SCHOOL OF ELECTRICAL ENGINEERING AND TELECOMMUNICATIONS

Energy-Efficient Resource Allocation for Multiuser WPCN

By

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Abstract

With the development of wireless communications, the traditional battery replacement and its charging way are not suitable for the new wireless devices. Establishing a high effective green communication system has become an important study topic. This thesis focuses on the beamforming design for the wireless powered communication network and its resource allocation. A multiuser WPCN system was proposed as an advanced network structure, where wireless users can harvest energy from the power station and then use the energy to transmit information. This paper firstly does a literature survey on the previous WPCN works and introduces some basic theory of WPCN, multi-antennas and beamforming. Then the system model and its optimization problem are designed in this paper to maximize the energy efficiency of this WPCN system. In this thesis, we have proposed a series of transformations to convert the non-convex problem and obtain the optimum solution. Numerical simulation results show the relationship for average minimum transmitted power versus minimum required system throughput and the distance between wireless users and information access points respectively. It also verified that the system can provide a remarkable performance gain with extra transmit antennas equipped at the base station.

Acknowledgement

I would like to express my greatest gratitude to my supervisor Derrick Wing Kwan Ng, who gave me the opportunity to do this topic and supported me throughout the project. It’s been really helpful with his aspiring guidance, invaluably constructive criticism and friendly advice through the learning process of master thesis.

Abbreviations

WPCN	Wireless Powered Communication Network
ICT	Information and Communication Technology
RF	Radio Frequency
WET	Wireless Energy Transmission
WIT	Wireless Information Transmission
SWIPT	Simultaneous Wireless Information and Power Transfer
DMC	Discrete Memoryless Channels
AWGN	Additive White Gaussian Noise
MISO	Multiple Input Single Output
DL	Downlink
UL	Uplink
HTT	Harvest Then Transmit
TDMA	Time Division Multiplexing Access
HAP	Hybrid Access Point
SDMA	Space Division Multiple Access

Table of Contents:

1. Introduction:

1.1 Background

With the rapid development of communication technologies, mobile communication systems have experienced many times of evolutions from the first generation to 4G. There are more and more mobile phone users and the coverage of cellular networks has become more and more intensive. That makes the energy consumption of communication networks increases continually. According to the statistics, the information and communication industry has become the fifth largest energy-consuming industry in the world because its carbon dioxide emissions account for about 2% of the total emissions of the world. [1] It's estimated that by 2020, the carbon dioxide emissions generated by the mobile communication network will be 178 megatons which will account for 22% of the total ICT industry emissions and will continue to grow in the future. [2] The annual maintenance cost of network equipment and environmental is approximately 15 billion dollars. Driven by the strong demand for energy conservation and emission reduction, in recent years, the concept of green communication has been proposed for the fifth generation of communications (5G) to reduce the energy consumption of communication and information technology and CO_2 emissions. In green communications, the researchers are focusing on the energy consumption of communication networks while paying attention to the communication rate, spectrum utilization, and network delay reduction.

During the study of modern wireless communication technologies, the limited device battery life has become quite a big problem in the development of sustainable Green 5G Networks. For example, more and more wireless sensor nodes are widely deployed in indoor areas, streets and lakes to implement indoor monitoring, logistics examination, environmental measurement and other functions [3]. At present, for a traditional relay or sensor network, its network nodes are usually powered by batteries with limited energy, and can only use the power supplied by the built-in battery to do the environmental parameter collection and information reporting, which seriously limits the service life of the sensor nodes. In order to delay the battery consumption, it is usually necessary to control the information reporting rate of sensor nodes, and it reduces the effectiveness of data collection and environmental monitoring. Although the service life of sensor nodes can be extended by replacing the batteries, in many cases, the cost of battery replacement for the node is too high or even this kind of replacement is impossible to implement. It is not conducive to the entire system maintenance. Such as in a smart home system, in order to reduce a large number of redundant indoor wirings and enhance aesthetics, the sensor nodes are generally deployed inside the building in a concealed manner. So the battery replacement needs to damage the building itself, which is costly. Similarly, in the environmental monitoring system of a lake or ocean, sensor nodes are distributed on the water surface, and the replacement costs are very high as well. To solve this problem, Radio Frequency Wireless Energy Transmission (RF-enabled WET) technology has emerged to provide wireless devices with a stable and continuous power supply. By using the far-field radiation characteristics of the electromagnetic wave, this technology enables the wireless receiver to remotely receive the radio frequency signal which radiated by the energy transmitter, thereby solving the problem of energy supply. Radio frequency wireless energy transmission technology has many practical advantages, such as its wide scope of work, low production cost, and efficient energy multicast characteristics due to the broadcast nature of electromagnetic waves.

A significant application of radio frequency Wireless Energy Transmission technology is Wireless Powered Communication Networks, in which wireless devices use the received radio frequency energy to communicate with other devices. In wireless powered communications, wireless devices will not run out of power due to their communications. This advantage improves the user experience and makes the communications have a greater throughput and stronger sustainability than the traditional battery-powered communications. Wireless powered communication technology can also be applied to wireless sensors, reducing the sensor maintenance costs, enhancing the flexibility of sensor deployment. Microwave energy transmission has high attenuation with increasing transmission distance, so in the past, the radio frequency wireless energy transmission was widely used to support low-power devices such as RFID and wireless sensors. However, in recent years, with the development of antenna technology and radio frequency energy harvesting circuits, the wireless devices can transmit and collect microwave energy more efficiently. Based on the WPC technology above, the wireless powered communication networks (WPCN) has proposed to realize the continuous power supply, in which, wireless devices use harvested energy to transmit information. In this network architecture, some dedicated energy nodes are deployed or all sensor nodes are controlled by the central to transmit the electromagnetic wave signals directionally, in order to implement wireless energy supply to sensor nodes, improve the available energy of the nodes and extend the service life of the nodes.

1.2 Literature Review

Since the 1970s, wireless communication technology has gone deep into people's lives and work. But in many fields, battery-powered wireless communication networks have not been able to meet the demand for the communication energy. That's why wireless powered communication networks (WPCN) [4-7] emerged. WPCN is a new network technology that makes it possible for wireless communication devices to realize wireless energy transmission (WET) remotely, and the complicated operation of the frequent battery replacement can be avoided. Compared with the traditional battery-powered communication network, it greatly improves the communication system performance in many aspects, such as its greater throughput, longer service life of communication equipment, and lower network operation cost. Therefore, more and more wireless communication scholars have gradually devoted themselves to the research of wireless powered communication networks.

Suzhi Bi, Chin Keong Ho, and Rui Zhang presented a classic RF energy receiver based on a rectifying circuit in [7], and showed the technological basis of the WET design, including RF energy receiving formulas given in [8] and energy beamforming formulas given in [9]. The article [5] studied the effect of transmission distance, direction, voltage, frequency on wireless transmission characteristics through a series of experiments. There are two main study directions in WET, the first is simultaneous wireless information and power transfer, in which wireless devices can do the information interaction and energy transmission synchronously, that means it can provide energy supply while transmitting the information [9-13]. Based on the WET technology, Varshney firstly proposed the idea of transporting the RF signals with the same information and energy synchronously (SWIPT) in [14] - [18], and defined the rate- energy(RE) tradeoff in discrete memoryless channels (DMC), which also defines the maximum achievable data rate under the received energy constraints. In the studies of rate-energy tradeoff, the authors of [35] extended it to frequency selective channels,

while [20] - [23] extended it to multi-access and multi-hop channels and literature [40] extended it to bi-directional channels. In addition, the article [9] designed the first practical receiver architecture which is based on the research of SWIPT. It takes the time-selection (TS) signal separation scheme and the energy separation (PS) signal separation scheme into consideration and allows the receivers can periodically switch between two time slots to harvest energy and operate information decoding. This kind of receiver did improve the performance of communication system. Different from separating signals at radio frequencies in [9], [8] gave another SWIPT practical integrated receiver structure that integrates front-end information decoding and energy reception. This kind of receiver separates the received signals by converting the signal to direct current. Compared with the design in [8], [9] saves the power consumption of the circuit generated by the mixer in the information decoding. SWIPT technology is more focused on the simultaneous transmission of wireless information and energy, and it can improve the spectrum utilization compared to the way that transmitting information energy along with orthogonal time or through the frequency channels. However, in SWIPT, the technical requirements and deployment environment requirements of wireless devices are relatively high. It's not the most suitable technology for reducing the system maintenance costs and solving the energy supply issues. Therefore, the second study direction of WET, which is wireless powered communication networks (WPCN) has become a new study area for the scholars, and it is also mentioned in [18] - [34] that WPCN technology can better satisfy the market's demand for low-power wireless devices.

The wireless powered communication networks are not constrained by the traditional battery life, and it aims to seek a balance between energy supply and energy consumption or data transmission in order to optimize the performance of the communication networks. The wireless powered communication networks refer to that the base station supplies energy to the sensor nodes in the downlink(DL) communication, and then the sensor nodes use the received energy to transmit information to the access points in the UL communication. After the wireless powered communication network structure has been proposed, in order to ensure the entire communication system can run orderly and sustainably, a new generation communication protocol came into being. The most widely used protocol is Harvest Then Transmit Protocol (HTT Protocol). In [41], the author first proposed the concept of the wireless power supply and information transmission, and the content of HTT protocol, which stipulates that in the wireless powered communication networks, the receiving mode in the uplink is Time Division Multiplexing Access (TDMA). It effectively eliminates shared channel interference and proposes a strategy for how to maximize system throughput. In [35], based on the protocol mentioned in [41], the author analyzed the impact of communication link loss probability on the system throughput, and proposed two methods that can maximize the throughput. Through the way of combining the HTT protocol with the TDMA technology, the signal interference among wireless communication devices can be avoided, the quality and confidentiality of the communication can be improved, and the capacity of the system is also increased.

Since the design of the WPCNs system directly affects the energy consumption of the system, the optimization design of the WPCNs system has attracted much attention in recent years. There have been many studies on the WPCNs system design. The difficulty of designing a WPCN is mainly reflected in two aspects in [48] - [49]: (1) Energy and information transmission in the downlink or uplink are essentially asymmetric; (2) Transmission in the downlink or uplink and their energy constraints are coupling with each other. Moreover, in the WPCNs, the sensor nodes usually cannot receive energy and report information at the same time. Therefore, it is necessary to optimize the transmission time allocation of energy and information, and jointly consider the energy harvesting and data reporting in order to achieve the optimal overall performance. Both [36] and [37] proposed a single-antenna WPCN transmission model based on TDMA. Authors in [37] used a single antenna wireless hybrid access point (HAP) and multiple wireless devices to construct a WPCN using HTT protocol. This network uses the energy base station in the hybrid network architecture which as the energy source. Its purpose is to directly maximize the data transmission rate of all nodes through reasonably allocating time for wireless power transmission (WPT) in the downlink and wireless information transmission (WIT) in the uplink under the premise of guaranteeing the maximum transmission power constraint of the central node. Moreover, a full-duplex wireless hybrid access point is applied to the system models in [38] and [39], in order to transmit the power to the target wireless device and receive the information transmitted from other devices. Their research results show that the WPC network architecture using HAP to transmit power has a better performance in the system throughput or user throughput fairness. However, the biggest challenge of designing this hybrid access point structure was to overcome the information interference caused by its own full-duplex operation model. In order to improve the performance of HAP, article [47] proposed a user-cooperative approach that wireless devices which are close to the HAP can help the devices which are farther from the HAP transfer the information, to overcome the doubly near-far problem and did some useful research on improving end-to-end throughput. The motivation of most researchers work on WPCN is to maximize the system throughput or improve the information transmission rate and they didn't pay too much attention to reducing the energy consumption. As the concept of green communication is quite essential in 5G, WPCN researchers are supposed to take the energy utilization efficiency into consideration. Different from [37], the research motivation of [36] is to minimize the energy consumption and information transmission time on the premise of guaranteeing the minimum transmission rate demand of all nodes. [44] has made preliminary research progress in the optimization of energy efficiency and resources allocation in WPCN. In this paper, the main research purpose will focus on maximizing the energy efficiency and it jointly considers the power and time allocation in a multiuser WPCN system model.

Due to the great decline of electromagnetic wave signals in the transmission, the academia has introduced multi-antenna technology into the WPCN research. This improvement is that the central node can adjust its own energy beam signal direction through configuring multiple transmitting antennas. It effectively improves the energy signal receiving efficiency of the sensor nodes [40-41]. The authors in [40] extends the single-antenna HAP in [37] to a multi-antenna HAP, they applied the design of SISO wireless energy transmission system to the MISO system, and jointly allocated the power and time in the downlink and uplink. They redesigned the energy beam in the downlink to ensure that the system model supports Space Division Multiple Access (SDMA), and better solves the near-far problem by maximizing the minimum throughput in the uplink of all wireless devices. It has achieved certain success in reducing communication interference. The energy beamforming algorithm designed for MISO system was discussed in [42]. Article [43] compared the differences between the resource allocation strategies for multiple-input single-output (MISO) WPCN and multiple-input multiple-output (MIMO) WPCN, and studied optimization of power transmission strategies. Both [43] and [45] studied the performance of WPCN based on the massive MIMO and did a lot of research to explore the joint optimization of channel length estimation, energy transmission, and information transmission. [46] studied the design of multi-user low-complexity MIMO systems based on wireless energy transmission. Combining the MISO technology with energy beamforming for HAP with multi transmitting antennas and multi receiving antennas, [48] discussed the effect of using energy beamforming technology to allocate the harvested energy for every user in the downlink on a multiuser FD-WPCN model. The research results in [48]-[53] demonstrate that energy beamforming can improve the energy efficiency, transmission rate, and fairness, and can effectively suppress interference signals through the difference in spatial channel characteristics such as angles of useful signals and interference signal. In conclusion, the articles above indicate that energy beamforming as one of the key technologies for multi-antenna systems and has great potential in the future study of WPCNs.

2. System Model and Problem Formulation:

2.1 System Model

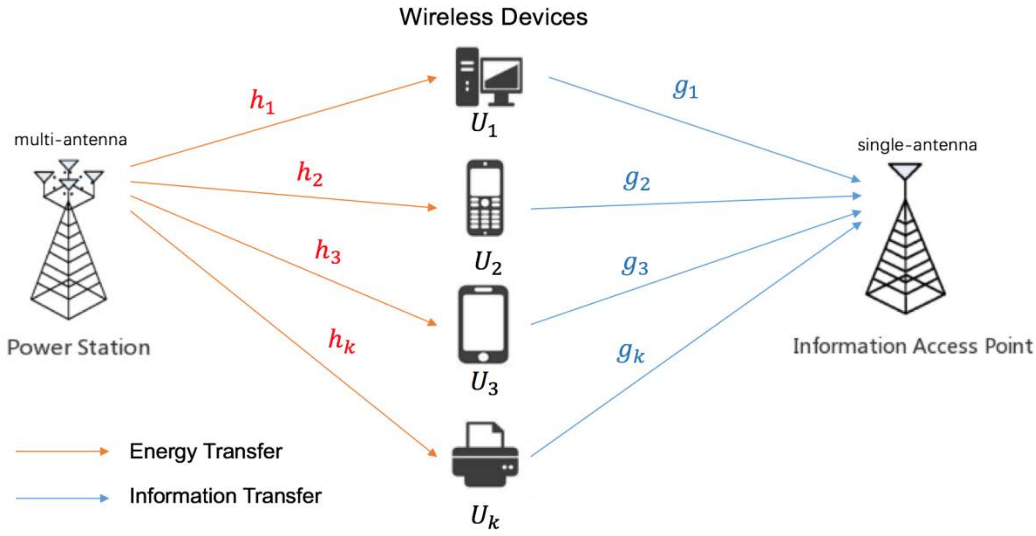
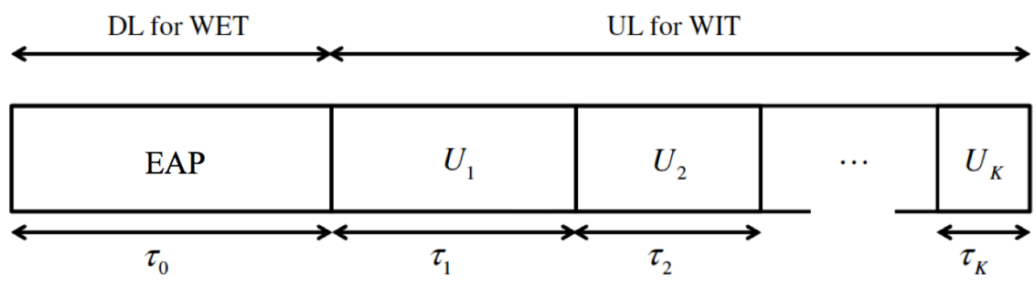


Fig. 1 The system model of a multiuser WPCN

This paper considers a multiuser wireless powered communication network model as shown in Fig.1, which is composed of a power station, multiple wireless devices and an information access point. In this network, the power station in this network is assumed as a multi-antenna power transmitter which is equipped with N transmitting antennas. There are K wireless users which need to be powered from the power station and then transfer their own information to the IAP, denoted by $U_k(k = 1,2,3, \dots, \mathrm{K})$. Each wireless user in this system has a single antenna at its terminal. Different from the system models which adopted hybrid access point mentioned above, in order to simply the analysis of system throughput in the uplink and lower the hardware requirement of the network structure, this network separates the power transmitting antennas and information receiving antennas from one hybrid access point, makes two stations to service as transmitting station and receiving station respectively. It is assumed that the information access point only has one receiving antenna to receive information.

The "Harvest Then Transmit" protocol which is commonly used in WPCNs is also applied to the system. All the wireless devices in the system are set to have no any built-in energy sources, that means each user has no power in its initial state. It is



assumed that there is a rechargeable battery equipped inside the user which is used to store the harvested energy from the base station first and then provide the device with the harvested energy for information transmission. This project mainly studies on the power efficiency and in order to pursue the fair conditions, the assumption for the WPCN is based on that all signals and energy are transferred over the same frequency band. Therefore, for the purpose of avoiding the same frequency interference, the HTT protocol in this model will be based on the time-division multiple-access time allocation as shown in Fig.2, each user will operate information transmission only under its own time slot.

Fig.2 The harvest-then-transmit protocol based on TDMA

The total operating time T is divided into K +1 time blocks, each time block is denoted by τ_i (i = 0,1,2,...,K) as show in Fig.2, so it could have:

$$\sum_{i=0}^{K} \tau_i \leq T, \quad \tau_i \geq 0 \tag{1}$$

The first time slot τ_0 is arranged for wireless energy transmission, the power station broadcasts radio frequency signal with certain energy to all the users, and all the wireless users do the energy harvesting in the downlink during this stage. The rest time blocks represent the time used for wireless information transmission in the uplink, as shown in Fig.2, the i-th time slot τ_i is assigned for the corresponding user U_i (i = 0,1,2,...,K) to transfer the signal information to information access point. The details of transmission in UL and DL will be explained in the next two sections.

2.2 Downlink Wireless Energy Transfer

Since in the downlink of the system model, the power station as the transmitter has multiple antennas and each wireless user as a receiver is equipped with single antenna, the energy transfer can be considered as in a multiuser MISO model shown in Fig.3. In a typical MISO channel, the transmitted signal vector of the power station is $\vec{x}$ which can be written as a N×1 matrix, and the received signal of the k-th single-antenna receiver can be given by:

$$y_k = \overrightarrow{h_k^H}\vec{x} + n_k, \quad k = 1,2,\ldots K \tag{2}$$

where $\overrightarrow{h_k}$ is the channel vector between the power station and k-th single-antenna wireless user, which can be formed as a N×1 matrix and obeys the some kinds of distribution with specific mean and variance. n_k is the Gaussian white noise which is used to simulate the noise in an ideal channel.

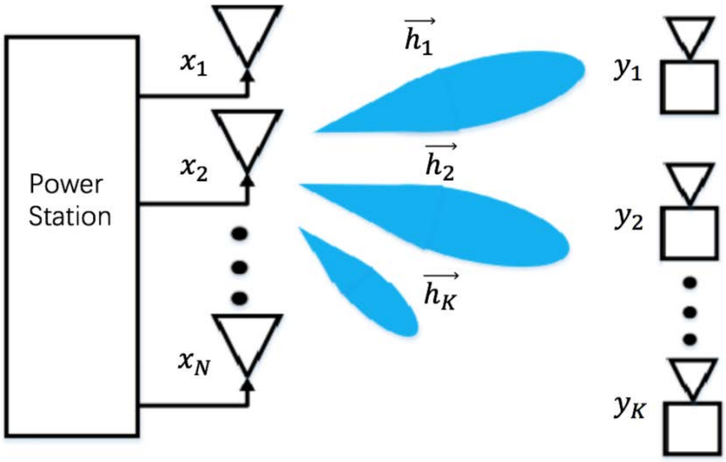
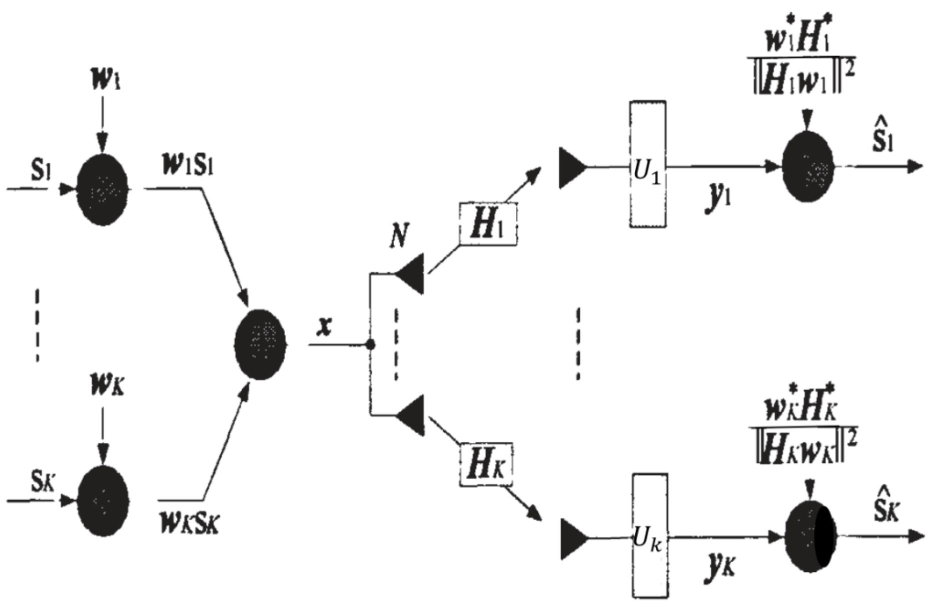


Fig.3 The multiuser MISO model in DL

As mentioned above, all the wireless users and two stations are working with the same frequency in the system, TDMA is employed to reduce the same frequency interference in uplink. However, in the downlink, while the power station transmitting its energy signal to all users, the transmissions between PS and users are all at the same time duration τ_0 and with the same frequency. Under this circumstance, each wireless user must be interfered with by other users. Therefore, it is necessary to use the beamforming of the transmitter to eliminate the interference among these users.

Energy beamforming technology is a digital signal processing technique which is generally applied to antenna array. It makes use of the difference between the useful signal and the interference signal in the spatial channel characteristics such as angle, and then appropriately weights the antenna array. It aims to isolate the expected signal and the interference signal spatially to achieve the enhancement of the desired signal and the suppression of the interference signal, thereby improving the capacity and quality of the communication. Generally, beamforming can be divided into transmit beamforming and receive beamforming according to their location in the system. Both beamforming multiple antennas are often set at the base stations, except that transmit beamforming is used for downlink signal transmission and receive beamforming is mainly used for uplink signal reception. In this paper, only the transmit energy beamforming will be studied in the downlink WET, and the channel response among users in the system is assumed to be irrelevant.

There are three main advantages of using energy beamforming at the transmitter terminal to solve the multiuser interference problem in MISO downlink [48]: 1) First,



beamforming processing at the transmitter can effectively eliminate downlink multiuser interference and increase the system capacity greatly. 2) Second, the receiver's algorithm can be greatly simplified to solve the problem of power consumption and volume of the terminal. 3) Third, since the transmitter accurately knows each user's data, there is no error diffusion problem while using feedback interference cancellation, and the system performance can be improved.

Fig.4 Energy beamforming for a multiuser MISO

The the simulated energy beamforming model at the transmitter is shown as Fig.4, it shows the principle of signal beamforming in the DL. In Fig.4, the data stream for k-th wireless user is denoted by $S_k,\ k = 1,2,\dots,K$. Transmit beamforming is the transmission of a transmitter with a set of weight vectors working on the transmit antennas to realize phase shift. So each transmitted symbol will be processed by a weight-update processor. The total transmitted signal vector $\vec{x}$ from the antennas of the power station in this structure is updated to the expression:

$$\vec{x} = \sum_{k=1}^{K} \overrightarrow{w_k}\, S_k \tag{3}$$

where $\overrightarrow{w_k}$ is the N×1 dimensional beamforming vector for the k-th user. If the precondition is that there is no channel loss, the sequence of S_k can be independent and follows the arbitrary distribution, and the symbol stream S_k can be normalized as:

$$\mathrm{E}(|S_k|^2) = 1, \quad k = 1,2,\dots K \tag{4}$$

The beamformed receiving signal y_k of the k-th single-antenna receiver can be given by the new expression based on (2):

$$y_k = \overrightarrow{h_k^H}\left(\sum_{k=1}^{K} \overrightarrow{w_k}\, S_k\right) + n_k \tag{5}$$

and the total transmission power can be expressed by the beamforming vector:

$$P = \left|\left|\overrightarrow{W}\right|\right|^2 = \sum_{k=1}^{K} ||\,\overrightarrow{w_k}\,||^2 \tag{6}$$

where $\overrightarrow{W}$ is the overall beamforming vectors for the MISO system.

In this paper, the transmitted power of power station is assumed as P_0 in the system model. It can be seen that P_0 is equal to P in (6), also equal to $\left||\overrightarrow{W}|\right|^2$. If this system doesn't take the circuit energy consumption into consideration temporarily, the total energy that the power station need to provide in the downlink is given by:

$$E_T = \left||\overrightarrow{W}|\right|^2 \tau_0 \tag{7}$$

While the wireless users are harvesting energy in the DL, the energy from the channel noise is considered to be ignored because it's too smaller than the energy harvested from the received signal. Due to the transmission loss, the total power from received signal cannot be harvested completely. There will be energy-harvesting efficiency η_k for each wireless user. Thus, the amount of energy harvested by user U_k can be given by,

$$E_k = \eta_k \tau_0 P_0 \ \overrightarrow{h_k}, \quad k = 1,2, \dots, K \tag{8}$$

where $\eta_k \in (0,1]$, it also can be written in the form of energy beamforming by combining formulations (6) and (8):

$$E_k = \eta_k \left||\overrightarrow{W}|\right|^2 \tau_0 \ \overrightarrow{h_k}, \quad k = 1,2, \dots, K \tag{9}$$

also is:
$$E_k = \eta_k \left|\overrightarrow{h_k^H}\overrightarrow{W}\right|^2 \tau_0, \quad k = 1,2, \dots, K \tag{10}$$

2.3 Uplink Wireless Information Transfer

In the wireless information transmission stage, wireless user U_k uses the harvested energy stored in the rechargeable battery to transfer its information signal to the information access point during the k-th time block τ_k in Fig.2. It's further assumed that U_k transmits signal with its transmit power is denoted by $P_k,\ k = 1,2,\dots,K$. Because each user only has one antenna and the information access point is also set one antenna, also because the system is operating in a TDMA mode, the WIT in the uplink can be considered independent for each user. The uplink channel power gain between the user U_k and the IAP is denoted by g_k as shown in Fig.1. g_k will be the overall power gain in the channel which will take the effect of the path loss, shadowing, and multipath fading into consideration. While analyzing the information transmission in the uplink of this system model, according to Shannon theorem which shows the maximum information transmission rate over a channel interfered by Gaussian white noise is:

$$\mathrm{C} = \mathrm{B}log_2\left(1 + \frac{S}{N}\right) \tag{11}$$

where $\frac{S}{N}$ is the signal-to-noise ratio at the receiver; B is the bandwidth of the channel,

the amount of the transmitted information data in bps/Hz, also is the achievable transmission rate of U_k can be achieved as:

$$R_k = \tau_k log_2\left(1 + \frac{P_k g_k}{\sigma^2}\right), \qquad k = 1,2,\dots,K \tag{12}$$

where σ^2 is the noise variance, the noise also follows Gaussian white noise in the system. Based on this formulation, it can be seen that SNR of the U_k's channel in the uplink link is $\frac{P_k g_k}{\sigma^2}$ and $P_k g_k$ is used to express the transmission power gain.

3. Problem formulations:

In the real world, there are mainly two approaches that can improve the energy efficiency and realize the concept of green communication, one is gathering renewable energy from the nature as much as possible, such as solar energy, wind energy and hydro energy. Another one is minimizing the total transmission energy for a communication system. The problem motivation of this thesis project is to minimize the total transmission energy of the power station and maximize the energy efficiency while guaranteeing the QoS and energy harvesting requirements of all wireless users in the WPCN. The energy harvesting constraint requires that the harvested energy of each user during the power transmission time must be larger than the energy for each user to finish the information transmission during its own WIT time slot to ensure each user can operate normally. The QoS constraint represents that the achievable transmission rate of each user is higher than the minimum transmission rate of the system in order to make sure the system can have the minimum required throughput. Since beamforming design is a very essential part in this project, in order to minimize the total transmitted energy, the optimization problem can be formulated as follows:

$$\text{minimize}_{|\vec{W}|, P_k, \tau_k} \quad \left|\left|\vec{W}\right|\right|^2 \tau_0$$

(13)

$$\text{s.t.} \quad \text{C1: } \eta_k \left|\overrightarrow{h_k^H}\vec{W}\right|^2 \tau_0 \ \geq \ P_k \tau_k, \quad \forall k \in \mathrm{K}$$

C2: $\tau_k log_2\left(1+\frac{P_k g_k}{\sigma^2}\right) \geq R_{min}, \quad \forall k \in \mathrm{K}$

C3: $\sum_{i=0}^{K}\tau_i \leq T, \quad \tau_i \geq 0$

C4: $P_k \geq 0, \quad \forall k \in \mathrm{K}$

4. Solution for Optimization Problem:

4.1 Mathematic Theory of Convex Optimization

The propose of this section is to get the optimal solution to the system problem. It is obviously that the objective function above is an optimization problem with constraints. That means the first thing to deal with this problem is to determine it is a convex optimization problem or non-convex optimization problem. In mathematics, the general expression of the optimization problem is to find $x^* \in \chi$, which can make:

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

where x is n-dimension vector, χ is the feasible region of x and f is a real-valued function. Convex function is defined in [54]: a real-valued function $f\colon \mathbb{R}^n \to \mathbb{R}$ is convex if its domain is a convex set, and if , for all $x, y \in D(f)$ and $\theta \in \mathbb{R}$, $0 \leq \theta \leq 1$, there is $f(\theta x + (1-\theta)y) \leq \theta f(x) + (1-\theta)f(y)$. If χ in (14) is a closed convex set and the function f is a convex function on set χ, the optimization problem (14) can be considered as a convex optimization problem.

Therefore, determining whether an optimization problem is a convex optimization problem, generally depends on the following points: 1) If the objective function f is not a convex function, it is not a convex optimization problem; 2) If the decision variable x contains discrete variables (0-1 variables or integer variables), it is not a convex optimization problem; 3) If the constraint is $g(x) \leq 0$ and $g(x)$ is not a convex function, it is not a convex optimization problem. Based on the mathematic theory above, the optimization problem for this project system model (13) is a non-convex optimization problem because the objective function $\left|\left|\overrightarrow{W}\right|\right|^2 \tau_0$ is non-convex and the constraints C1 and C2 are also non-convex functions.

The most significant difference between the convex optimization problem and the non-convex optimization problem is that only the local optimal solution to the convex optimization problem equals to its global optimal solution as shown in Fig.5[55]. This feature makes the convex optimization problem easier to solve, so the best method to solve the non-convex optimization problem in this project is converting non-convex optimization problems into convex optimization problems.

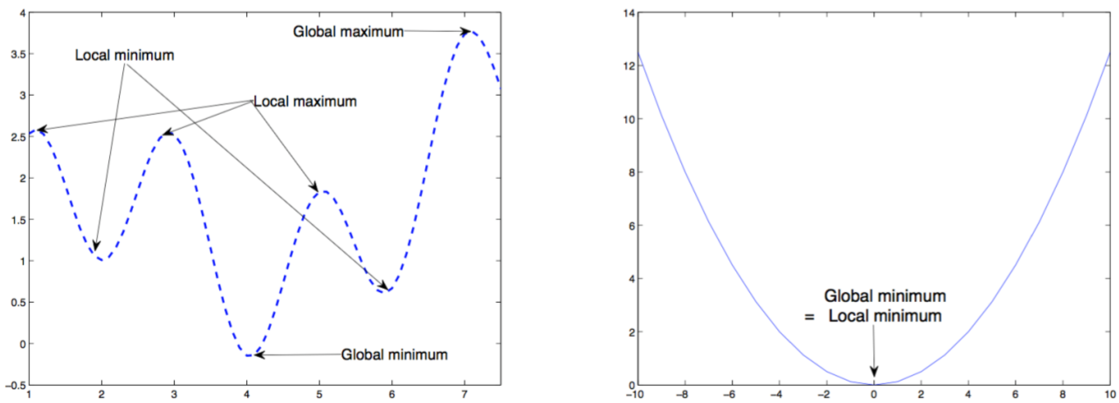


Fig.5 Local Optimal versus Global Optimal

4.2 Transformation of Optimization Function

In general, there are two main methods for transforming non-convex optimization problems into convex optimization problems in [54] - [56]:

1) Modify the objective function and convert it into a convex function;

2) Discard some constraints so that the new feasible domain is a convex set and contains the original feasible domain.

When analyzing the primal problem formulations, it can be found that the beamforming vector $\overrightarrow{\mathrm{W}}$ is the main factor which causes the non-convexity of the optimization problem. For a non-convex problem, it is impossible to use the traversal search method to search the optimal solution because the feasible domain is continuous. Therefore, the semi-definite programming relaxation can be applied to this optimization problem. SDP relaxation is an efficient method to eliminate the non-convexity of the problem. Firstly, $\left|\left|\overrightarrow{W}\right|\right|^2$ in the project objective formulation (13) can be written in the form of a trace of $\overrightarrow{W^H}\overrightarrow{W}$, because in mathematics：

$$\left|\left|\overrightarrow{W}\right|\right|^2 = \overrightarrow{W^H}\overrightarrow{W} = \mathrm{Tr}\left(\overrightarrow{W^H}\overrightarrow{W}\right) = \mathrm{Tr}\left(\overrightarrow{W}\overrightarrow{W^H}\right) \tag{15}$$

Then, the objective function can be transferred into a new optimization problem:

$$\underset{|\overrightarrow{W}|}{\text{minimize}} \quad \left|\left|\overrightarrow{W}\right|\right|^2 \tau_0$$

$$\Leftrightarrow \underset{|\overrightarrow{W}|}{\text{minimize}} \quad \mathrm{Tr}\left(\overrightarrow{W}\overrightarrow{W^H}\right)\tau_0$$

$$\Leftrightarrow \underset{\boldsymbol{W},|\overrightarrow{W}|}{\text{minimize}} \quad \mathrm{Tr}(\boldsymbol{W})\tau_0 \tag{16}$$

$$\text{s.t. } \mathrm{W} = \overrightarrow{\mathrm{W}}\overrightarrow{\mathrm{W}^{\mathrm{H}}},\ \mathrm{Rank}(\mathrm{W}) = 1$$

where $\boldsymbol{W} \succcurlyeq 0,\ \boldsymbol{W} \in \mathbb{H}^{N_T}$ are imposed to guarantee $\boldsymbol{W} = \overrightarrow{W}\overrightarrow{W^H}$. The rank constraint relaxation $Rank(\boldsymbol{W}) = 1$ is a necessary and sufficient constraint condition of (16). In addition, for C1 and C2 in (13), we define $\widetilde{P_k} = P_k \tau_k$ to facilitate the transformation of optimization function. After replacing C1, C2 by $\overline{\mathrm{C1}}$, $\overline{\mathrm{C2}}$, the transformed project problem is represented as:

$$\text{minimize}_{\mathbf{W},P_k,\tau_k} \quad \mathrm{Tr}(\boldsymbol{W})\tau_0$$

(17)

$$\text{s.t.} \quad \overline{\mathrm{C1}}:\ \eta_k \mathrm{Tr}(\overrightarrow{h_k^H}\overrightarrow{h_k}\,\boldsymbol{W})\tau_0 \ \geq\ \widetilde{P_k}, \quad \forall k \in \mathrm{K}$$

$$\overline{\mathrm{C2}}:\ \tau_k log_2\left(1 + \frac{\widetilde{P_k} g_k}{\tau_k \sigma^2}\right) \ \geq\ R_{min}, \quad \forall k \in \mathrm{K}$$

C3-C4

$$\text{C5:}\ \ \mathrm{Rank}(\boldsymbol{W}) \leq 1$$

After doing this SDP reformulation, the problem (17) still cannot be considered as a convex optimization problem due to the constraint C5 is a combinatorial rank constraint. In order to realize the optimum resource allocation algorithm more efficiently and minimize the energy consumption, SDP relaxation is adopted to relax C5. This approach removes C5 from the transformed project problem and can make the problem be a convex SDP problem:

$$\text{minimize}_{\mathbf{W},P_k,\tau_k} \quad \mathrm{Tr}(\boldsymbol{W})\tau_0$$

(18)

$$\text{s.t.} \quad \overline{\mathrm{C1}},\ \overline{\mathrm{C2}},\ \mathrm{C3},\ \mathrm{C4},$$

C5: ~~Rank($\boldsymbol{W}$) ≤ 1~~

Note that the relaxed formulation is now convex and can be solved efficiently via standard convex program solvers, such as CVX in [62] – [63]. If the rank of the optimal beamforming vector obtained from the solver equals to one, this solution $\boldsymbol{W}$ can be used to achieve the optimal energy efficiency in this project.

4.3 KKT Conditions and SDP Relaxation Proof

In this part, the tightness of the SDP relaxation in (18) is revealed to prove that applying SDP relaxation to the primal problem will not affect the convexity of the optimization problem. It can be verified that a minimization problem and a maximization problem are a pair of dual problems. In [57] - [61], the Lagrange Multiplier and KKT conditions can use the duality of the primal problem to convert a minimization problem into a maximization problem, so they are two very important methods for solving constrained optimization problems. When solving an optimization problem with inequality constraints such as:

$$\underset{\boldsymbol{x}}{\text{minimize}} \quad f(x) \tag{19}$$

$$\text{s.t.} \;\; g_i(x) \leq 0, i = 1, \dots, I$$

$$h_j(x) = 0, j = 1, \dots, J$$

the Lagrange function of (19) is:

$$\mathrm{L} = f(x) + \sum_{i=1}^{I} \lambda_i g_i(x) + \sum_{j=1}^{J} \beta_j h_j(x) \tag{20}$$

The dual function of (19) will be represented as $\inf_{x \in D} L(x, \lambda, \beta)$ and the dual problem of (19) is:

$$\max_{\lambda_i,\beta_j\geq 0} \ \inf_{x\in D} L(x,\lambda,\beta) \tag{21}$$

Then KKT conditions mean that the optimal value must satisfy the most important stability condition:

$$\frac{\partial \mathrm{L}}{\partial \mathrm{x}} = 0 \tag{22}$$

and the constraint condition of the dual problem: $\lambda_k \geq 0$. Meanwhile, KKT conditions also include that $g_i(x)$ and $h_j(x)$ must satisfy the original conditions, and the complementary slackness: $\lambda_i g_i(x) = 0$.

Now, the key to solve this project optimization problem is proving that if the transformation in (18) is feasible and channels of WET and WIT are independent, the rank of the optimal beamforming vector matrix is less than or equal to 1. The first step of the proof is adjusting some forms of the constraints in (18) to cater to the form of Lagrange function, problem formulations in (18) can be rewritten as:

$$\text{minimize}_{\mathbf{W},P_k,\tau_k} \quad \mathrm{Tr}(\boldsymbol{W})\tau_0$$

(23)

$$\text{s.t.} \quad \overline{\mathrm{C1}}\text{: } \widetilde{P_k} - \eta_k \mathrm{Tr}(\overrightarrow{h_k^H}\overrightarrow{h_k}\boldsymbol{W})\tau_0 \leq 0, \quad \forall k \in \mathrm{K}$$

$$\overline{\mathrm{C2}}\text{: } R_{min} - \tau_k log_2\left(1+\frac{\widetilde{P_k}g_k}{\tau_k\sigma^2}\right) \leq 0, \quad \forall k \in \mathrm{K}$$

C3-C4

$$\overline{\mathrm{C5}}\text{: } -\boldsymbol{W}_k \leq 0, \quad \forall k \in \mathrm{K}$$

where $\overline{\mathrm{C5}}$ represents positive semidefinite in SDP relaxation. The second step is getting the Lagrange equation by applying $\overline{\mathrm{C1}}, \overline{\mathrm{C2}}, \overline{\mathrm{C5}}$ to function (20):

$$\mathrm{L} = \mathrm{Tr}(\boldsymbol{W})\tau_0 + \sum_{k=1}^{K} \lambda_k \left(\widetilde{P_k} - \eta_k \mathrm{Tr}\left(\overrightarrow{h_k^H}\overrightarrow{h_k}\,\boldsymbol{W}\right)\tau_0\right)$$
$$+ \beta\left(R_{min} - \tau_k log_2\left(1 + \frac{\widetilde{P_k} g_k}{\tau_k \sigma^2}\right)\right)$$
$$- \sum\nolimits_k Tr(\boldsymbol{Y}_k \boldsymbol{W}_k)\,, \forall k \tag{24}$$

Due to the duality of the problem, the minimization problem in (23) can be solved by dealing with its dual problem, which is a maximization problem in (21). The third step is that the KKT conditions require the Lagrange equation (24) to take its partial respect to the beamforming vector $\boldsymbol{W}$ and get:

$$\frac{\partial \mathrm{L}}{\partial \boldsymbol{W}} = I\tau_0 - \lambda_k \eta_k \boldsymbol{H} + \beta I - \boldsymbol{Y}_k = 0 \tag{25}$$

$$\boldsymbol{Y}_k = I\tau_0 + \beta I - \lambda_k \eta_k \boldsymbol{H} \tag{26}$$

where $\boldsymbol{H} = \overrightarrow{h_k^H}\overrightarrow{h_k}$ and I is identity matrix. Define $\boldsymbol{B} = I\tau_0 + \beta I$ and $\alpha = \lambda_k \eta_k$, then all the KKT conditions can be summarized as:

$$\boldsymbol{Y}_k \succcurlyeq 0, \lambda_k, \eta_k, \beta \geq 0 \tag{27}$$

$$\boldsymbol{Y}_k \boldsymbol{W}_k = 0 \tag{28}$$

$$\boldsymbol{Y}_k = \boldsymbol{B} - \alpha \boldsymbol{H} \tag{29}$$

The condition (28) is the complementary slackness condition, which will be satisfied when the columns of beamforming vector $\boldsymbol{W}$ falls into the null space of $\boldsymbol{Y}_k$ and $\boldsymbol{W}$ is not zero. It can be proved that if the rank of $\boldsymbol{Y}_k$, i.e. $\mathrm{Rank}(\boldsymbol{Y}_k) = N_t - 1$, the rank of optimal beamforming vector $\boldsymbol{W}$ must be one. Therefore, in order to prove $\mathrm{Rank}(\boldsymbol{Y}_k) = N_t - 1$, firstly it has to be proved that $\boldsymbol{B}$ is a positive definite matrix with full rank by contradiction. Suppose that $\boldsymbol{B}$ is a positive semidefinite matrix, the rank of $\boldsymbol{B}$ is less than N_t, there is at least one zero eigenvalue with the associated eigenvector, which is denoted as u. Define $\boldsymbol{U} = uu^H$ by the eigenvector and multiply $\boldsymbol{U}$ to both sides of the KKT condition equation (29), we can get:

$$\mathrm{Tr}(\boldsymbol{Y}_k\boldsymbol{U}) = \mathrm{Tr}(\boldsymbol{B}\boldsymbol{U}) - \alpha\mathrm{Tr}(\boldsymbol{H}\boldsymbol{U}) = -\alpha\mathrm{Tr}(\boldsymbol{H}\boldsymbol{U}) \tag{30}$$

The channel matrix of WET and WIT are statistically independent, so that $\mathrm{Tr}(\boldsymbol{H}\boldsymbol{U}) > 0$ must be true. However, in (30), $\alpha = \lambda_k\eta_k > 0$ will lead that $\mathrm{Tr}(\boldsymbol{Y}_k\boldsymbol{U}) = -\alpha\mathrm{Tr}(\boldsymbol{H}\boldsymbol{U}) < 0$, and it is contrary to the original assumption in this project. By now, $\boldsymbol{B}$ is a positive definite matrix is proved and $\mathrm{Rank}(\boldsymbol{B}) = N_t$ is satisfied. It is known in mathematics that there is:

$$\mathrm{Rank}(\mathbf{A} + \mathbf{B}) \leq \mathrm{Rank}(\boldsymbol{A}) + \mathrm{Rank}(\boldsymbol{B}) \tag{31}$$

Applying (29) to (31), the final result can be obtained:

$$\mathrm{Rank}(\boldsymbol{Y}_k + \alpha\boldsymbol{H}) = \mathrm{Rank}(\boldsymbol{B}) \leq \mathrm{Rank}(\boldsymbol{Y}_k) + \mathrm{Rank}(\alpha\boldsymbol{H})$$

$$\Leftrightarrow \mathrm{Rank}(\boldsymbol{Y}_k) \geq \mathrm{Rank}(\boldsymbol{B}) - \mathrm{Rank}(\alpha\boldsymbol{H})$$

$$\Leftrightarrow \mathrm{Rank}(\boldsymbol{Y}_k) \geq N_t - 1 \tag{32}$$

where $\mathrm{Rank}(\alpha\boldsymbol{H}) = 1$. Finally, $\mathrm{Rank}(\boldsymbol{W}) \leq 1$ can be verified as $\mathrm{Rank}(\boldsymbol{Y}_k) \geq N_t - 1$ is manifested.

5. Simulation Results:

In this section, the simulation results of the proposed system performance will be discussed in order to observe the maximize energy efficiency of the power station under this optimal resource allocation. The simulation is processed in Matlab and simulation parameters are shown in Table 1. Since the channels in the downlink is

Table 1: System Simulation Parameters

Carrier center frequency	915 MHz
Small-scale fading distribution	Rician fading with Rician factor 3 dB
Total noise variance, σ_s^2	-23 dBm
Transmit power budget, P_{max}	46 dBm
Number of receive antennas at each ER, N_R	1
Receive antenna gain	6 dB
Max. tolerable channel capacity at ERs, R_{ER}	1 bit/s/Hz
RF energy to electrical energy conversion efficiency for ER k , η_k	0.5

designed to be MISO channels, each energy receive users is equipped with single antenna. The MISO channels between power station and wireless users follow the Rician fading distribution with Rician factor 3 dB, and the channels between users and information access point in the uplink follow the Rayleigh distribution. In the simulation, taking the real situation into consideration, the transmitted power should have a budget and is restricted by P_{max}.

The first simulation result Fig. 6 shows the trade-off between the average minimum transmitted power of the power station and the minimal required channel capacity for the multiuser WPCN system under the optimal resource allocation. It can be observed that when the number of transmitting antennas N equipped at the power station is fixed, if the requirement of the minimum system throughput becomes more stringent, the power station will need to transmit more power to satisfy the minimum data rate requirement. On the other hand, by comparing different number of the transmitting antennas, it can be seen that when the system channel capacity requirement is given, the average minimum transmitted power will increase with the decrease of N_T. In Fig. 6, the system performance when $N_T = 12$ is much better than the performance when $N_T = 4$. That means in order to save more transmitting power, the power station of this system should install more antennas to get larger system throughput.

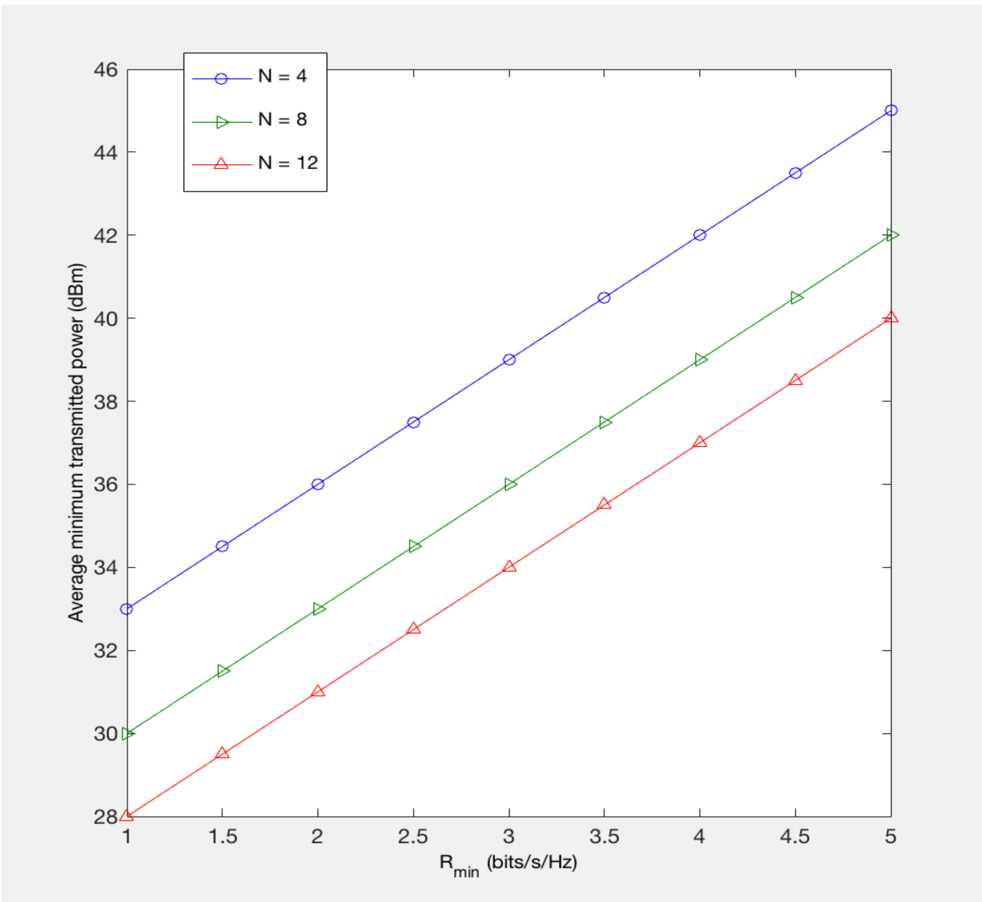


Fig. 6 Average minimum transmitted power(dBm) versus R_{min}(bits/s/Hz)

Figure 7 indicates another kind of trade-off simulation result under the proposed optimal beamforming vector scheme, it shows the relationship between the average minimum transmitted power and different distances between different wireless users and information access points. In this case, three kinds of the number of antennas $(N_T = 4, 8, 12)$ are also simulated as in the first case. The result shows that if the distance between the wireless users and the information access point is longer, the correspond energy consumption will be more due to the path loss. It also can be found that equipping more antennas at the power station can provide more spatial degrees of freedom and improve the energy efficiency. However, the cost of building the WPCN system will be more if it wants better energy-saving performance in practice. In summary, the minimum requires data rate, the number of transmitted antennas and the distance between users and information access points should be all taken into consideration in this system model.

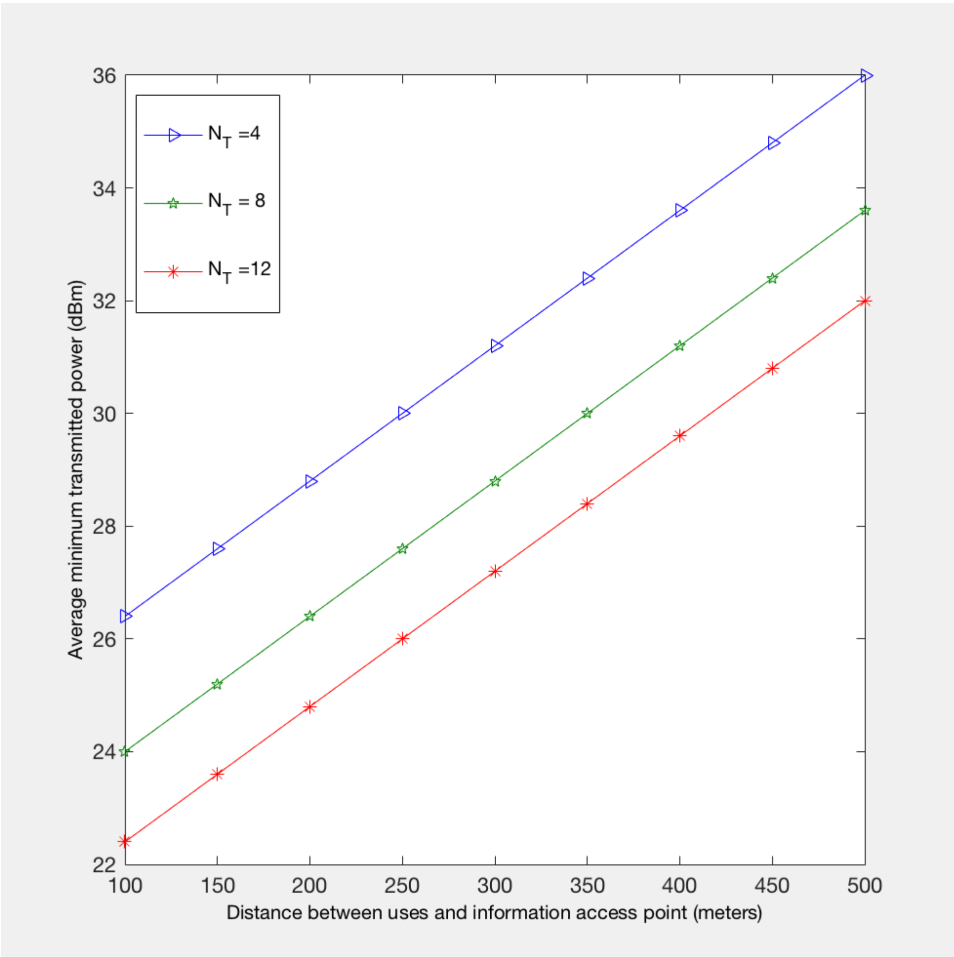


Fig. 7 Average minimum transmitted power(dBm) versus distance between users and information access points (meters)

6. Conclusion:

In this paper, we proposed a multiuser WPCN system which is based on energy beamforming technology and designed an optimal resources allocation to maximize energy efficiency. Firstly, the background of the emergence of wireless powered communication networks and the concept of green communications in the next generation are introduced at first. It illustrates the importance of developing WPCN in 5G. Then we discussed the related WPCN researches based on multiple technologies and investigated the merit and demerit of different WPCN models. It concludes that energy beamforming technology has great potential in the development of WPCN. We designed an optimal algorithm for this multiuser WPCN system to optimize the EE, which can be formulated as a non-convex optimization problem. SDP relaxation was used to convert the formulations and get the optimal solution. The simulation results show the system performance of our system and this presented optimal resource allocation scheme.

Researches for WPCN based on energy beamforming still need more works. In the future, the information security in the transmission and the application of WPCN in microwave wireless communication system are two research directions with great prospects.

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