case of the 2-user, the performance trend when the distances to the H-AP are 5 meters for user 1 and 10 meters for user 2, and 5 meters for user 1 and 5 meters for user 2, respectively, is shown in Figures 2.5 and 2.6. For users with (5, 10) meters, it is shown that user 1 acheives better throughput, because more time resources are allocated to user 1, who is close to H-AP. Otherwise, For users with (5, 5) meters, since the channel gains of the two users have similar values, the throughput achieved by the two users is also similar level.

This phenomenon in the WPCN is called doubly near far problem. A far user from the H-AP harvests less amount of wireless enerergy than a closer user in the downlink. On the other hands, a far user has to transmit with more power in the uplink to achieve the same throughput due to the doubly distance dependent signal attenuation in the downlink for WET and uplink for WIT. Therefore, in order to maximize sum throughput, more time resources should be allocated to close users and relatively less time resources should be allocated to distant users. However, if the problem is considered in terms of user fairness, the allocation method is reversed. In other words, more time resources should be allocated to distant users.

In [7] that considers user fairness, it was proposed a new criteria referred to as common-throughput with the additional constraint that all users should be allocated with an equal throughput in their uplink WIT times regardless of the channel gain condition to the H-AP. If the criteria are applied, fairness between users is guaranteed, but the sum throughput is significantly reduced. Therefore, it is important to set criteria according to the network situation. Subsequently, additional criteria were studied that were not common throughput. Several criteria have been proposed to consider sum throughput and fairness simultaneously.

In this dissertation, we consider the most representative criteria, sum throughput, and further analyze how the throughput of each user differs through simulation.

# Chapter 3

# Sum Rate Maximization in WPCN with Power Level Modulation

Traditionally, in wireless communication metworks, the energy sources are fixed, such as batteries which limited operation time. Many researches have proposed energy saving protocols and transmission schemes for longer battery life. As an alternative to conventional energy harvesting techniques such as magnetic induction or other types of WPT, application of energy harvesting using radio-frequency signal was considered in [1]. Recently, wireless powered communication networks have been proposed for wireless communication environment such as sensor networks or internet of things [2], [3]. Such radio-frequency energy harvesting has emerged as an alternative solution for prolonging the lifetime of wireless devices.

There are two main research categories for RF-EH based wireless communication systems, which are SWIPT and WPCN. In the SWIPT, wireless energy transfer and wireless information transmission are simultaneously accomplished in the downlink [4]-[6]. However, in WPCN, there is no downlink data transmission. An H-AP broadcasts only energy transfer RF signals in the downlink phase and users charge their energy storages such as batteries or supercapacitors from received WET signals. In the uplink phase, users transmit their WIT signals to the H-AP using harvested energy.

A harvest-then-transmit protocol was proposed for an efficient establishment of WPCN in wireless sensor networks [7], where the H-AP broadcasts a WET signal in the downlink phase and recovers user messages from the WIT signals in the uplink phase. In general, TDMA was adopted in the uplink, where time slots are optimally allocated to each user for maximizing the uplink throughput. In [8], a general scheme for wireless powered cellular networks was studied, which incorporates a two-way information transmission together with energy transfer in the downlink from the H-AP to the cellular users. Heterogeneous WPCNs were also studied, where EH nodes and non-EH nodes coexist in [9] and WPCN with full-duplex was considered in [10]. However, the previous works [7, 8, 9, 10] miss the discussion on how to provide the scheduling information to users.

For WPCNs with an energy storage constraint, the optimal downlink power allocation policy was proposed in [11], where the transmitted downlink signals have different power levels in the time slots. The H-AP concentrates all available energy in the first few downlink time slots but the power profile does not carry any scheduling information in [11]. We intend to use such a power variation of the WET signal for information transmission.

In this dissertation, we assume a WPCN composed of an H-AP and users without an information receiver, which is a feasible assumption in sensor networks. We focus on how to schedule the users' uplink transmission according to a quasi-static fading channel. We propose a power level modulation of the donwlink WET signal at H-AP so as to provide the uplink scheduling information to users, where the users extract their uplink time slot information from the received power level modulated WET signal. We formulate the sum-rate maximization problem where the proposed downlink signaling is incorporated and prove its convexity. Use of reduced dynamic range of H-AP is applied to alleviate the performance loss due to the peak power constraint. Numerical analysis shows that the throughput of the proposed WPCN with power level modulation scheme outperforms that of the conventional schemes in the quasi-static channel condition. Imperfect synchronization scenario of WPCN is also studied. The packet is in outage if synchronization error applies. Inclusion of guard time in each subslot mitigates the synchronization error. It is proved that the sum rate maximization problem still convex and can easily be solved. The outage constrained sum rate is still outperforms the conventional scheme. The optimization of the dynamic range of power level modulation in terms of outage constrained sum rate is also shown.

This chapter is organized as follows. In Section 3.1, we describe the system model. First, the proposed downlink signal design is introduced and the optimization problem formulation and its convexity proof follow in Section 3.2. Next, we apply the proposed scheme to the noisy environment in Section 3.3. Numerical analysis for the proposed WPCN with power level modulation is given and the performance of the proposed scheme in WPCN is evaluated in Section 3.4.

## 3.1 System Model

WPCN with one H-AP and $K$ users is shown in Figure 3.1, where it operates in a time division duplexing (TDD) manner with WET in the downlink and WIT in the uplink. H-AP broadcasts a WET signal to the users and then each user transmits its WIT signal to the H-AP by utilizing the harvested energy. All the energy and information transfers are operated via TDD over the same frequency band to attain high spectrum efficiency.

It is assumed that the total operation time for WPCN is normalized as one. Quasi-static fading channel is considered, that is, the downlink and the uplink channel states are constant over a communication frame and we assume the channel reciprocity between the uplink and downlink channels since the system operates in time division duplex. The H-AP then acquires the downlink channel state information from the uplink signals in the previous epoch time. In the conventional WPCN, the downlink signal transmits a WET signal with a fixed average power intensity during the allotted time slot and there is no transmission of uplink scheduling information. For synchronous

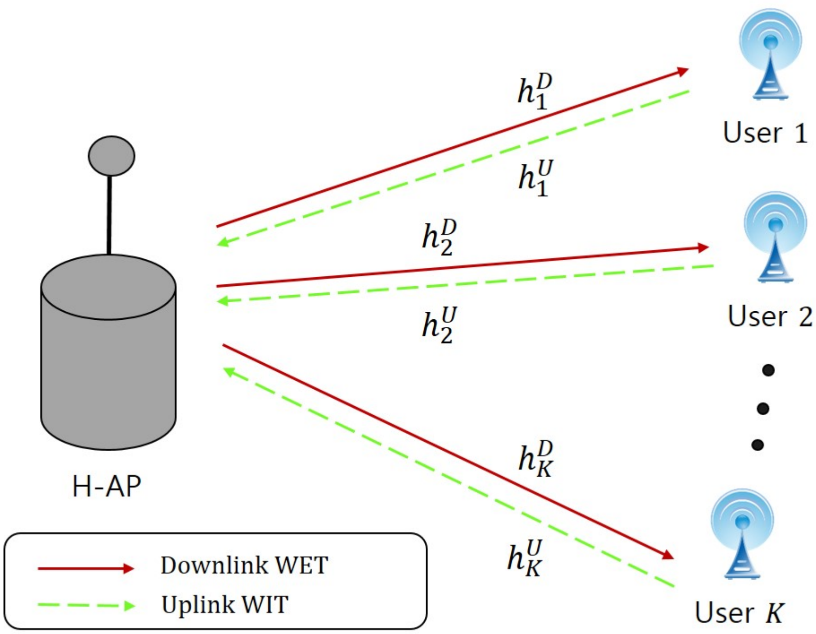


Figure 3.1: Wireless powered communication network with $K$ users.

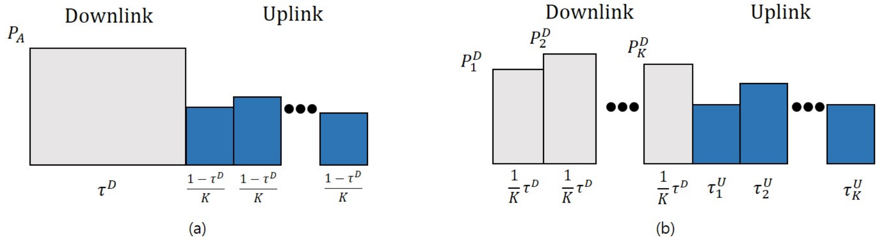


Figure 3.2: Downlink and uplink signal frames; (a) Conventional WPCN, (b) Proposed WPCN.

transmission, the user time slots should be uniform and predetermined in the uplink. In this chapter, we propose to divide the downlink time slot into a number of subslots and to power level modulate the WET signal and the scheduling information for each user in the uplink is transmitted to the users by the power level modulated WET signal.

The downlink and uplink signal frame structure of WPCN is depicted in Figure 3.2. In the conventional WPCN with assumption that the users cannot be dynamically scheduled in the uplink for low cost, the downlink transmission power is constant over the downlink time slot $\tau^D$ and the uplink transmission signals of $K$ users are transmitted over the equal time subslots $\frac{1-\tau^D}{K}$ with power $P_i^U$. In the proposed WPCN, the downlink energy transfer signals are transmitted over $K$ subslots with the different powers $P_i^D$, $i = 1, 2, ..., K$ and the time subslot $\frac{\tau^D}{K}$. The uplink transmission time slot is divided into $K$ time subslots, $\tau_1^U, \tau_2^U, ..., \tau_K^U$ and each user transmits its information signal to H-AP with transmit power $P_i^U$ in the subslot $\tau_i^U$, $i = 1, 2..., K$.

It is assumed that the H-AP has an energy constraint $E^D$ in a single time slot of the downlink. The peak power constraint and the average power are denoted by $P_P$ and $P_A$, respectively, so that the downlink time slot is bounded as

$$\tau^D \leq \frac{E^D}{P_A}. \tag{3.1}$$

The downlink channel power gain from the H-AP to user $i$ is denoted by $h_i^D$. It is assumed that energy harvesting due to receiver noise is negligible compared to the sufficiently large $P_i^D$. Then, the amount of harvested energy $E_{i,j}$ of user $i$ in the $j$-th downlink time subslot and the total harvested energy $E_i$ at user $i$ are given as

$$\begin{aligned} E_{i,j} &= \eta h_i^D P_i^D \tau^D \frac{1}{K} \\ E_i &= \sum_{j=1}^{K} \eta h_i^D P_j^D \tau^D \frac{1}{K} \leq \eta h_i^D P_A \tau^D, \;\; i = 1, 2, ..., K, \end{aligned} \tag{3.2}$$

where $\eta$ is the energy harvesting efficiency at all users. We basically assume linear devices in this dissertation. Nonlinear cases as in [13] may be further studied in future studies. In the uplink WIT phase, users transmit their information signals to the H-AP in TDMA manner. The total consumed power at user $i$ and the channel power gain from user $i$ to the H-AP are $P_i^U + p_i^c$ and $h_i^U$, respectively, where $p_i^c$ is the circuit power dissipation of user $i$. The achievable rate of user $i$ measured in nats/s/Hz is expressed as

$$R_i = \tau_i^U \log{(1 + \frac{h_i^U P_i^U}{N_0})}, \;\; i = 1, 2, ..., K, \tag{3.3}$$

where $N_0$ is the one-sided power spectral density of the additive white Gaussian noise.

## 3.2 Power Level Modulation Scheme and Problem Formulations with Convexity

In this section, we propose power level modulation schemes and an optimization problem of the proposed schemes. We optimize downlink time, uplink times, and power levels in order to maximize the total sum rate of the WPCN and prove a convexity of the problem.

### 3.2.1 Sum Rate Maximization for Power Level Modulation Scheme with Peak Power Constraint

In the proposed WPCN scheme, downlink time slot is uniformly divided into $K$ subslots. Each downlink subslot is then equal to $\frac{\tau^D}{K}$ and H-AP transmits energy signals using power $P_i^D, i = 1, 2, ..., K$ in the $i$-th downlink subslot. Since the channels from H-AP to users are not homogeneous, the amount of harvested energies of the users are different from each other. However, the relative ratio of power levels $P_i^D,\ i = 1, 2, ..., K$ of the received WET signals from the H-AP is preserved for all users. Furthermore, it is assumed that users can calculate their harvested energy for each time subslot accurately. Thus, even though the channel condition changes, the time duration $\tau_i^U$ allocated to user $i$ in the uplink time slot can be computed using the relative ratio of $E_{i,j}$, that is,

$$\begin{aligned} &\tau_1^U : \tau_2^U : ... : \tau_K^U = E_{i,1} : E_{i,2} : ... : E_{i,K} \\ &\sum_{j=1}^{K} \tau_j^U = 1 - \tau^D. \end{aligned} \tag{3.4}$$

Then, we have

$$\tau_i^U = \frac{E_{i,i}}{\sum_j^K E_{i,j}}(1 - \tau^D). \tag{3.5}$$

The optimal values of $\tau^D$ and $P_i^D$ are obtained by solving the following optimization problem at H-AP. Let $R_{sum}$ be the sum rate defined as

$$R_{sum} = \sum_{i=1}^{K} R_i \tag{3.6}$$

and let $\boldsymbol{P} = [P_1^D, P_2^D, ..., P_K^D, P_1^U, P_2^U, ..., P_K^U]$ and $\boldsymbol{\tau} = [\tau^D, \tau_1^U, \tau_2^U, ..., \tau_K^U]$. Then, we can formulate the optimization problem as follows:

$$\begin{aligned}
&\max_{\boldsymbol{P},\boldsymbol{\tau}} \; R_{sum} \\
&\quad \text{subject to} \\
&\qquad \text{C1: } \tau^D \geq 0, \quad \tau_i^U \geq 0, \quad P_i^D \geq 0 \\
&\qquad \text{C2: } \tau^D + \tau_1^U + ... + \tau_K^U \leq 1 \\
&\qquad \text{C3: } P_1^D + P_2^D + ... + P_K^D \leq K P_A \\
&\qquad \text{C4: } P_i^D \leq P_P \\
&\qquad \text{C5: } (P_i^U + p_i^c)\tau_i^U \leq \sum_{j=1}^{K} \eta h_i^D P_j^D \frac{\tau^D}{K} \\
&\qquad \text{C6: } \tau_i^U \leq \frac{P_i^D}{\sum_{j=1}^{K} P_j^D}(1 - \tau^D) \\
&\qquad\quad i = 1, 2, ..., K.
\end{aligned} \tag{3.7}$$

The constraint C5 implies that the total energy consumed by the $i$-th user cannot exceed the harvested energy in the uplink phase. The condition for uplink time allocation of the $i$-th user through power level modulation of the downlink signal is given by C6.

**Lemma 3.1.** *The objective function $R_{sum}$ is a concave function of $\tau^D$.*

*Proof.* Let $R' = \log(1 + \mu\tau^D \sum_{j=1}^{K} P_j^D)$. Since the logarithm of an affine function is concave, $R'$ is a concave function of $\tau^D$. Then, $R_{sum}$ is a perspective function of $R'$ and it preserves the concativity of original function $R'$ [12]. ■

The above optimization problem has multiple variables $P_i^D$, $\tau^D$, and $\tau_i^U$. Since these variables are coupled in the constraints C5 and C6, it is not straightforward to find the globally optimal solution to this problem. A proper transformation of the problem can lead to the straightforward proof of the convexity of the problem. The above optimization problem can be transformed using the variable substitution proposed in [14]. First, note that the variables $P_i^D$, $\tau^D$, and $\tau_i^U$ are positive. Then, we can take variable substitution as $P_i^D \triangleq \exp(p_i^D)$, $P_i^U \triangleq \exp(p_i^U)$, $\tau^D \triangleq \exp(t^D)$, and $\tau_i^U \triangleq \exp(t_i^U)$ for all $i = 1, 2, ..., K$. Let $\boldsymbol{p} = [p_1^D, p_2^D, ..., p_K^D, p_1^U, p_2^U, ..., p_K^U]$, and $\boldsymbol{t} = [t^D, t_1^U, t_2^U, ..., t_K^U]$. Then, (7) can be rewritten as

$$
\begin{aligned}
&\max_{\boldsymbol{p},\boldsymbol{t}} \; R_{sum} \\
&\quad \text{subject to} \\
&\qquad \text{C1: } \exp(t^D) + \exp(t_1^U) + \exp(t_2^U) + ... \\
&\qquad\quad + \exp(t_K^U) \leq 1 \\
&\qquad \text{C2: } \exp(p_1^D) + \exp(p_2^D) + ... \\
&\qquad\quad + \exp(p_K^D) \leq K P_A \\
&\qquad \text{C3: } \exp(p_i^D) \leq P_P \\
&\qquad \text{C4: } (\exp(p_i^U) + p_i^c) \exp(t_i^U) \\
&\qquad\quad \leq \sum_{j=1}^{K} \frac{\eta h_i^D}{K} \exp(p_j^D + t^D) \\
&\qquad \text{C5: } \exp(t_i^U) \leq \\
&\qquad\quad \frac{\exp(p_i^D)}{\sum_{j=1}^{K} \exp(p_j^D)} (1 - \exp(t^D)) \\
&\qquad\quad i = 1, 2, ..., K.
\end{aligned}
\tag{3.8}
$$

**Theorem 3.1.** *The optimization problem in* (3.8) *is convex.*

*Proof.* The objective function $R_{sum}$ is concave and the constraints C1, C2, and C3 are convex. For convenience of proof, we take the logarithm on both sides of C4 and then we have

$$\log(\exp(p_i^U + t_i^U) + p_i^c \exp(t_i^U)) \leq \sum_{j=1}^{K} (p_j^D + t^D) \log(\frac{\eta h_i^D}{K}). \tag{3.9}$$

The right-hand side is a linear sum of the variables $P_j^D, t^D$ multiplied by a constant $\log(\frac{\eta h_i^D}{K})$ and the left-hand-side is a log-sum-exp function that has been proved to be convex in [12]. Finally the inequality in C5 can be rewritten as

$$\begin{aligned}&\exp(t_i^U + p_1^D) + \exp(t_i^U + p_2^D) + ... + \exp(t_i^U + p_K^D)\\&+ \exp(t^D + p_i^D) \leq \exp(p_i^D).\end{aligned} \tag{3.10}$$

The right-hand side is convex and the left-hand side is a linear sum of convex function and thus it is also convex. ■

The convexity of sum rate maximization is proved and thus the maximum value of sum rate can be obtained by an optimization problem solver [8]. Compared to the conventional equal resource allocation problem, only linear constraints are added and the computational complexity of the proposed one is kept almost the same.

### 3.2.2 Modified Sum Rate Maximization for Power Level Modulation Scheme with Reduced Dynamic Range

In general, maximal sum rate with peak power constraint C3 is lower than that with no peak power constraint in the power level modulation for uplink scheduling. Now, we introduce reduced dynamic range for the power level modulation in H-AP as

$$\begin{aligned}&P_A(1-\alpha) \leq P_i^* \leq P_P, \;\; i = 1, 2, ...K, \;\; 0 \leq \alpha \leq 1\\&P_i^* = P_i^D - P_A(1-\alpha),\end{aligned} \tag{3.11}$$

where $\alpha$ denotes the dynamic range index.

Figure 3.3 shows the power level modulation with reduced dynamic range, where $\alpha$ is known to all users. Thus, $\alpha = 1$ means that there is no limitation of dynamic range as in (3.7) and $\alpha = 0$ means the conventional WPCN with constant power level.

The following two propositions give upper bounds on $\alpha$ and $K$.

**Proposition 3.1.** *The condition for dynamic range index $\alpha$ such that it is not affected by C4 is given as*

$$\alpha \leq \frac{\frac{P_P}{P_A} - 1}{K - 1}. \tag{3.12}$$

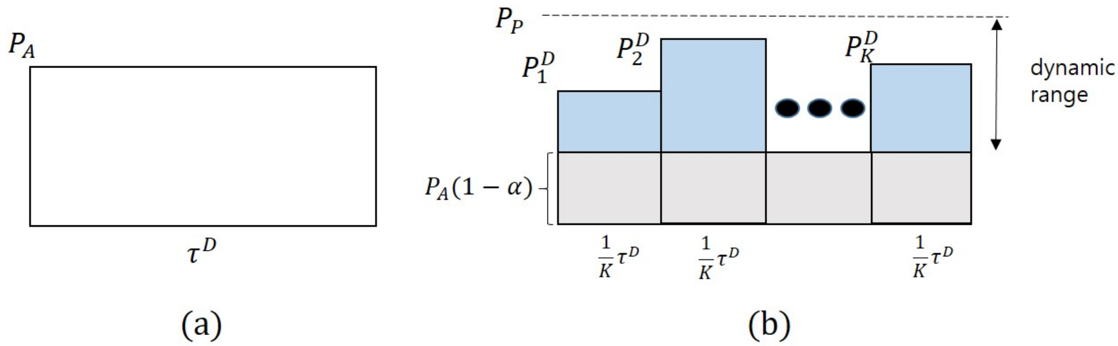


Figure 3.3: Downlink WET signals; (a) Conventional WPCN, (b) Proposed WPCN with reduced dynamic range.

*Proof.* Consider the case that the H-AP allocates all uplink time to a single user $i$ because its channel is extremely better than other users' channels. The transmission power $P_i^D$ takes its maximum possible value in the downlink time slot corresponding to the user and the transmission power $P_i^D$ of the user $i$ in the $i$-th time slot becomes $\alpha P_A K + (1-\alpha)P_A$. Then, the condition for not being affected by constraint C5 is $P_i^D \leq P_P$. Thus, (3.12) can be derived. ■

**Proposition 3.2.** *For the case that dynamic range index, peak power, and average power constraints are given, the number of users that is not affected by C4 is also given as*

$$K \leq \lfloor \frac{\frac{P_P}{P_A} - 1}{\alpha} + 1 \rfloor. \tag{3.13}$$

*Proof.* Proof can be done similarly to Proposition 3.12. ■

Similar to the case in Subsection 3.21, each user can determine the uplink time $\tau_i^U$ based on the ratio of $E_{i,j}$ and $\alpha$, that is,

$$\begin{aligned} \tau_1^U : \tau_2^U : \ldots : \tau_K^U =& (E_{i,1} - \bar{E}_i) : (E_{i,2} - \bar{E}_i) : \ldots \\ & : (E_{i,K} - \bar{E}_i) \\ \sum_{j=1}^{K} \tau_j^U =& 1 - \tau^D, \end{aligned} \tag{3.14}$$

$$\text{where} \qquad \bar{E}_i = \frac{1-\alpha}{K} \sum_{j=1}^{K} E_{i,j}.$$

Then, the uplink time for user $i$ is then calculated as

$$\tau_i^U = \frac{E_i - \frac{\sum_i^K E_i (1-\alpha)}{K}}{\alpha \sum_i^K E_i} (1 - \tau^D). \tag{3.15}$$

Similar to (3.8), the problem that H-AP should solve for optimal uplink scheduling of modified sum rate maximization for the power level modulation with reduced dynamic range is transformed into:

$$
\begin{aligned}
&\max_{\boldsymbol{P},\boldsymbol{\tau}} \ R_{sum} \\
&\text{subject to} \\
&\qquad \text{C1: } \tau^D \geq 0, \quad \tau_i^U \geq 0, \quad P_i^D \geq 0 \\
&\qquad \text{C2: } \tau^D + \tau_1^U + ... + \tau_K^U \leq 1 \\
&\qquad \text{C3: } P_1^D + P_2^D + ... + P_K^D \leq KP_A \\
&\qquad \text{C4: } P_i^D \leq P_P \\
&\qquad \text{C5: } (P_i^U + p_i^c)\tau_i^U \leq \sum_{j=1}^{K} \eta h_i^D P_j^D \frac{\tau^D}{K} \\
&\qquad \text{C6: } \tau_i^U \leq \frac{P_i^D - (1-\alpha)P_A}{\alpha \sum_{j=1}^{K} P_j^D}(1-\tau^D) \\
&\qquad\quad i = 1, 2, ..., K.
\end{aligned}
\tag{3.16}
$$

**Theorem 3.2.** *The optimization problem in* (3.16) *is convex.*

*Proof.* The convexity is proved similarly to Theorem 3.1. ■

Since the problem in (3.16) is convex, the maximum value of sum rate with limited dynamic range can also numerically be obtained.

## 3.3 Sum Rate Maximization in Noisy Environments

In this section, we consider more practical issues that we can come across when we realize our proposed scheme. In the previous section, we assumed that the time slots in the uplink are perfectly assigned from the detected power levels of the received signal at the users. However, it is inevitable to undergo the power level detection error which may cause the time slot assignment errors in the uplink transmission. If the uplink signals are tightly coded and modulated, then outage may occur in the imperfect synchronization scenario. Thus, we consider the power level detection error due to Gaussian noise for the uplink time slot assignment and the insertion of synchronization margin called a guard time to mitigate the outage problem.

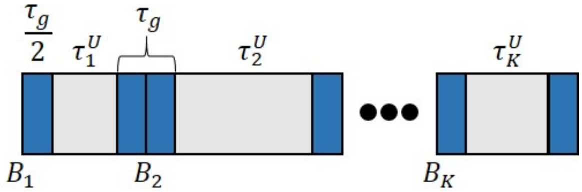


Figure 3.4: Time slot assignment of uplink WIT signals with guard time.

**Definition 3.1.** *We define the outage constrained rate for outage probability* $Pr(x)$ *as*

$$R_{out,i} = R_i(1 - Pr(x)). \tag{3.17}$$

In addition, we introduce the guard time $\tau_g$ for the proposed system to withstand the slot timing errors. Figure 3.4 exhibits the modified frame of the proposed WPCN scheme. The left boundary of the $i$-th user's time slot is $B_i$ in the uplink as in Figure 3.4. The $i$-th user's time slot and tentative packet occupation are $(B_i,\ B_{i+1})$ and $(B_i + \tau_g/2,\ B_{i+1} - \tau_g/2)$, respectively. Then, the time slot duration allocated to the $i$-th user is $B_{i+1} - B_i - \tau_g$. We assume that users use their detected power level suffered from the Gaussian noise. For simplicity, we assume that the noise variance is inversely proportional to detected power level by $\alpha h_i^D$. That is, it is assumed that a noise random variable of the $i$-th time slot of the $i$-th user causing time slot assignment error is $N_i^{det} \sim \mathcal{N}(0, \sigma^2)$, which is modified as $\frac{N_i^{det}}{\alpha h_i^D}$. Then, the estimated $\hat{B}_i,\ \hat{B_{i+1}}$ can be given as $\hat{B}_i = B_i + \frac{N_i^{det}}{\alpha h_i^D},\ \hat{B_{i+1}} = B_{i+1} + \frac{N_i^{det}}{\alpha h_i^D}$ and packet transmission start at $\hat{B}_i + \tau_g/2$. Note that $\hat{B}_i$'s are a Gaussian random variable with mean $B_i$ and variance $(\frac{\sigma}{\alpha h_i^D})^2$. We consider that an outage occurs when the $i$-th packet invades the adjacent time slots or the adjacent packets intrude the $i$-th slot. The estimated bounds of the left and right users ($(i-1)$-th and $(i+1)$-th users) adjacent to the $i$-th user are set to $B_i'$ and $B_{i+1}'$, respectively. In this assumption, the outage events of the $i$-th uplink signal are defined as

$$\begin{aligned}
&\text{i) } \mathrm{E}_{i1} : \{\hat{B}_i < B_i - \tau_g/2\} \bigcup \{\hat{B}_{i+1} > B_{i+1} + \tau_g/2\} \\
&\text{ii) } \mathrm{E}_{i2} : \hat{B}'_i > B'_i + \tau_g/2 \\
&\text{iii) } \mathrm{E}_{i3} : \hat{B}'_{i+1} < B'_{i+1} - \tau_g/2.
\end{aligned} \tag{3.18}$$

Thus, probabilities of the outage events can be represented by $Q$ function as

$$\begin{aligned}
P_{\mathrm{E}_{i1}} &= \mathrm{Pr}(\mathrm{E}_{i1}) \\
&= (1 - (1 - Q(\frac{\alpha h_i^D \frac{\tau_g}{2}}{\sigma}))^2) \\
&= 2Q(\frac{\alpha h_i^D \frac{\tau_g}{2}}{\sigma}) - Q(\frac{\alpha h_i^D \frac{\tau_g}{2}}{\sigma})^2 \\
P_{\mathrm{E}_{i2}} &= \mathrm{Pr}(\mathrm{E}_{i2}) = Q(\frac{\alpha h_{i-1}^D \frac{\tau_g}{2}}{\sigma}) \\
P_{\mathrm{E}_{i3}} &= \mathrm{Pr}(\mathrm{E}_{i3}) = Q(\frac{\alpha h_{i+1}^D \frac{\tau_g}{2}}{\sigma}).
\end{aligned} \tag{3.19}$$

For the first and the last time slots, we set $P_{\mathrm{E}_{12}} = P_{\mathrm{E}_{K3}} = 0$.

For the Gaussian noise with small $\sigma^2$, the outage probability can be approximated by the union bound of the error events as

$$\begin{aligned}
\mathrm{Pr}(\bigcup_j \mathrm{E}_{ij}) \leq \sum_j P_{\mathrm{E}_{ij}} &= 2Q(\frac{\alpha h_i^D \frac{\tau_g}{2}}{\sigma}) - Q(\frac{\alpha h_i^D \frac{\tau_g}{2}}{\sigma})^2 \\
&\quad + Q(\frac{\alpha h_{i-1}^D \frac{\tau_g}{2}}{\sigma}) + Q(\frac{\alpha h_{i+1}^D \frac{\tau_g}{2}}{\sigma}) \\
\mathrm{Pr}(\bigcup_j \mathrm{E}_{ij}) \approx \sum_j P_{\mathrm{E}_{ij}}.
\end{aligned} \tag{3.20}$$

Using Definition 3.1, the outage constrained rate of the $i$-th user is approximated as

$$R_{out,i} \approx R_i(1 - P_{\mathrm{E}_{i1}} - P_{\mathrm{E}_{i2}} - P_{\mathrm{E}_{i3}}). \tag{3.21}$$

The outage constrained sum rate is obtained as

$$\begin{aligned}
R_{out,sum} \approx \sum_{i=1}^{K} R_i(1 &- 2Q(\frac{\alpha h_i^D \frac{\tau_g}{2}}{\sigma}) + Q(\frac{\alpha h_i^D \frac{\tau_g}{2}}{\sigma})^2 \\
&- Q(\frac{\alpha h_{i-1}^D \frac{\tau_g}{2}}{\sigma}) - Q(\frac{\alpha h_{i+1}^D \frac{\tau_g}{2}}{\sigma})).
\end{aligned} \tag{3.22}$$

Similar to the previous optimization problem, the sum rate maximization problem with guard time is set as follows;

$$\begin{aligned}
&\max_{\boldsymbol{P},\boldsymbol{\tau}} \ R_{sum} \\
&\text{subject to} \\
&\quad \text{C1: } \tau^D \geq 0, \ \ \tau_i^U \geq 0, \ \tau_g \geq 0, \ P_i^D \geq 0 \\
&\quad \text{C2: } \tau^D + \tau_1^U + ... + \tau_K^U + K\tau_g \leq 1 \\
&\quad \text{C3: } P_1^D + P_2^D + ... + P_K^D \leq KP_A \\
&\quad \text{C4: } P_i^D \leq P_P \\
&\quad \text{C5: } (P_i^U + p_i^c)\tau_i^U \leq \sum_{j=1}^{K} \eta h_i^D P_j^D \frac{\tau^D}{K} \\
&\quad \text{C6: } \tau_i^U \leq \frac{P_i^D - (1-\alpha)P_A}{\alpha \sum_{j=1}^{K} P_j^D}(1 - \tau^D \\
&\qquad\qquad - K\tau_g) \\
&\qquad i = 1, 2, ..., K.
\end{aligned} \tag{3.23}$$

**Theorem 3.3.** *The optimization problem in* (3.23) *is convex.*

*Proof.* In C2 and C6, the convexity is preserved because $\tau_g$ is simply added to the linear sum. The convexity of the remaining inequality is also proved similarly to $Theorem$ 3.1. ■

Thus, we can obtain the time slot assignment values of the uplink that maximize the sum rate through the above convex optimization problem with a given guard time. Then, we calculate the outage constrained sum rate $R_{out,sum}$ as in (3.22).

## 3.4 Simulation Results

In this subsection, we provide numerical results to show the performance of the proposed WPCN schemes. In the network setting for simulation, we adopt the distance-dependent path loss model and assume a quasi-static Rayleigh fading channel [15].

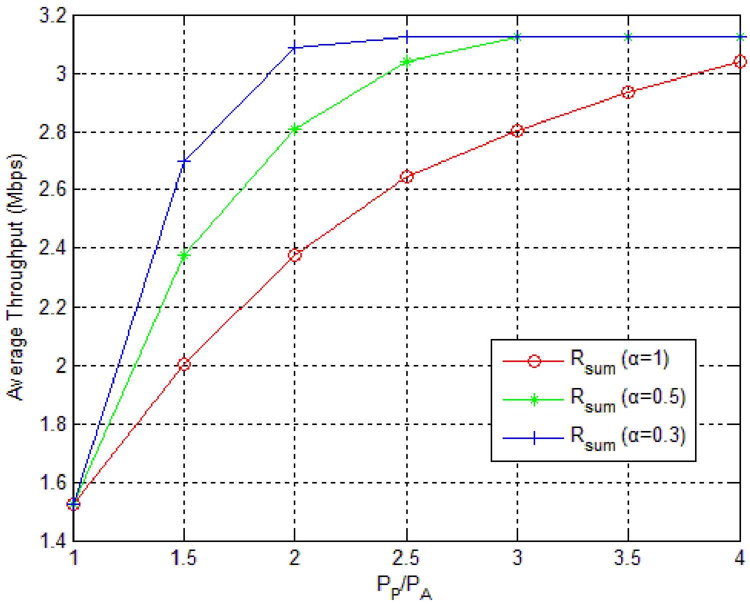


Figure 3.5: Comparison of average sum rate of WPCN with $P_A = 20$ and $K = 5$.

Therefore, the downlink channel power gain for user $i$ is given as $h_i^D = \beta_i D_i^{-\gamma}$, where $\beta_i$ is an exponential random variable with unit mean, $D_i$ is the distance of H-AP from user $i$, and the path loss exponent $\gamma$ is set to two [7], [14]. The channel variables are assumed to be i.i.d. at all nodes. Since the forward and reverse links are reciprocal, $h_i^U = h_i^D$ within a block time. Harvesting efficiency $\eta$ is set to 0.5 as in [16]. The noise power $N_0$ is assumed to be $-160$ [dBm]. Power consumed by circuit is set as $p_i^c = 0$[W]. The simulation results are averaged over 1000 channel realization.

### 3.4.1 Comparison of Average Sum Rate of WPCN with $P_A = 20$ and $K = 5$ versus the Ratio of Peak Power and Average Power

In this section, analyze the performance trend according to the ratio of peak power and average power. In general, the higher the peak power, the higher the value that can be assigned to the downlink signal to which power level modulation in H-AP is applied.

If a certain level of peak power is secured compared to the average power, it is confirmed that there is no performance improvement by increasing the peak power value. In addition, this performance trend is related to the alpha value, which is the dynamic range value. For this purpose, we analyze the performance of each of the three values of $\alpha$. In Figure 3.5, we consider a five-user WPCN and set $P_A = 20$[dBm/Hz], $K = 5$, and $\alpha = 0.3, 0.5, 1$, where the average throughput versus the ratio of peak power and average power $P_P/P_A$ is plotted. It is shown that the proposed WPCN with lower dynamic range index, that is, small value of $\alpha$ achieves higher throughput than high value of $\alpha$.

### 3.4.2 Comparison of Average Sum Rate of WPCN.

The average throughput for the proposed uplink time scheduling scheme with power level modulation is compared with the equal uplink time allocation scheme under the same network setting in Figures 3.6 and 3.7. In order to analyze the performance trends according to the distance distribution of users, we classify the users into two groups

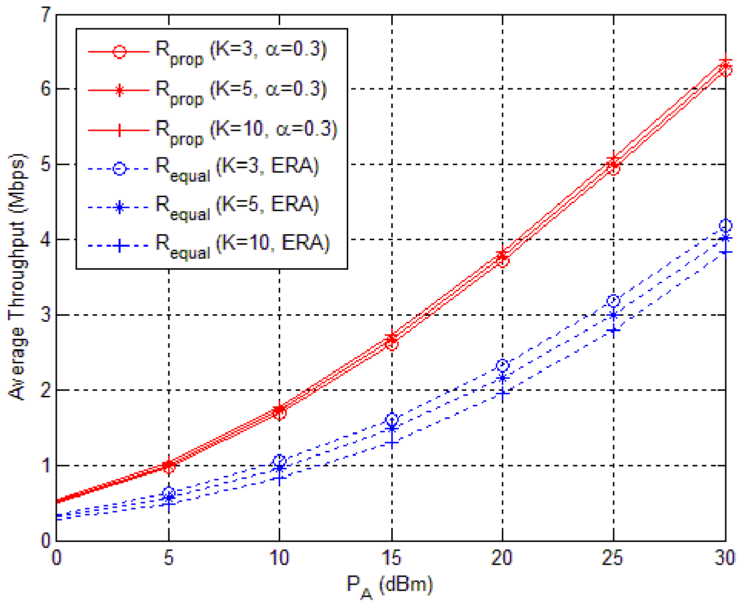


Figure 3.6: Comparison of average sum rate of WPCN with $P_P/P_A = 4, \alpha = 0.3$, and distances $\{5, 10, 15\}$ for $K = 3$ and $\{5, 10, 15, 15, 15, ..., 15\}$ for $K = 5, 10$.

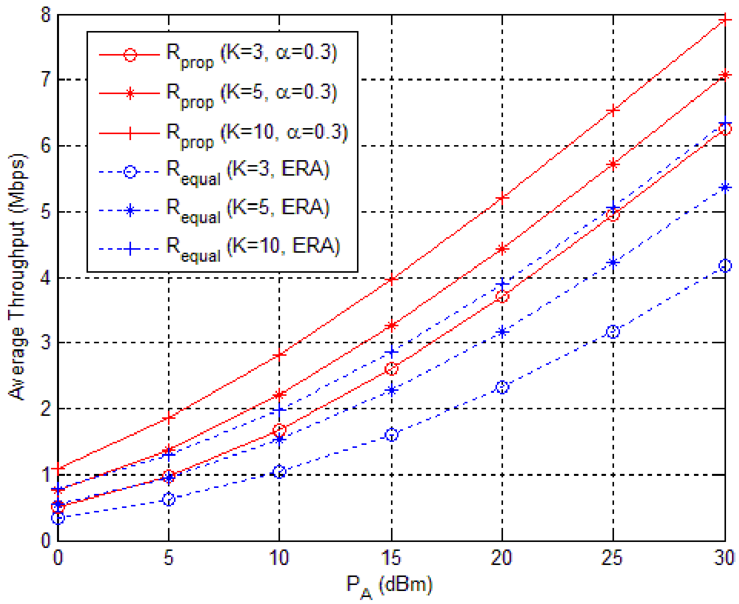


Figure 3.7: Comparison of average sum rate of WPCN with $P_P/P_A = 4, \alpha = 0.3$, and distances $\{5, 10, 15\}$ for $K = 3$ and $\{5, 10, 15, 10, 10, ..., 10\}$ for $K = 5, 10$.

with respect to the distance distribution, one with a large distance deviation and the other with a small distance deviation. In Figure 3.6, the distance profile of $K = 3$ users is given as $\{5, 10, 15\}$ in meters and for $K = 5, 10$, distances of $15$[m] are added. In this setting, we confirm that regardless of the number of users, the performance of the proposed WPCN scheme is always better than that of equal resource allocation (ERA). In the proposed scheme, performance is slightly improved as the number of users increases. From (3.13), we have the restriction as $K \leq 11$.

In the case of ERA, the performance is better when the number of users is small. This is because of the distance profile. Users from rather far distance are added, that is, the number of users with relatively poor channel power gain is increased, and uplink time of users with poor channel power gain is allocated at the same ratio as users with good channel power gain. In Figure 3.7, when $K = 3$, the distance is the same as the previous case, and for $K = 5, 10$, the distance of the added users is $10$[m]. In Figure 3.7, the performance improvement of the proposed scheme increases, as the number of users increases, which is due to the addition of users with relatively good channel power gain compared to Figure 3.6. Due to the same reason, the more the number of users in the ERA, the better the performance.

### 3.4.3 Comparison of Error Constrained Sum Rate of WPCN

The outage constrained sum rate for the proposed uplink time scheduling scheme with power level modulation under the noisy power level detection environment is compared with the ideal noiseless case and ERA in Figure 3.8. The detection noise is assumed to be $\sigma = -50$ [dBm]. Gurard time $\tau_g$ is set to 0.01 and other parameters are set as $P_P/P_A = 3$ and $\alpha = 0.3, 0.5$. Compared with the ideal case, the performance drops to about 95$\%$ with guard time, because of uplink transmission time loss due to guard time and the effect of detection noise, but we obtain an improved sum rate compared with conventional ERA. In Figure 3.9, under the given guard time $\tau_g = 0.01$, the outatge constrained sum rate of the proposed scheme is plotted versus the value

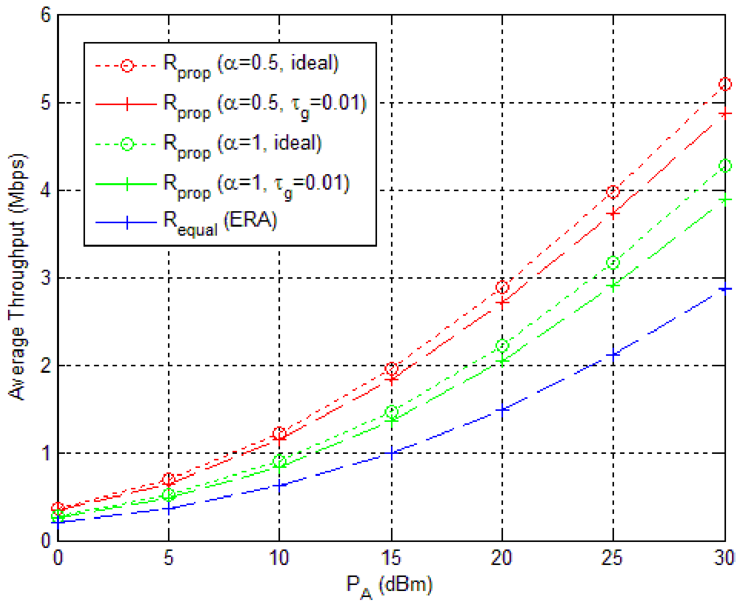


Figure 3.8: Comparison of error constrained sum rate of WPCN with $P_P/P_A = 3$.

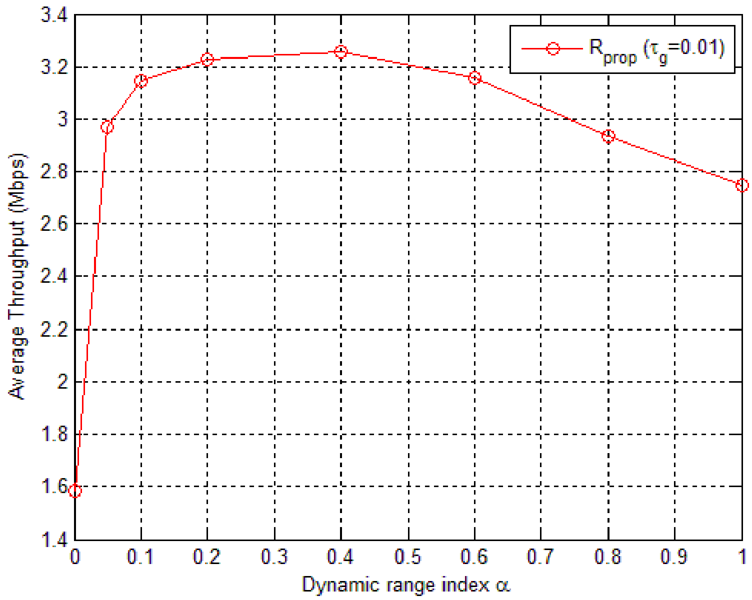


Figure 3.9: Error constrained sum rate of WPCN according to $\alpha$ with $P_P/P_A = 3$ and $P_A = 20$ [dBm].

of $\alpha$. As expected, a proper choice of $\alpha$ maximizes the outage constrained sum rate. First, for $\alpha = 0$, the zero dynamic range means the conventional ERA, whose sum rate performance is bad compared to the proposed scheme. Next, the sum rate performance of the proposed scheme is getting better upto $\alpha = 0.4$ and then its performance is degraded because the outage probability is inversely proportional to $\alpha$.

# Chapter 4

# Sum Rate Maximization in WPCN with Relay and Multi-User Pairs

Wireless power transfer is an effective technology to prolong the lifetime of wireless devices and WPCN is a represantative model which is received attention from both academia and industries [17]-[19]. In this chapter, a WPCN with relay and multi-user pairs is studied. The important restriction of the conventional WPCN is the short transmission distance because of the dual path loss and fading for both uplink information transfer and downlink energy transfer [20]. Recently, a relay node in WPCN was introduced to extend coverage of H-AP in [21]-[26]. In a WPCN with relay model, communication with the help of relays is performed. Also, the energy efficiency was studied in [27]-[29], since the dissipation of the RF energy during the energy transfer time at the H-AP decreases the efficiency of WPCNs.

Since then, several modified WPCN models have been proposed including WPCN with relay as in Figure 4.1. There are two main streams among the current related works for WPCN with relay. One is source powering relay [30]-[32] and the other is relay powering source [33]-[37].

As a study of the first category, source powering relay, a harvest-then-cooperate protocol was proposed in [30]. In that protocol, both source and relay can harvest

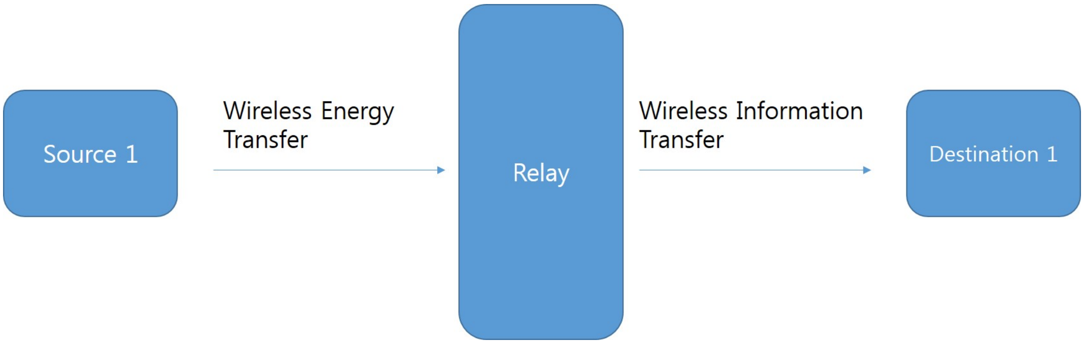


Figure 4.1: Example; Single source-destination pair in WPCN.

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energy from the RF signals from a base station or AP. The two-user WPCN with relay was studied in [31]. In the WPCN, the closer user to H-AP harvests more energy sent by H-AP and the closer users relay information of distant users. The full duplex relay, which is not only powered by the source but also harvests its own energy through energy recycling was proposed in [32].

Next, in the study of relay powering source, the sum rate maximization problem was studied in [33]. In that study, the source may harvest energy not only from the AP but also from the relay before transmitting the information. In [34], the authors studied the channel capacity subject to an additional energy transmission cost at the energy source, which is AP. In [33] and [34], it is considered that there is a single source destination pair. In [38], the communication flow is one-way and two-way communication was not considered.

In this chapter, it is assumed that a WPCN was a relay which operates as the hybrid node and multiple peer to peer links. We focus on how to maximize the sum throughput over a quasi-static fading channel. It is assumed that each user pair is composed of left and right users, where the relay is located in the middle of each user pairs as in Figure 4.2. Therefore, each user pairs must communicate during the allocated time slots with the help of relays. In order to obtain the optimal time slot of each user pairs, we formulate the sum-rate maximization problem for the given WPCN system model setting and prove its convexity. We also propose an opportunistic scheduling of the proposed WPCN to improve the performance rather than the general communication model. In that case, users not communicating in the uplink phase harvest energy from the communication signals of other user pairs. The numerical results show that the proposed schemes perform better than the conventional equal time resource allocation scheme. Numerical analysis shows that the throughput of the proposed WPCN with relay and multi-user pairs is higher than that of the conventional schemes which allocate the time slot equally in the quasi-static channel condition. It is also shown that the

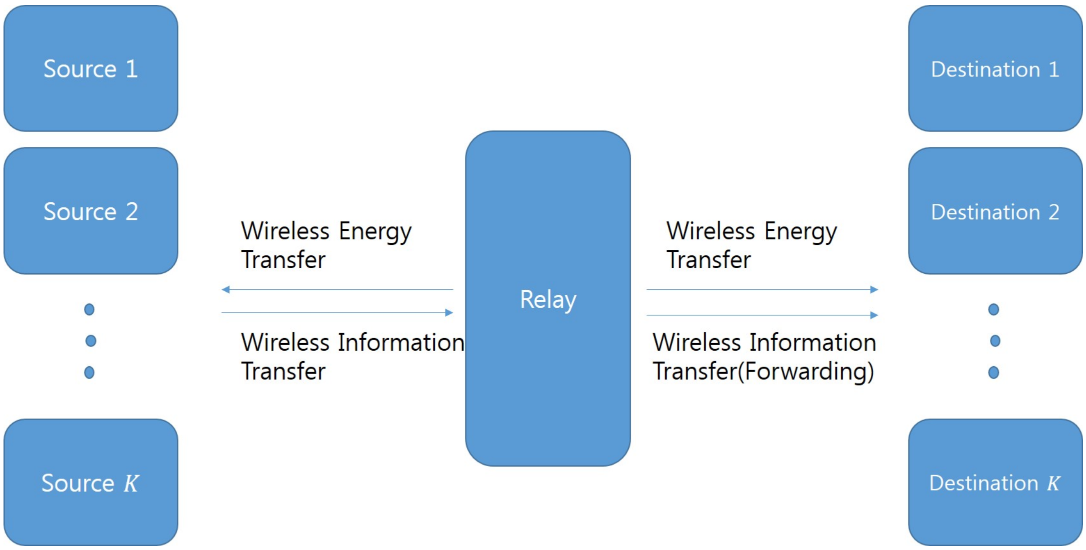


Figure 4.2: Example; Multiple source-destination pairs in WPCN.

opportunistice harvesting improves the performance compared to the basic model of the proposed WPCN.

This chapter is organized as follows. In Section 4.1, we describe the system model. First, the proposed WPCN model is introduced and the link and communication time slot between nodes are described. The optimization problem formulation and its convexity proof follow in Section 4.2. Next, we apply the opportunistic scheme in the proposed WPCN in Section 4.3. Numerical analysis for the proposed WPCN with relay and multi-user pairs is given and the performance of the proposed scheme which includes opportunistic scheme is evaluated in Section 4.4.

## 4.1 System Model of WPCN with Relay and Multi-User Pairs

WPCN with one hybrid relay and $K$ user pairs is depicted in Figure 4.3. It operates in TDD manner as;

i) WET in the downlink from relay to nodes in the both sides

ii) WITs in the uplink from nodesin the both sides to relay

iii) WITs in the amplify and forward downlink phase from relay to nodes in the both sides

Unlike the previous chapters, there are $K$ users on the left and right sides of the relay, totaling $K$ user pairs. In addition, each user pair wants to send an information signal to its counterpart user and transmission intervals are allocated to each user pair. Direct communication between paired users is assumed to be impossible and each user pairs communicates with the help of relays. Relay broadcasts a WET signal to all users in both sides and then each user transmits its WIT signal to the relay by utilizing the harvested energy. Then, the relay forwards each WIT signal to its counterpart user. All the energy and information transfers are operated via TDD over the same frequency band to attain high spectral efficiency.

It is assumed that the total operation time for WPCN is normalized as one. Quasi-

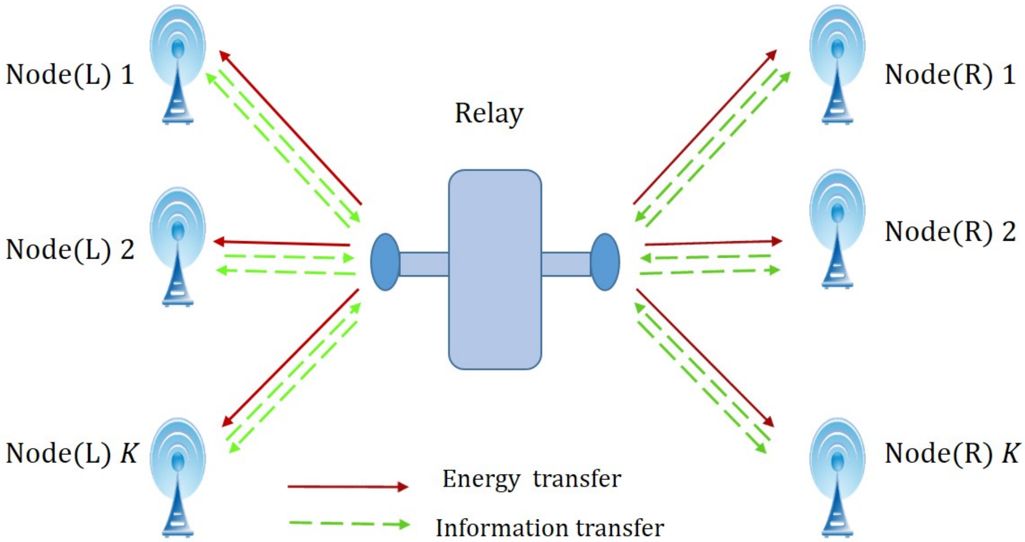


Figure 4.3: Wireless powered communication network with relay and $K$ user pairs.

static fading channel is considered, that is, the downlink and the uplink channel states are constant over a communication frame and we assume that the channel reciprocity between the uplink and downlink channels holds since the system operates in the TDD mode. The relay then acquires the downlink channel state information from the information signals of users in the previous epoch time. In this chapter, we formulate the sum rate maximization problem in WPCN with relay and multiple user pairs. We also prove that the problem is convex and verify the performance. In addition, we propose an opportunistic harvesting scheme in WPCN to improve performance.

First, user nodes are defined as $U_k^L$ and $U_k^R$, $k = 1, 2, ..., K$, and two nodes of the same index want to send information signals to each other. The transmission frame structure of WPCN is depicted in Figure 4.4. One transmission slot is divided into a wireless power transfer and a wireless information transfer. In the power transmission interval $\tau_0$, the relay transmits a signal for energy transfer to all user nodes, and the nodes harvest energy from this signal. In the next WIT phase, the information signal is transmitted in a TDMA manner for each user and the transmission interval assigned to the $i$-th pair is set to $\tau_i$. The $i$-th node exploits the harvested energy to pass information to the $i$-th corresponding user node. Each WIT time for the $i$-th user is split into two subslots ($\frac{\tau_i}{2}$, $\frac{\tau_i}{2}$). In the amplify-and-forward relay scheme, total time duration needs to be divided with the equal length [39]. In the first subslot $\frac{\tau_i}{2}$, the $i$-th user sends an information signal to the relay. It is assumed that the relay has two directional antennas and there is no interference between the two antennas. In the second subslot $\frac{\tau_i}{2}$, the relay amplifies and forwards the information signals to the corresponding $i$-th user. It is assumed that the relay assumes that it has a sufficient energy source and can always transmit signals with a constant power $P_R$. This operation is described in Figure 4.5.

The channel power gain from the relay to left side user $i$ is denoted by $h_i$ and the gain from the relay to right side user $i$ is denoted by $g_i$. It is assumed that energy harvesting due to receiver noise is negligible compared to the sufficiently large $P_R$. Then, the amounts of harvested energy $E_i^L$ of left side user $i$ and $E_i^R$ of right side user

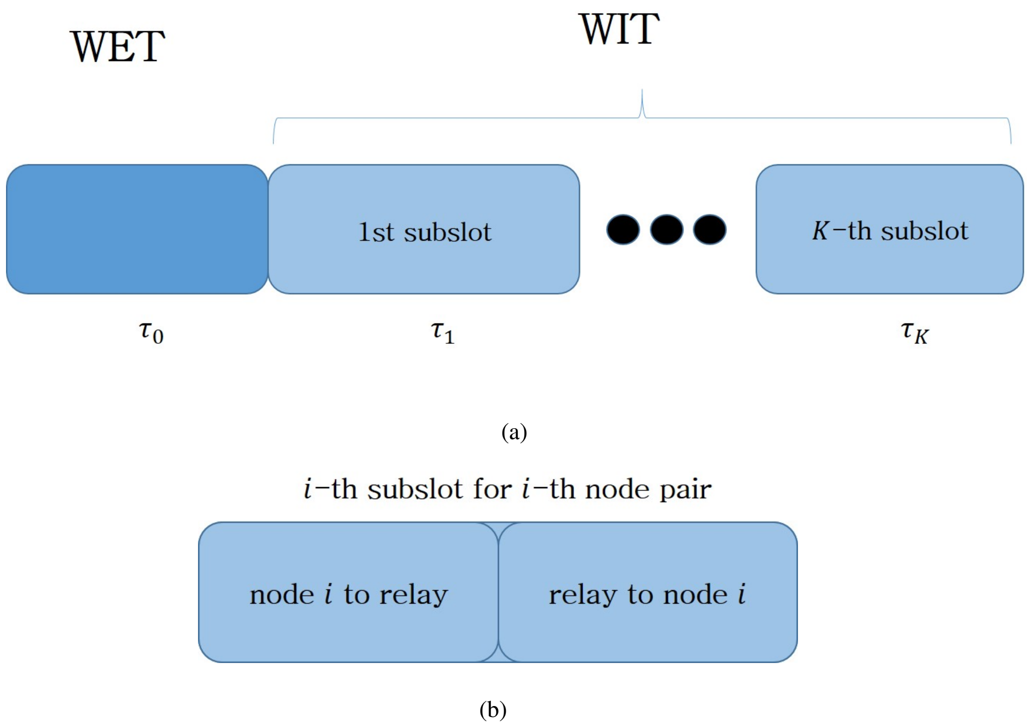


Figure 4.4: Transmission frames in the proposed WPCN; (a) Downlink and uplink signal frames, (b) Detail of subslots.

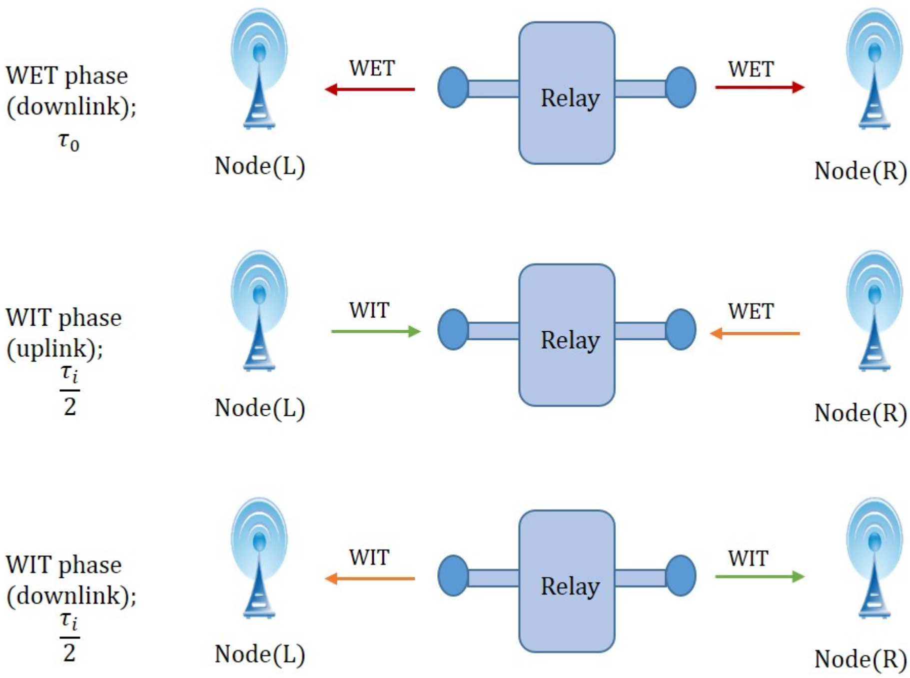


Figure 4.5: Operation of the proposed WPCN with relay and $K$-user pairs.

$i$ are given as

$$\begin{aligned} E_i^L &= \eta h_i P_R \tau^0 \\ E_i^R &= \eta g_i P_R \tau^0, \end{aligned} \tag{4.1}$$

where $\eta$ is the energy harvesting efficiency at all users. We basically assume linear devices in this chapter. Nonlinear cases as in [13] can may be further studied in the future. When the $i$-th user nodes of the left and right sides transmit information signal using harvested energy to the relay, their powers $P_i^L$ and $P_i^R$ are given as

$$\begin{aligned} P_i^L &= \frac{E_i^L}{\frac{\tau_i}{2}} \\ P_i^R &= \frac{E_i^R}{\frac{\tau_i}{2}}. \end{aligned} \tag{4.2}$$

According to [40], in amplify and forward relaying, the signal to noise ratio of received signal at the $i$-th pair of user nodes are given as

$$\begin{aligned} SNR_i^R &= \frac{\frac{P_i^L h_i}{N_0} \frac{P_R g_i}{N_0}}{\frac{P_i^L h_i}{N_0} + \frac{P_R g_i}{N_0} + 1} \\ SNR_i^L &= \frac{\frac{P_i^R g_i}{N_0} \frac{P_R h_i}{N_0}}{\frac{P_i^R g_i}{N_0} + \frac{P_R h_i}{N_0} + 1}, \end{aligned} \tag{4.3}$$

where $N_0$ is the single sided power spectral density of the additive white Gaussian noise. Then, the achievable rate of user $i$ at each side measured in nats/s/Hz is expressed as

$$\begin{aligned} R_i^R =& \frac{\tau_i}{2} \log\left(1 + SNR_i^R\right) \\ R_i^L =& \frac{\tau_i}{2} \log\left(1 + SNR_i^L\right). \end{aligned} \tag{4.4}$$

## 4.2 Problem Formulations with Proof of Convexity

In this section, we propose an optimization problem of WPCN with relay and multi-user pairs. We optimize time resource $\tau_0$ and $\tau_i$'s, $i = 1, ..., K$, to maximize the total sum rate of the WPCN and prove the convexity of the problem. Let $R_{sum}$ be the sum rate defined as

$$R_{sum} = \sum_i (R_i^R + R_i^L) \tag{4.5}$$

and $\boldsymbol{\tau} = [\tau_0, \tau_1, \tau_2, ..., \tau_K]$. Then, we can formulate the optimization problem as follows:

$$\begin{aligned}
&\max_{\boldsymbol{\tau}} \ R_{sum} \\
&\quad \text{subject to} \\
&\qquad \text{C1: } 0 \le \tau_i \le 1 \\
&\qquad \text{C2: } \tau_0 + \tau_1 + ... + \tau_K \le 1 \\
&\qquad \text{C3: } P_i^L \frac{\tau_i}{2} \le \eta h_i P_R \tau_0 \\
&\qquad \text{C4: } P_i^R \frac{\tau_i}{2} \le \eta g_i P_R \tau_0 \\
&\qquad\quad i = 1, 2, ..., K.
\end{aligned} \tag{4.6}$$

The constraints C3 and C4 imply that the total energy consumed by the $i$-th user cannot exceed the harvested energy in the WIT phase.

**Lemma 4.1.** *The objective function $R_{sum}$ is a concave function of $\boldsymbol{\tau}$.*

*Proof.* By using variable substitution, we have $\gamma^L, \gamma^R, \theta_i^L, \theta_i^R, \epsilon_i^L$, and $\epsilon_i^R$ as

$$\begin{aligned}
\gamma_i^L &= \frac{h_i^2}{N_0},\ \gamma_i^R = \frac{g_i^2}{N_0} \\
\theta_i^L &= P_R g_i,\ \theta_i^R = P_R h_i \\
\epsilon_i^L &= 2\gamma_i^L P_R \tau_0,\ \epsilon_i^R = 2\gamma_i^R P_R \tau_0.
\end{aligned} \tag{4.7}$$

Using the above new variables, the rate expression in (4.4) can be modified as

$$\begin{aligned} R_i^L =& \frac{\tau_i}{2} \log\left(1 + SNR_i^L\right) \\ =& \frac{\tau_i}{2} \log\left(1 + \frac{\frac{P_i^R g_i}{N_0} \frac{P_R h_i}{N_0}}{\frac{P_i^R g_i}{N_0} + \frac{P_R h_i}{N_0} + 1}\right) \\ =& \frac{\tau_i}{2} \log\left(1 + \frac{2\gamma_i^L P_R \theta_i^L \tau_0}{2\gamma_i^L P_R N_0 \tau_0 + (\theta_i^L + N_0)\tau_i}\right) \\ =& \frac{\tau_i}{2} \log\left(1 + \frac{c\tau_0}{a\tau_0 + b\tau_i}\right). \end{aligned} \tag{4.8}$$

Let $\hat{R}_i^L = \frac{1}{2}\log(1 + \frac{c\tau_0}{a\tau_0 + b})$. It is known that $\hat{R}_i^L$ is concave when $\tau_0$ is positive. Then, $R_i^L$ is a perspective function of $\hat{R}_i^L$ and it preserves the concativity of original function $\hat{R}_i^L$ [12]. Then, $R_{sum}$ is the non-negative weighted sum of concave function, which is a concave function. ■

**Lemma 4.2.** *The optimization problem in (4.6) is convex optimizaiton problem.*

*Proof.* The objective function $R_{sum}$ in (4.6) is concave and the constraints are affine. Then, the convexity of the problem is established. ■

The convexity of the sum rate maximization is proved and thus the maximum value of sum rate can be obtained by a convex optimization problem solver [8]. Compared to the equal resource allocation problem for the WPCN with relay and $K$ user pair, only linear constraints are added and the computational complexity of the proposed one is kept almost the same. However, it will be shown that the throughput performance of the proposed scheme can be improved.

## 4.3 Opportunistic Energy Harvesting Scheme in WPCN with Relay and Multi-User Pairs

In this section, we propose an opportunistic energy harvesting scheme that can obtain better throughput than the proposed scheme in the previous section. In the previous

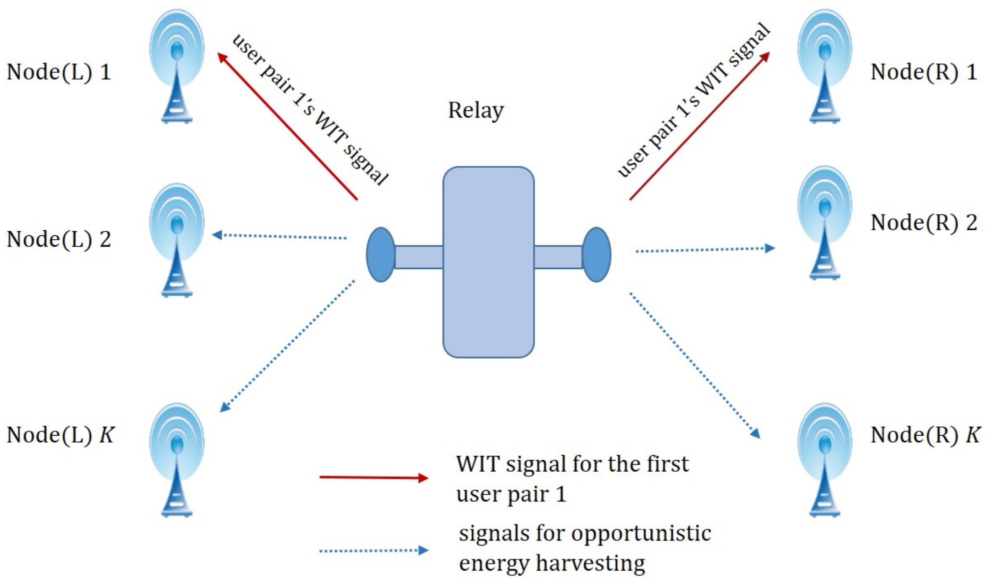


Figure 4.6: Opportunistic energy harvesting in WPCN when the relay transmits the WIT signal for the first user pair.

section, user pairs communicating in the TDMA and user pairs that do not communicate during other user pairs' communication slot also receive other users' unnecessary information signals. Here, opportunistic energy harvesting means that each user node do energy harvesting from other users' information signals transmitted by the relay. In this scheme, the $i$-th user harvests energy from signals that are broadcast from pair 1, pair 2, ... , pair $i-1$ before the $i$-th WIT subslot as an energy source as in Figure 4.6. Then, the harvested energies of the $i$-th user pair in the opportunistic scheme are given as

$$\begin{aligned} E_k^L &= \eta h_i P_R \tau_0 + \eta h_i P_R \sum_{j=1}^{i-1} \frac{\tau_j}{2} \\ &= \eta h_i P_R (\tau_0 + \sum_{j=1}^{i-1} \frac{\tau_j}{2}) \\ E_k^R &= \eta g_i P_R \tau_0 + \eta g_i P_R \sum_{j=1}^{i-1} \frac{\tau_j}{2} \\ &= \eta g_i P_R (\tau_0 + \sum_{j=1}^{i-1} \frac{\tau_j}{2}), \end{aligned} \tag{4.9}$$

where $\eta$, $0 < \eta < 1$ is the energy harvesting efficiency at all users. When the $i$-th user nodes transmit information signal to the relay using harvested energy, the transmission powers of the $i$-th user node pair are given as

$$\begin{aligned} P_i^L &= \frac{E_i^L}{\frac{\tau_i}{2}} \\ P_i^R &= \frac{E_i^R}{\frac{\tau_i}{2}}. \end{aligned} \tag{4.10}$$

According to [40], in amplify and forward relaying, the signal to noise ratios of received signals at the $i$-th pair of user nodes are given as

$$\begin{aligned} SNR_i^R &= \frac{\frac{P_i^L h_i}{N_0} \frac{P_R g_i}{N_0}}{\frac{P_i^L h_i}{N_0} + \frac{P_R g_i}{N_0} + 1} \\ SNR_i^L &= \frac{\frac{P_i^R g_i}{N_0} \frac{P_R h_i}{N_0}}{\frac{P_i^R g_i}{N_0} + \frac{P_R h_i}{N_0} + 1} \end{aligned} \tag{4.11}$$

where $N_0$ is the single sided power spectral density of the additive white Gaussian noise. Then, the achievable rate of user $i$ at each side measured in nats/s/Hz is expressed as

$$\begin{aligned} R_i^R =& \frac{\tau_i}{2} \log{(1 + SNR_i^R)} \\ R_i^L =& \frac{\tau_i}{2} \log{(1 + SNR_i^L)}. \end{aligned} \tag{4.12}$$

Then, $R_{sum}$ is given as

$$R_{sum} = \sum_i (R_i^R + R_i^L) \tag{4.13}$$

and $\boldsymbol{\tau} = [\tau_0, \tau_1, \tau_2, ..., \tau_K]$. Then, we can formulate the optimization problem as follows:

$$\begin{aligned} &\max_{\boldsymbol{\tau}} \ R_{sum} \\ &\quad \text{subject to} \\ &\qquad \text{C1: } 0 \leq \tau_i \leq 1 \\ &\qquad \text{C2: } \tau_0 + \tau_1 + ... + \tau_K \leq 1 \\ &\qquad \text{C3: } P_i^L \frac{\tau_i}{2} \leq \eta h_i P_R (\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2}) \\ &\qquad \text{C4: } P_i^R \frac{\tau_i}{2} \leq \eta h_i P_R (\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2}) \\ &\qquad\quad i = 1, 2, ..., K. \end{aligned} \tag{4.14}$$

The constraints C3 and C4 imply that the total energy consumed by the $i$-th user cannot exceed the harvested energy in the WET place as well as the WIT phase.

**Lemma 4.3.** *The objective function $R_{sum}$ is a concave function of $\boldsymbol{\tau}$.*

*Proof.* By using variable substitution, we have $\gamma^L, \gamma^R, \theta_i^L, \theta_i^R, \epsilon_i^L$, and $\epsilon_i^R$ as

$$\begin{aligned}
\gamma_i^L =& \frac{h_i^2}{N_0},\ \gamma_i^R = \frac{g_i^2}{N_0} \\
\theta_i^L =& P_R g_i,\ \theta_i^R = P_R h_i \\
\epsilon_i^L =& 2\gamma_i^L P_R(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2}) \\
\epsilon_i^R =& 2\gamma_i^R P_R(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2}).
\end{aligned} \tag{4.15}$$

Using the above variable substitution, the rate expression in (4.12) can be modified as

$$\begin{aligned}
R_i^L =& \frac{\tau_i}{2} \log\left(1 + SNR_i^L\right) \\
=& \frac{\tau_i}{2} \log\left(1 + \frac{\frac{P_i^R g_i}{N_0} \frac{P_R h_i}{N_0}}{\frac{P_i^R g_i}{N_0} + \frac{P_R h_i}{N_0} + 1}\right) \\
=& \frac{\tau_i}{2} \log\left(1 + \frac{2\gamma_i^L P_R \theta_i^L(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2})}{2\gamma_i^L P_R N_0(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2}) + (\theta_i^L + N_0)\tau_i}\right) \\
=& \frac{\tau_i}{2} \log\left(1 + \frac{c(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2})}{a(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2}) + b\tau_i}\right).
\end{aligned} \tag{4.16}$$

Let

$$\begin{aligned}
\hat{R_i^L} =& \frac{1}{2} \log(1 + \frac{c(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2})}{a(\tau_0 + \sum_{j=1}^{K} \frac{\tau_j}{2}) + b}) \\
f(x) =& \frac{1}{2} \log(1 + \frac{cx}{ax + b}) \\
g(x_0, x_1, ..., x_{i-1}) =& x_0 + \sum_{j=1}^{i-1} \frac{x_j}{2}.
\end{aligned} \tag{4.17}$$

Then $f$ is concave from the proof of the previous section and the fact that $g$ is linear sum. Then, $f(g)$ is concave, which means that $\hat{R_i^L}$ preserves concavity when $\tau_i, \tau_0 \in (0, \infty)$ are positive. Then, in the same way as Lemma 4.1, $R_i^L$ is a concave function. ∎

**Lemma 4.4.** *The optimization problem in* (4.16) *is convex optimizaiton problem.*

*Proof.* The objective function $R_{sum}$ is concave and the constraints are affine. Then, the convexity of the problem is established. ■

Since the problem in (4.16) is a convex optimization problem, the maximum value of sum rate with opportunistic harvesting scheme can also numerically be obtained.

## 4.4 Simulation Results

In this section, we provide numerical results to show the performance of the proposed schemes with relay and $K$ user pairs in WPCN. In the network setting for simulation, we adopt the distance-dependent path loss model and assume a quasi-static Rayleigh fading channel [15]. Therefore, the downlink channel power gain for user $i$ is given as $h_i^D = \beta_i D_i^{-\gamma}$, where $\beta_i$ is an exponential random variable with unit mean, $D_i$ is the distance of H-AP from user $i$, and the path loss exponent $\gamma$ is set to two [7], [14]. The channel variables are assumed to be i.i.d. at all nodes. The forward and reverse channels are reciprocal within a time slot. Harvesting efficiency $\eta$ is set to 0.5 as in [16]. The noise power spectral density $N_0$ is assumed to be $-160$ [dBm]. Power consumed by circuit is set as $p_i^c = 0$ [W]. The simulation results are averaged over 1000 channel realizations.

### 4.4.1 Comparison of Average Sum Rate of WPCN

The average throughput for the proposed WPCN with relay and $K$ user pairs scheme is compared with the equal uplink time allocation scheme under the same network setting in Figures 4.7, 4.8, and 4.9. In order to analyze the performance according to the distance distribution of users, we classify the users into three groups with respect to the distance distribution, that is, a large distance deviation, a middle distance deviation, and a small distance deviation. In Figure 4.7, the average throughput for the distance profile of $K = 3$ user pairs is shown. In this setting given as $\{5, 7.5, 10\}$ in meters, we confirm that the performance of the proposed WPCN scheme is always better than that of equal time resource allocation and the opportunistic scheme achieves better performance than the other proposed WPCN schemes.

In the case of distance distribution $\{5, 10, 15\}$ and $\{5, 15, 30\}$, the proposed scheme achieves the performance similar to that in Figure 4.7 where the throughput is highest when the opportunistic energy harvesting scheme is applied. The overall sum rate is the highest for $\{5, 7.5, 10\}$ because the closer users have a relatively good channel gain compared to the other cases. In the equal time resource allocation scheme of WPCN, when the distance variance is small, relatively high performance is achieved, but when the distance variance is large, the performance is low. In the case when the variance of the distance distribution is high, this may occur because equal time resource allocation scheme unnecessarily allocates a lot of resources to users with low channel gains. From these results, it can be seen that proper allocation of time resources is an important issue. In addition, it can be seen that the difference in performance appears clearly according to the distance distribution. In particular, in the case of $\{5, 15, 30\}$ having a large variance of the distance distribution, the overall throughput attenuation is particularly severe. This phenomenon is noticeable in the WPCN because of the 'doubly-near-far' problem mentioned in Chapter 2.

### 4.4.2 Comparison of Average User Rate of WPCN

The average throughput of each user for the proposed WPCN scheme with relay and $K$ user pairs is compared with the equal uplink time allocation scheme under the same network setting in Subsection 4.4.1.

In order to analyze the performance according to the distance distribution of users, we classify the users into two groups with respect to the distance distribution, that is, a large distance deviation $\{5, 15, 30\}$, a middle distance deviation $\{5, 10, 15\}$, and a small distance deviation $\{5, 7.5, 10\}$. In Figures 4.11, 4.10 and 4.12, it is shown that user pairs close to the relay, that is, user pairs with a high channel power gain, achieve the higher throughput. In this dissertation, we focuse on maximizing the total

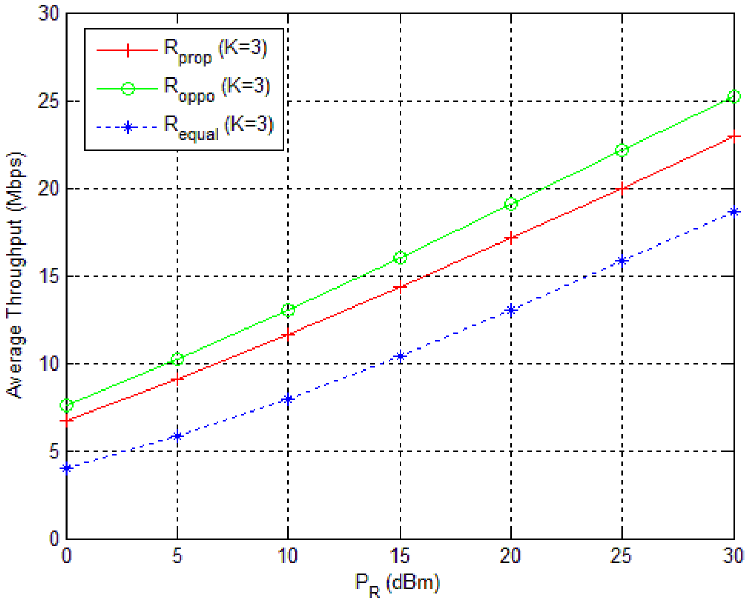


Figure 4.7: Comparison of average sum rate of the proposed WPCN with distances $\{5, 7.5, 10\}$.

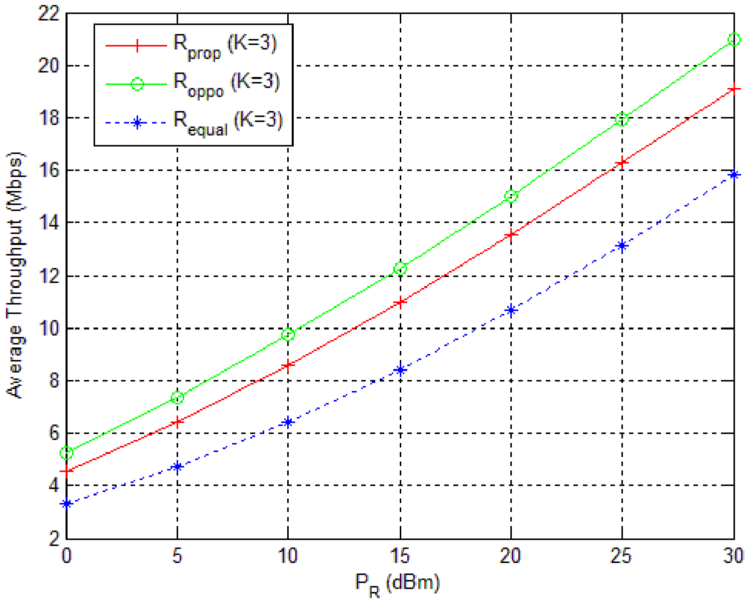


Figure 4.8: Comparison of average sum rate of the proposed WPCN with distances $\{5, 10, 15\}$.

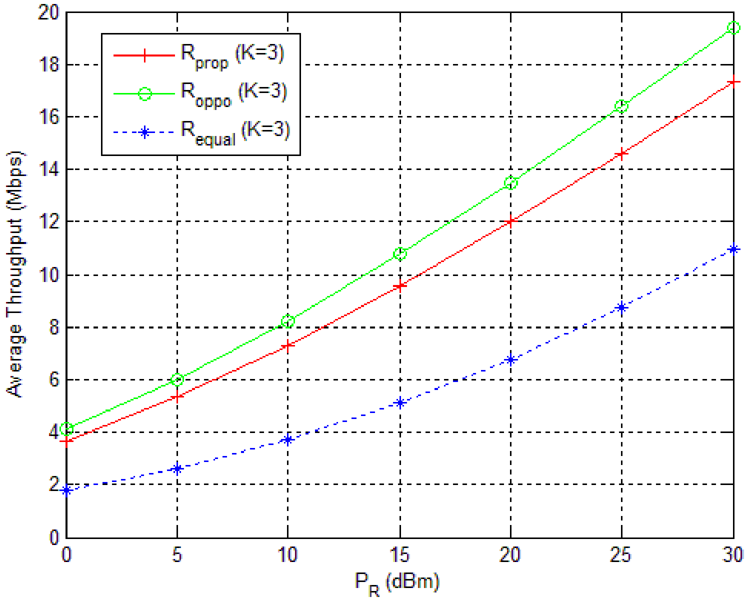


Figure 4.9: Comparison of average sum rate of the proposed WPCN with distances $\{5, 15, 30\}$.

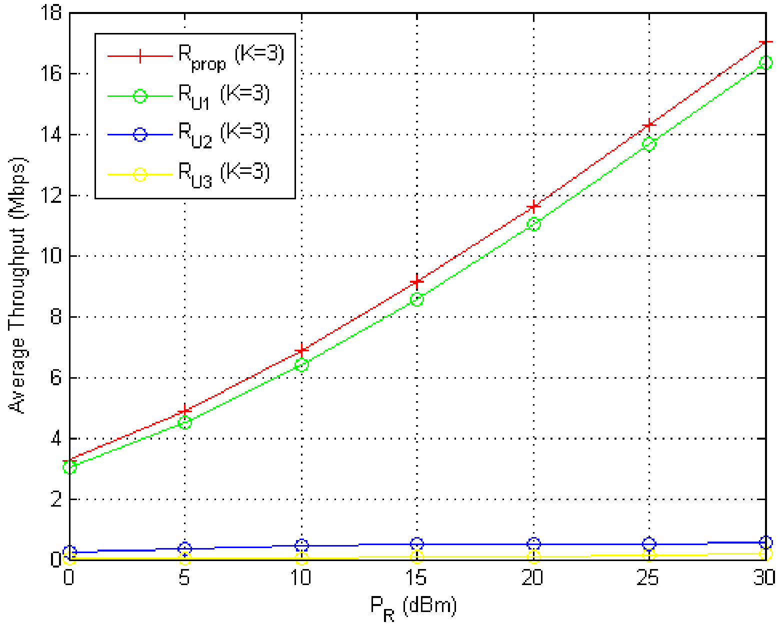


Figure 4.10: Comparison of average user rate of WPCN with distances $\{5, 15, 30\}$.

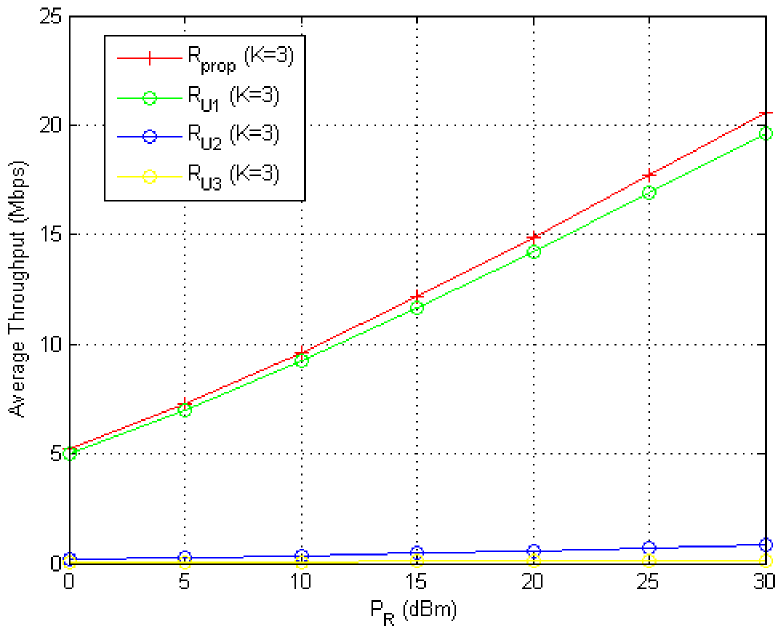


Figure 4.11: Comparison of average user rate of WPCN with distances $\{5, 10, 15\}$.

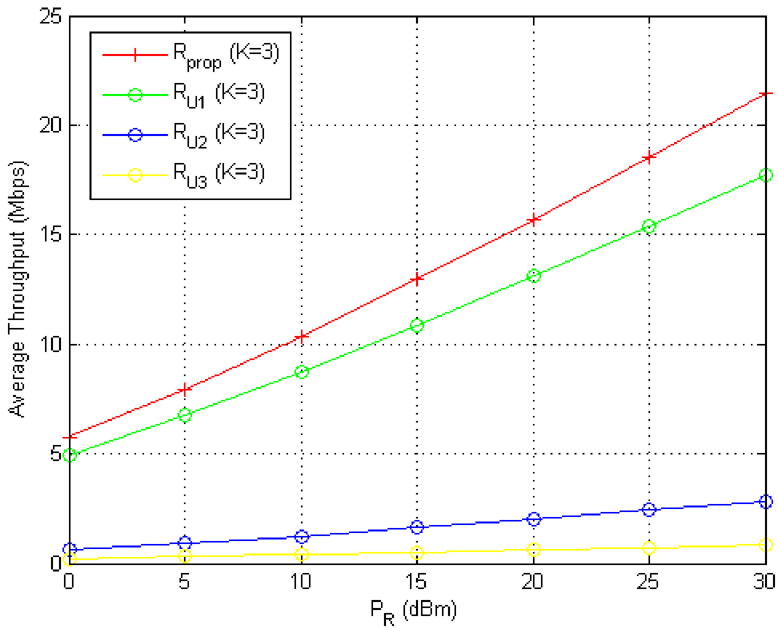


Figure 4.12: Comparison of average user rate of WPCN distances $\{5, 7.5, 10\}$.

sum rate. However, from the viewpoint of user fairness, it is confirmed that the difference in transmission rates achieved by each user is too large. For example, In Figure 4.12, when the relay power is 15, the throughput for each user shows a difference of 8:2.2:0.2. This is because most of time resources are allocated to users with high channel power gain. Also, in a situation when the difference in channel power gain among users is large, this throughput imbalance may be more severe.

Therefore, the necessity of new research to solve user fairness problem is raised. As a future research direction, it is conceivable to set the objective function of the optimization problem to a criterion other than the sum rate. These considerations can be considered as a future work.

### 4.4.3 Comparison of Average User Rate of 1:3 WPCN

In this subsection, we analyze the simulation results for a particular situation where a WPCN with relay can be applied. The average throughput of each user for the proposed WPCN scheme with relay and $K$ user pairs is compared with the equal uplink time allocation scheme under the same network setting in Subsection 4.4.1.

The previous subsection assumes that there are $K$ users on both sides of the relay. To consider the practical situation, we apply the proposed scheme to the case where both users are asymmetric. As a basic example, we set the 1: 3 WPCN model and apply the proposed scheme. In other words, assume that a user communicates with a peer to peer of one or more users.

It is assumed that there is one user node on the left side and three users on the right side based on the relay position and the distance disributions are assumed at $\{5, 15, 30\}$, $\{5, 10, 30\}$, and $\{5, 7.5, 10\}$. That is, one user on the left side communicates with each of the three users and peer to peer. In Figures 4.13 and 4.14, the average throughput achieved in that case is shown. Compared to the situation where the same number of users are paired, the difference between the performance of the proposed scheme and the performance of equal resouce allocation is relatively small.

This is because there is only one left user, which means that the gain of allocating time resources as the channel changes is relatively small. In addition, it can be analyzed for 2: 3 WPCN and is expected to show a similar result.

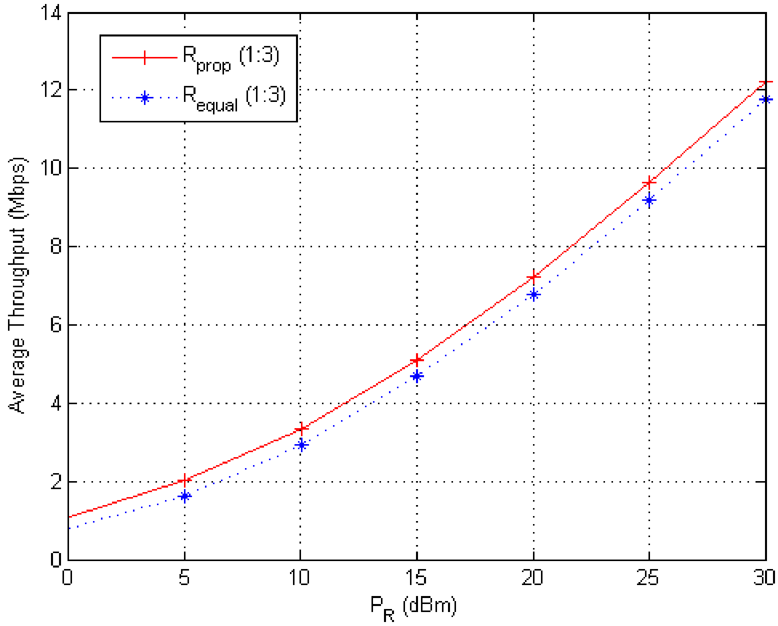


Figure 4.13: Comparison of average sum rate of 1:3 WPCN with distances $\{5, 15, 30\}$.

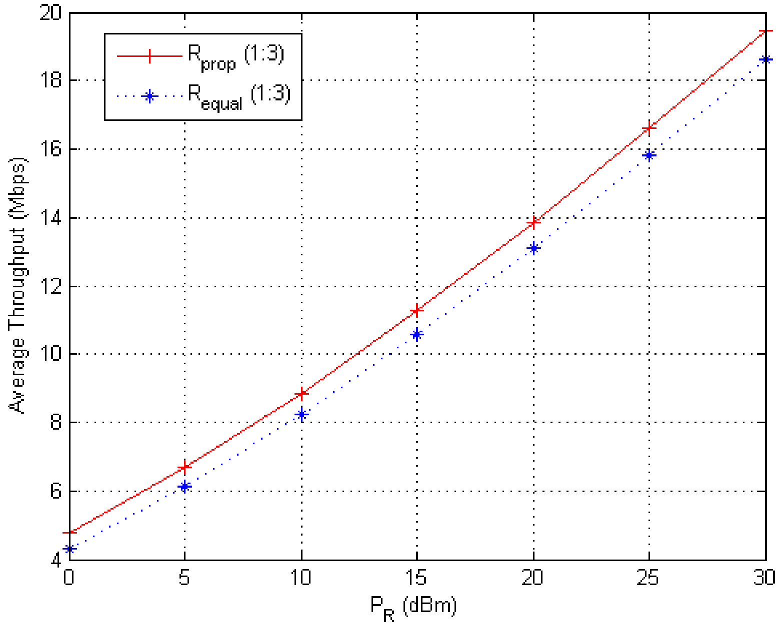


Figure 4.14: Comparison of average sum rate of 1:3 WPCN with distances $\{5, 10, 15\}$.

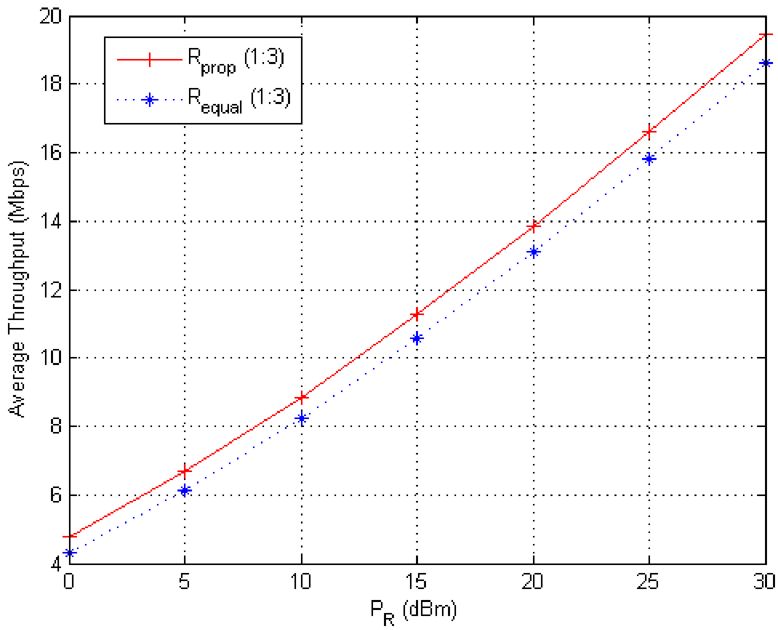


Figure 4.15: Comparison of average sum rate of 1:3 WPCN with distances $\{5, 7.5, 10\}$.

# Chapter 5

# Conclusions

In this dissertation, research on the sum rate maximization using time resource allocation scheduling in WPCN was presented.

In Chapter 2, some preliminaries of WPCN were briefly overviewed. Basic concepts, sum rate maximization, and property of WPCN were presented. The convex optimization was also introduced.

In Chapter 3, it is proposed that the power level modulation of the downlink WET signal for uplink time scheduling in WPCN, where users are not equipped with an information receiver. In the conventional scheme, it is difficult for the users to adjust their time slots according to the channel change. However, the proposed WPCN with power level modulation can achieve a high sum rate in response to the channel change by adjusting time slots of users by power level modulation. The sum rate maximization problems for the WPCN with the proposed power level modulation was formulated and the convexity of the problem was proved. Also, it is considered that a practical scenario where the synchronization exists error is included in the analysis. Numerical result shows that the proposed WPCN scheme with optimal parameters significantly outperforms the conventional equal time allocation scheme and it is shown that the optimization problem and its solution are still valid when guard time for robust packet synchronization is added to each time slot.

In Chapter 4, sum rate optimization problem in WPCN with relay and multi-user pairs were proposed. In this WPCN, each user pair communicates each other in the TDMA mode with the help of relay, and a scheme for maximizing sum rate in a given channel situation is formulated. In addition, in a situation when one pair communicates an information signal, the other of WPCN scheme is also proposed in which the remaining pairs opportunistically harvest the signal as an energy source. Compared with equal time resource allocation, it is shown that the proposed opportunistic WPCN scheme achieves better performance than that of WPCN without opportunistic harvesting.

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# 초 록

이 학위 논문에서는, i) 무선 전력 전달 네트워크에서 하향 통신 신호의 전력 변조 기법을 이용하여 유저들의 전송률 총 합을 최대화 하는 기법과 해당 기법에 대하여 문제를 수식화하고 컨벡스 최적화를 이용하여 해결 가능함을 증명 하였으며, ii) 릴레이와 다중 유저 쌍이 있는 무선 전력 전달 네트워크에서의 총 전송률을 최대화 하는 문제를 수식화함과 해당 문제가 컨벡스함을 증명하는 방법들이 연구되었다.

먼저, 무선 전력 전달 네트워크에서 가장 기본적인 모델인 하나의 H-AP와 다중 유저가 존재하는 시스템 모델에서, 하향 통신 신호의 전력 변조 기법을 제안한다. 일반적으로 WPCN에서 유저들은 전력 신호를 전달받는 안테나만을 가지고 있다고 가정하기 때문에 채널 상황이 변화하는 경우 정보 신호를 전송하는 상향 통신 구간을 최적화 하기 어렵다. 제안하는 방법은 유저들이 받는 하향 통신에서의 전력 전달 신호를 유저 수 만큼의 서로 다른 평균 전력값을 가지는 신호로 변조하여 위와 같은 문제를 해결하고 있다. 이러한 방법에 기반하여 유저들이 달성하는 총 전송률을 최대화 하는 최적화 문제를 수식화 하고 컨벡스 최적화를 이용하여 해당 문제가 해결 가능함을 증명한다. 추가적으로, 시간 자원 할당 시 실제 채널모델에서 발생 가능한 잡음을 고려하여 가드 시간을 삽입하는 기법을 제안하였다. 시뮬레이션을 통하여 제안하는 기법들이 기존의 시 자원 균등 할당 기법 대비 높은 성능을 달성함을 확인하였다.

두 번째로, 릴레이와 다중 유저 쌍이 있는 무선 전력 전달 네트워크를 고려하였다. 해당 네트워크 모델에 대하여 총 전송률을 최대화 하는 문제를 수식화 하고 첫 번째 연구에서와 같이 컨벡스 최적화를 이용하여 해당 문제가 해결 가능함을 증명하

였다. 또한 시분할 다원접속 방식의 통신에서, 한 쌍의 유저가 정보 신호를 통신하는 구간에 나머지 유저들은 필요없는 신호를 받게 되는데, 이를 에너지원으로서 수확하여 성능을 향상시키는 기법을 제안하였다. 또한, 제안된 기법과 기존 시 자원 균등 할당 기법을 동일한 가정하에 비교하여 성능이 개선됨을 보여주었다.

**주요어**: 에너지 수확 기술, 하이브리드 접근점, 자원 할당 기법, 무선 전력 전달 네트워크, 릴레이

**학번**: 2014-21612