SCHOOL OF ELECTRICAL ENGINEERING
AND TELECOMMUNICATIONS

Power Splitting in Simultaneous Wireless Information and Power Transfer

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Abstract

With the increasing maturity of the Fifth-Generation mobile communication technology, the emergence of new services and the improvement of user demand not only require the system to carry more traffic but also bring colossal energy consumption. Nevertheless, the explosive development of the Internet fabricates it more undemanding to obtain all kinds of information, especially social information. Therefore, the cooperation of information and energy will be the trend of future development. In wireless communication systems, radio waves carry both energy and information. Simultaneous Wireless Information and Power Transfer (SWIPT) Systems would permit wireless energy and information transmitting together, which is of great significance for wireless sensor networks. In today's wireless networks, sensors or nodes are equipped with batteries, which can sometimes be challenging to replace, limiting the lifetime of the network. The energy collected from the surrounding radio signals can balance the energy distribution of the network and significantly extend the service life.

This project invents a multi-input-single-output (MISO) scheme, in which the SWIPT will be provided for each user on the basis of a power splitting receiver framework. Assuming that the channel state information (CSI) of the base station would be imperfect, we use SDP relaxation and KKT conditions in this system to maximise the minimum power received by the energy harvesting receiver under the constraints of the signal-to-noise-ratio (SINR) and transmission power of each user. Also, the

convex optimisation method will be adopted to analyse the system problem, and the simulation will be accomplished in MATLAB in the next term.

TABLE OF CONTEXT

Introduction

1. The Fifth Generation communication (5G)

The Fifth Generation communication (5G) is the research and development focus of the communication industry in recent years and will become the backbone of the communication industry [1]-[3]. In 2012, lots of major countries and regions in the world started research on 5G mobile communication demand and technology in succession [4]. At the same time, the international telecommunication union (ITU) launched a series of 5G work, such as 5G vision, demand, evaluation methods, and formally released the 5G vision in June 2015, which defined the development trend of mobile communication market, users and business applications oriented to 2020 and the future, and proposed the framework and critical capabilities of future mobile communication system[5].

5G will revolutionise applications in other markets, including industry, automobiles, healthcare and even defence. Due to the Internet of Things (IoT) to contact the increasingly close world, 5G has significant improvements in the speed which is at least ten times faster than 4G, up to 10 GBPS, and the delay which is ten times less than 4G, as low as 1 ms, and the density that is 1 million per square kilometre IoT devices. Thus, 5G will apply it possible for a mass of innovative applications, especially in security, reliability, service quality, efficiency and cost, as well as other essential areas [6]-[9].

As shown in figure 1, 5G will realise the interconnection of goods and services, while "goods" reside in user or enterprise space, while "services" usually reside in the cloud. 5G networks will be able to shred parallel connections flexibly, adjust the level of service required by users, and provide excellent cost and performance balancing solutions [10]-[11].

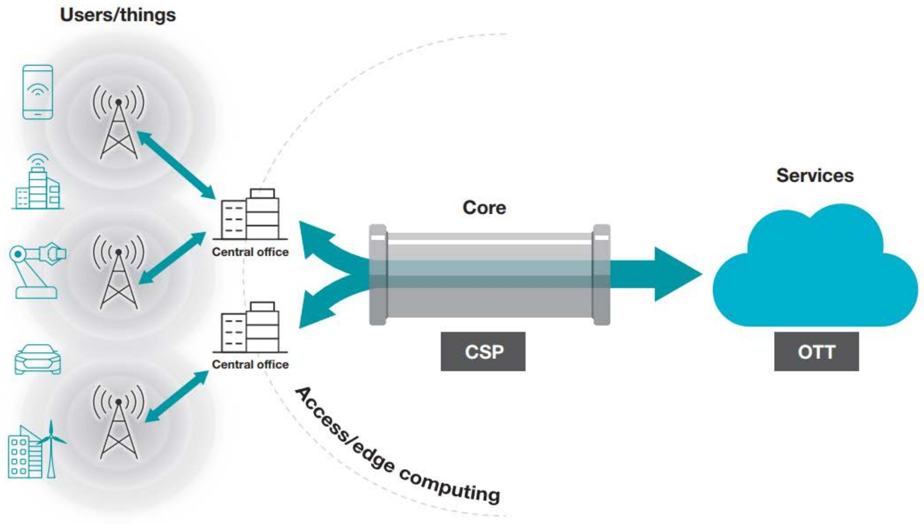

Figure 1 the structure of 5G communication [12]

2. Energy harvest technology

With the extensive application of information technology in social production and life, the business volume of mobile communication network shows explosive growth. The continuous expansion of network scale, diversification of base station and other communication equipment, as well as randomization of communication equipment site selection, have brought the sharp increase of the total network energy consumption and the multiple of the difficulty of base station energy supply [13]-[15]. The construction of a sustainable and deployable communication network has become a crucial issue. Owing to the flexible deployment and uninterrupted green pollution-free energy providing, energy harvesting (EH) technology has become a particularly potential technology to resolve the difficulty of energy depletion in the future communication structure.

Researches [16]-[18] into energy harvest technologies initially focused on solar, wind and other renewable energy-powered devices. However, this technology does not only include renewable energy. The energy obtained by communication nodes from the surrounding environment does not necessarily refer to the clean energy such as solar energy and wind energy, but may also refer to the energy sent separately by other devices, similar to wireless charging technology.

Using energy access technology in the wireless communication system, attributable to the changes of energy source, the obstacles and constraint conditions of traditional stable grid energy or limited battery power supply are no more applicable, so the algorithm of wireless communication, network protocol and even the hardware of transmission node are redesigned based on the needed energy for technical characteristics. In the wireless communication system actuated by energy harvest technology, the predicament to be dealt with firstly is the randomness of energy acquisition [19]. As a consequence of the unpredictable energy source, the energy collection technology will stack the arbitrary of accessible energy of the system in the light of the original unplanned of wireless communication channel also data arrival, thus greatly increasing the intricacy of the conundrum. The next is the causality, that is, the energy acquired can only be operated at the following time, and the energy consumed by the system cannot exceed the total energy currently acquired and stored. Finally, it is about the effectiveness of energy. Because the capacity of the energy storage device is limited, energy cannot be stored without limit, resulting in limited energy that can be used, and the part beyond the capacity can only be discarded. Meanwhile, different from the traditional power furnish network, the traditional power supply network is not constrained by energy, and its optimization goal is to ameliorate the network service performance, likely improving the throughput of the system and reducing the user’s blocking rate. However, in the wireless system based on energy harvest technology, due to the limitation of this technology, the optimization of service quality in the network must be considered on the basis of the optimization of energy use. If it is only to improve the throughput of the system and lessen the blocking rate of it, once the transmission is interrupted because of energy exhaustion, the information cannot be transmitted, which will urgently affect the quality of service. Therefore, the application of energy acquisition technology in wireless communication system must be thoroughly studied [20]-[23].

However, considering about the energy harvest at receivers, the energy on the sending end is supplied by the power grid or other stable energy sources, while the energy used by the communication on the receiving end is obtained from the electromagnetic wave sent by the sending end and then used for the transmission of information. Similar to wireless charging technology, it is generally called SWIPT.

3. SWIPT technology

With the development of scientific strategies, human has been trying to find a new source of energy instead of relying on natural resources like wind and solar energy. In the practical application system, for some small devices, such as sensor nodes, smartphones, artificial intelligence heart and so on, it is challenging to design energy collection circuit to use solar and wind energy to charge it, in order to maintain long-term stable work. To overcome the practical problem talked above, people began to explore a new energy source, which is called Radio Frequency signal. In the conventional sense of wireless communication systems, the role of radio frequency signals is to transmit information, but now it seems that can carry not only information but also energy. Therefore, radio frequency signals can be collected as energy by the receiver as a source of energy for the receiver to extend the life of the communication network. In this way, the receiver can not only demodulate information but also collect energy through the design of the receiver circuit. In light of this, the wireless communication system can transmit both information and electricity by the radio frequency signal. The communication system with this dual function is called SWIPT system [24]-[26].

The idea of SWIPT was brought forward by L. R. Varshney in 2008 primarily [27]. He observed that the SWIPT strategy not only responds to the green call but also extends the service life of energy-guarded wireless networks. The core idea of this concept is to equip the nodes in the communication system with an energy receiver. The receiver can divide the received signals into two parts, namely energy collection and signal demodulation, so as to obtain the energy of sustainable operation from the signals, so as to realize the deployment of communication nodes under the situation that the energy cannot be directly supplied.

In addition, the Beamforming strategy plays a positive role in optimizing the trade-off between information transfer rate and energy transfer rate in the SWIPT system, that can enhance the signal intensity of the antenna array direction output and reduce the interference signal intensity [28], consequently improving the accessible information proportion of the communication network. Beamforming strategy research in SWIPT system is divided into the following four aspects, respectively under different channel strategy research, different beamforming Receiver strategy research, different beamforming optimization goal of beamforming strategy research and Information Receiver (IR) and Energy Receiver (ER) without a total end joint beamforming strategy research [29]-[30].

The feasibility of the SWIPT study is based on the fact that the radio waves that transmit information are a source of energy and can be captured in the same way that electromagnetic energy can be. In a cellular system, for example, electromagnetic waves, which are useful signals for one user and noise for another, can be captured to save energy. In this direction, the receiver can receive information, energy, or both. Limited by the actual circuit, the receiver cannot demodulate and collect energy at the same time. Therefore, there are two receiver modes in SWIPT: time - domain switching and power splitting (PS) [31], which are shown in the figure 3, 4 below. The working mode of time domain switching is that the signal received by the receiver is either collected by the energy acquisition unit or received by the information receiving unit to solve the information. The working mode of energy segmentation is that the received signal is divided into two ways by an energy divider, one way is transmitted to the energy acquisition unit, and the other way is transmitted to the information processing unit. In this research point, the design of receiving mode working mode (such as the mode switching strategy of two parts in TS and the energy splitting strategy of two units in PS) is the research focus [32]-[34].

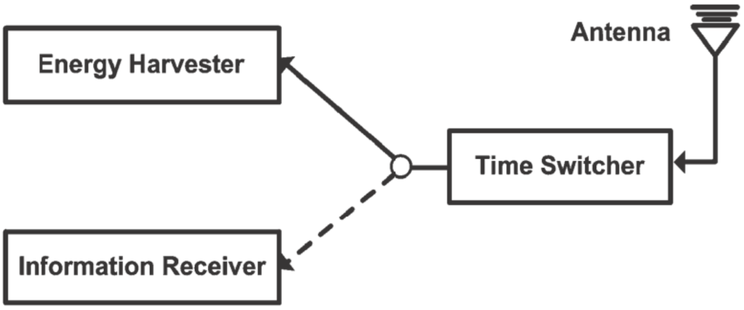

Figure 2 time - domain switching

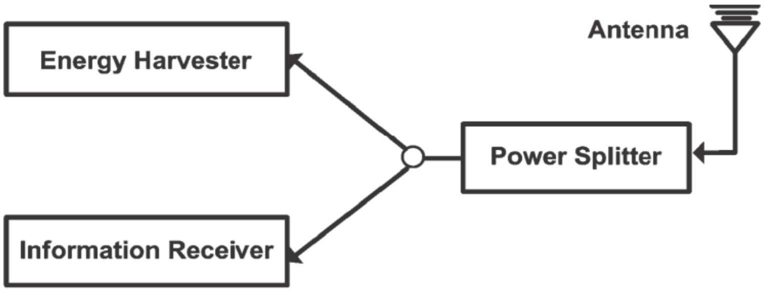

Figure 3 power splitting

Furthermore, the research on SWIPT isn't confined to the energy and information flow to be the same receiver to receive at the same time. Under the same access point

(AP), a few of terminals decoding effective message from received signals, which are called information receiver IR, while other terminals only concentrate on obtaining energy, which is called energy receiver (ER).

Literature review

Since 1831, when Faraday discovered the electromagnetic induction phenomenon, the wire has been the major carrier of electric energy spreading. However, the conventional method cannot have satisfied the requirements of serviceability and security of the modern electrical device. In addition, because the consciousness of environmental protection has been strengthened a lot, batteries have caused grievous destruction to the environment, in particular to groundwater resources and soil, which all urge people to explore a new way for energy provided.

In paper [35] shows that Nikola Tesla conceived the view of wireless energy transmission at first. The experiment investigates to operate the earth itself with the ionosphere as conductors to achieve wireless power transmission, nevertheless, in view of the previous technical predicaments, the experiment to accomplish the expected outcome was unsuccessful. At the 1950s, Goubau and Schweing calculated that the transmission efficiency of free-space beam-guided waves within the reflection beam guided wave system was able to reach almost 100 percent [36]. Subsequently, Raytheon corporation started studying this technology in 1964, achieving experiments with the 2.45GHz microwave powered helicopter [37]. Then, four years later, Peter

Glaser envisioned building solar power stations corresponding with satellite to solve the energy crisis [38]. In the late 1980s, a communication research centre in Canada assumed to establish a long-term high-altitude relay platform for broadcasting, communications and another different application services and suggested to apply wireless energy transmission mode to perform it [39]. After that, wireless energy transmission technology in little power and the close application has been widely concerned in the last ten years.

At the congress of wireless power transfer technology in France, in May, G. Pignolet had done the experiment according to the microwave wireless power conducting to light a 200-watt bulb far from 40 meters. In two years, this island has built a 10-kilowatt microwave transmission experimental facility and provided a point-to-point wireless power source of 2.45GHz frequency to the Grand Bassin village, near the bottom of the kilometre-deep ravine [40] In November 2006, Marin Soljacic and her team from Massachusetts Institute of Technology (MIT) victoriously recognized the wireless energy was supposed to transfer between two coils which have a distance of 2.13m taking advantage of the electromagnetic resonance rule to light a sixty Watt bulb, showed that it was one million times more valid than the ordinary non-resonant magnetic interaction [6]. After that, Lockheed Martin mentioned that a laser-based wireless charging system had been produced that could activate the drone wirelessly for 48 hours, expanding its flight range by 2400 per cent.

Thus, when WIT became increasingly popular, the significant breakthrough was made in the study of WPT. Scientists are not only just meet with the transmission of information by radio waves, but also expected that while transmitting information, they can also offer enough use of the valuable transmission power to transfer energy. Operated through this request, there is distinctly substantial to survey the architecture of SWIPT system ground on the continued transfer of information as well as energy, information modulation mode, energy relay mode, low-power and high-efficiency rectifier antenna and other vital technologies.

Varshney first put forward and evaluated the simultaneous transmission of information and energy problem [41], defined capacity energy function, and proposed the trade-off between limited amplitude binary discrete channel and additive Gaussian white noise (AWGN) channel capacity and energy transmission rate.

P. Grover cooperated with A. Sahai proposed a short-range wireless energy transmission circuit model on account of coupling inductance and inspected the problems of wireless information and energy transmission in noise-containing coupling inductance circuit [42]. They abstracted this circuit model into the frequency-selective AWGN channel with limited average power. For this channel model, the optimal power allocation was achieved by utilising the waterflood power allocation algorithm accompanied by the optimal trade-off between information transmission rate and energy conversion efficiency was given.

Liang Liu and his team members considered in a time-varying narrowband flat fading channel under the influence of the common channel interference problem of point to point wireless link in [43], aiming at the receiving end has no fixed power supply, which needs to be obtained from the received signal energy application scenario, the receiver is given the optimal working mode switching criterion in order to realize the optimal tradeoff between information transmission and energy transfer. Additionally, the joint optimization problems of transmission energy control, information and energy transmission scheduling and receiver mode switching are studied.

Omur Ozel and Jing Yang et al. studied the transmitter fading channel of the energy set function of the point-to-point data transmission in the optimization problem [44]: maximizing the information transfer rate and minimizing transfer time as their optimization objective, and discussing time series energy transfer issue, energy storage capacity and causal constraint optimization.

X. Zhou, R. Zhang and C.H. Keong [45] in order to overcome the limitation that real hardware was unable to simultaneously demodulate information and collect energy, they proposed a universal receiver method called Dynamic Power Splitting (DPS). Some of the received signals were distributed in a particular proportion, and some were used in energy collection and some in information demodulation. Furthermore, two receiver structures are given, which are separated receiver and integrated receiver. Moreover, the effects of circuit energy expenditure on the information transmission rate and energy efficiency of both receivers were studied respectively, and the performance of the two receivers using m-QAM modulation was compared.

Different from the point-to-point single antenna transmission system considered in literature [41-45], thesis [46-48] mainly supposes the simultaneous transmission of information and energy in the MIMO system.

R. Zhang and C.H. Keong [46] to deliberate in a 3 node SWIPT problem in MIMO wireless broadcasting system, this situation is fixed by the AP (Access Point, AP) as well as disseminated User Terminal (UT) of MIMO wireless broadcasting system, together with separately for a single user and multi-user circumstance, design the information transmission rate along with energy transfer efficiency between different weight of this optimal transmission strategy, gives the rate of energy domain boundary.

Beside of this, Batu k. Chalise et al. [47-50] researched the performance of a two-hop forward amplification relay structure including multi-antenna energy receiver. During this designed structure, Orthogonal space-time Block Code (OSTBC) is adopted for both source and relay nodes.

Ali Mohammad Fouladgar and O. Simeone examined the SWIPT in the multi-user system [51-53] and indicated that for the sake of maximize the total transmission rate of the system in the multi-access channel accompanied by limited receiving energy, TDM should be adopted.

In addition, [54] studied SWIPT resource allocation algorithms in multiuser OFDMA system, using the nonlinear fractional programming in addition to process the Lagrangian dual decomposition of the combination of convex optimization problem, design an unused iterative algorithm to gain the maximum energy efficiency system, so as to reveal the multi-user on energy efficiency and the potential benefits of system capacity. In [55-58], the hybrid network is studied. In the uplink of cellular network, energy beacons are randomly arranged to charge mobile devices wirelessly, and the tradeoff between network parameters is given under the constraint of data link interruption.

System model

we design a multi-user multiple input single output (MISO) system model with impact channel state information combine with power splitting scheme in the essay, so as to maximise the minimum energy harvesting power in each receiver.

The figure below shows the system model.

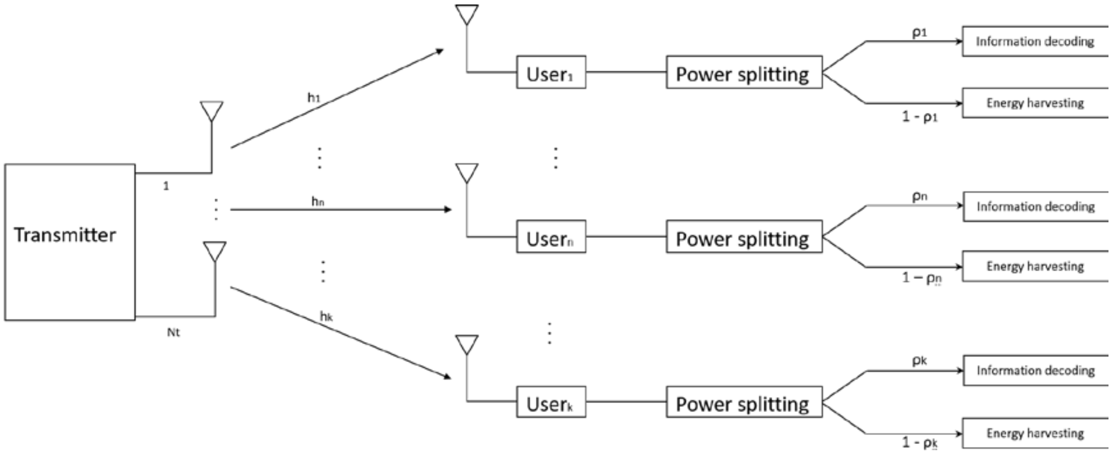

Figure 4 system model

In this model, we firstly assume that the channel is a correctly estimated flat fading channel, with no channel estimation error. The base station is a multi-antenna transmitter, which is equipped with Nt (Nt≥1) transmitting antennas and wants to transmit signals to multiple users at the same time. There are K users equipped with PS receiver in the system, and the PS receiver is a single-antenna receiver.

1. Beamforming model

The beamformed signal carries both information and energy signal from transmitter

[59-60], we use a transmitter to transmit signal by Nt ($Nt \geq 1$) antennas, the transmit signal **x** can be expressed as:

$$\boldsymbol{x} = \sum_{k=1}^{K} \boldsymbol{\omega}_k s_k \,, \ \forall k \in [1, K],$$

(3-1)

Where the $\mathbf{w}_k \in C_{Nt\times 1}$is the beamforming vector for users and the $s_k \in C_{1\times 1}$ is the pseudo-random transmit signal. Lacking loss of generality, we assume that $E\{[s]^2\}=1$. For assuming that there is no estimation error in the channel, the signal received by the kth user node is able to be expressed as:

$$\boldsymbol{y}_k = \boldsymbol{h}_k{}^H \boldsymbol{x} + n_k \,, \ \forall k \in [1, K],$$

(3-2)

Where $\mathbf{h}_k{}^H$ substitute for the conjugated channel (CSI) vector between the transmitter and the receiver which including the path loss and fading due to multipath, and n_k stands for the additive Gaussian noise in the middle of the transmitter and the receiver escorted by the zero mean as well as variance σ.

2. Power splitting model

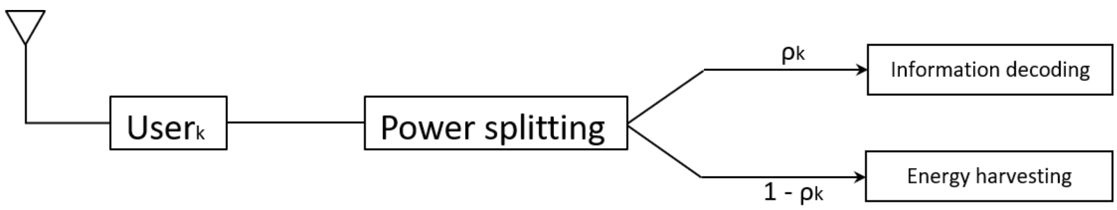

Figure 5 power splitting system model in this model system

The PS receiver will distribute the total power of received signal, which $\rho \in (0,1)$ part for information decoding, the rest of the (1-ρ) distribution to energy reception. After the PS receiver energy distribution, the proportion of received signal at kth user information decoding along with energy harvesting can be expressed respectively as:

$$y_{ID_k} = \sqrt{\rho_k}\left(\boldsymbol{h}_k{}^H \boldsymbol{x} + n_k \right) \ , \forall k \in \left[1, k \right] \qquad \rho_k \in (0, 1)$$

(3-3)

$$y_{ER_k} = \sqrt{1 - \rho_k}\left(\boldsymbol{h}_k{}^H \boldsymbol{x} + n_k \right) \ , \forall k \in \left[1, k \right] \qquad \rho_k \in (0, 1)$$

(3-4)

The power of the k_{th} user received by information receiver and energy received can be express respectively as:

$$\begin{aligned} P_{ID_k} &= E\left\{ \left| \sqrt{\rho_k}\left(\boldsymbol{h}_k{}^H \boldsymbol{x} + n_k \right) \right|^2 \right\} \\ &= \rho_k \sum_{k=1}^{K} \left| \boldsymbol{h}_k{}^H \boldsymbol{x} \right|^2 \\ &= \rho_k \sum_{k=1}^{K} \left| \boldsymbol{h}_k{}^H \boldsymbol{\omega}_k \right|^2 \ , \quad \forall k \in \left[1, k \right]; \rho_k \in (0, 1) \end{aligned}$$

(3-5)

$$\begin{aligned} P_{ER_k} &= E\left\{ \left| \sqrt{1 - \rho_k}\left(h_k{}^H \boldsymbol{x} + n_k \right) \right|^2 \right\} \\ &= \left(1 - \rho_k \right) \sum_{k=1}^{K} \left| \boldsymbol{h}_k{}^H \boldsymbol{x} \right|^2 \\ &= \left(1 - \rho_k \right) \sum_{k=1}^{K} \left| \boldsymbol{h}_k{}^H \boldsymbol{\omega}_k \right|^2 \ , \quad \forall k \in \left[1, k \right]; \rho_k \in (0, 1) \end{aligned}$$

(3-6)

3. **Signal-to-interference-noise ratio (SINR) expression**

The noise of different users' node is mainly the additive white Gaussian noise introduced in the energy distribution of the channel and PS receiver, so the SINR of each end user node can be expressed as：

$$SINR_k = \frac{\rho_k \left| h_k{}^H \omega_k \right|^2}{\rho_k \sum_{j \neq k} \left| h_k{}^H \omega_k \right|^2 + \sigma^2}, \ \forall k \in \left[1, K\right]; \rho_k \in (0, 1)$$

（3-7）

Problem Formulation

In this section, the paper is centred on beamforming design to maximise the minimum power received by each energy harvest receiver to ensure system fairness. Sometimes, in real life, if there is an energy harvest receiver near the transmitter, the transmitter will be more inclined to turn the beamforming direction to this energy harvest receiver than other receivers to get the most resources [61-65]. However, this will result in insufficient resources for other receivers. In order to ensure the fairness of the SWIPT system, we have developed the following optimisation issues:

$$\begin{aligned} & \underset{\rho_k,\ \omega_k}{Maximize} \ \underset{k \in [1,K]}{min} \left\{ P_{ER_k} \right\} \\ & s.t. \quad C1: 0 < \rho_k < 1, \ \forall k \in \left[1, K\right], \\ & \qquad\ \ C2: \sum_{k=1}^{K} \|\omega_k\|^2 \leq P_{max}, \\ & \qquad\ \ C3: min\ SINR_k \geq \Gamma_{req}, \ \forall k \in \left[1, K\right], \end{aligned}$$

（4-1）

The above optimization issue is based on perfect known CSI system. However, under practical circumstance, the channel state information is always imperfect, so it is inconsistent with our hypothesis that there is no channel interference. Thus, we have to add an imperfect CSI in our model.

The imperfect channel state information can be expressed as:

$$\boldsymbol{h}_k = \widehat{\boldsymbol{h}_k} + \Delta \boldsymbol{h}_k, \forall k \in [1, K],$$

(4-2)

where $\widehat{\boldsymbol{h}_k}$ means the channel estimate of the k_{th} energy harvesting receiver, while $\Delta \mathbf{h}_k$ denotes the unknown channel uncertainty of the energy harvesting receiver k.

The optimize problem can be shown as:

$$\begin{aligned} & \underset{\rho_k,\ \omega_k}{Maximize} \quad \underset{k \in [1,K],\ \Delta \boldsymbol{h}_\mathbf{k} \in \Phi}{min} \quad \{P_{ER_k}\} \\ & s.t. \quad C1: 0 < \rho_k < 1,\ \forall k \in [1, K], \\ & \qquad C2: \sum_{k=1}^{K} ||\boldsymbol{\omega}_k||^2 \le P_{max}, \\ & \qquad C3: \underset{\Delta \boldsymbol{h}_\mathbf{k} \in \Phi}{min} \quad SINR_k \ge \Gamma_{req}, \forall k \in [1, K], \end{aligned}$$

(4-3)

And then transfer to:

$$\begin{aligned} & \underset{\rho_k,\ \omega_k}{Maximize} \quad \underset{k \in [1,K],\ \Delta \boldsymbol{h}_\mathbf{k} \in \Phi}{min} \left\{P_{ER_k}\right\} \\ & s.t. \quad C1: 0 < \rho_k < 1,\ \forall k \in [1, K], \\ & \qquad C2: \sum_{k=1}^{K} ||\boldsymbol{\omega}_k||^2 \le P_{max}, \\ & \qquad C3: \underset{\Delta \boldsymbol{h}_\mathbf{k} \in \Phi}{min} \frac{\rho_k |\left(\widehat{\mathrm{h}}_k + \Delta \boldsymbol{h}_\mathbf{k}\right)^H \boldsymbol{\omega}_k|^2}{\rho_k \sum_{j \ne k} |\left(\widehat{\mathrm{h}}_k + \Delta \boldsymbol{h}_\mathbf{k}\right)^H \boldsymbol{\omega}_j|^2 + \sigma^2} \ge \Gamma_{req}, \forall k \in [1, K], \end{aligned}$$

(4-4)

We bring forward an enigma of the jointly transmit beamforming and receive power allowance with an imperfect CSI. In this question, the ratio of power splitting, ρ, which means the range of the part of received power in information decoding and energy harvesting, must between 0 and 1. Also, the transmit power of the base station should be below a given threshold P_{max} which cannot be infinite since the hardware limitation, to ensure that sufficient energy can be transmitted. Furthermore, the minimum signal to SINR among different customers should larger than a specific constant, in order to realise a continuous information transfer at all the time. Therefore, we draw up the beamforming transmitter optimisation problem as a maximisation of the minimum energy harvest power for each energy receiver.

Optimal solution

Due to solve the (4-4) we put forward above, we will use the convex optimization. However, the optimization problem in (4-4) is non-convex since this power of energy harvesting received must be discrete and constraint C3. Generally, the convex optimization problem may exist multiple local maximum values. Exhaustive search is a method to acquire the global optimal solution, but its computational intricacy growths exponentially as the number of transmitting antennas and ERs increases [66-68]. For the sake of deal with the non-smoothness of the objective function, we can transform this problem at hand into its equivalent representation and then apply the semidefinite programming (SDP) relaxation will be applied to the formulations. Firstly, we use τ to replace $\underset{k \in [1,K]}{min} \left\{ P_{ER_k} \right\}$

$$\begin{aligned}
&\underset{\rho_k,\boldsymbol{\omega}_k}{Maximize}\ \underset{k\in[1,K]}{min}\left\{P_{ER_k}\right\}\\
&\Rightarrow \underset{\boldsymbol{\omega}_k,\tau}{Maximize}\ \tau\\
&where\ \tau\le \underset{k\in[1,K]}{min}\left\{P_{ER_k}\right\},
\end{aligned}$$

(5-1)

Then the optimal problem can be expressed as:

$$\begin{aligned}
&\underset{\boldsymbol{\omega}_k,\tau}{Maximize}\ \tau\\
&\quad\tau\le P_{ER_k},\ \forall k\in[1,K],\\
s.t.\ &C1: 0\le\rho_k\le 1,\ \forall k\in[1,K],\\
&C2: \sum_{k=1}^{K}||\boldsymbol{\omega}_k||^2\le P_{max},\\
&C3: \Gamma_{req}\left(\sum_{j\ne k}|\boldsymbol{h}_k\boldsymbol{\omega}_j|^2+\frac{\sigma^2}{\rho_k}\right)\le|\boldsymbol{h}_k\boldsymbol{\omega}_k|^2,\ \forall k\in[1,K],
\end{aligned}$$

(5-2)

Since

$$\begin{aligned}
||\boldsymbol{\omega}_k||^2 &= \boldsymbol{\omega}_k{}^H\boldsymbol{\omega}_k,\ \forall k\in[1,K],\\
&=Tr(\boldsymbol{\omega}_k{}^H\boldsymbol{\omega}_k)\\
&=Tr(\boldsymbol{\omega}_k\boldsymbol{\omega}_k{}^H)\\
&=Tr(\boldsymbol{W}_k)\\
||\boldsymbol{\omega}_k||^2&=\boldsymbol{\omega}_k\boldsymbol{\omega}_k{}^{\mathrm{H}},\ \forall k\in[1,K]\Rightarrow Rank(\boldsymbol{W}_k)=1
\end{aligned}$$

(5-3)

The problem (5-3) can be converted to a linear form with two more constraint C4 and C5:

$$
\begin{aligned}
&\underset{\omega_k,\tau}{Maximize}\ \ \tau \\
&\qquad \tau \le P_{ER_k}\ ,\ \forall k \in \left[1, K\right], \\
s.t.\ \ & C1{:}\ 0 \le \rho_k \le 1,\ \forall k \in \left[1, K\right], \\
& C2{:}\ \sum_{k=1}^{K} Tr\left(W_k\right) \le P_{max}\ , \\
& C3{:}\ \Gamma_{req}\left(\sum_{j \ne k} Tr\left(H_k W_j\right) + \frac{\sigma^2}{\rho_k}\right) \le\ Tr\left(H_k W_k\right)\ ,\forall k \in \left[1, K\right], \\
& C4{:}\ W_k \ge 0\ ,\forall k \in \left[1, K\right], \\
& C5{:}\ Rank\left(W_k\right) \le 1,\ \forall k \in \left[1, K\right],
\end{aligned}
$$

(5-5)

However, the new optimization problem (5-5) is still non-convex because of constraint 5. Adopting SDP relaxation, we can remove constraint 6 and considered problem becomes a convex problem. Then, convex program solvers can solve the new problem efficiently and optimally. In order to obtain the Lagrangian function, the SDP relaxed problem formulation can be written as:

$$
\begin{aligned}
&\underset{\omega_k,\tau}{Maximize}\qquad \tau \\
&\qquad \tau \le P_{ER_k}, \forall k \in [1, K], \\
s.t.\,& C1{:}\ 0 \le \rho_k \le 1, \forall k \in [1, K], \\
& C2{:}\sum_{k=1}^{K} Tr\left(W_k\right) - P_{max} \le 0\ , \\
& C3{:}\Gamma_{req}(\ Tr\left(H_{\mathbf{k}} W_j\right) + \frac{\sigma^2}{\rho_k}) - Tr\left(H_k W_k\right) \le 0, \forall k \in [1, K], \\
& C4{:}\ -W_k \le 0, \forall k \in [1, K],
\end{aligned}
$$

(5-6)

Note that the converted problem is convex and can be worked out efficiently and optimally by a standard convex program solver. However, rank constraint relaxation may not occur with compact rank (**W**) > 1. Therefore, we reveal the tightness of SDP relaxation used in (5-6) as follows:

Theorem 1. *If channels* $\mathbf{H}$ *and* $\mathbf{G}_j$ *are statistically independent and the transformed problem in* $(5-6)$ *is feasible, then the optimal information beamforming matrix* $\mathbf{W}$ *is at most rank – one with probability one, i.e., Rank(*$\mathbf{W}$*)* ≤ 1.

Proof: the proof of theorem 1 can be seen in the appendix.

In light of this, if the channel condition in theorem 1 is satisfied, the SDP relaxation adopted would be tight. Therefore, the information beamforming considered is the best choice to maximize the available data rate.

Simulation Results

In this section, we proposed is studied through simulation of the performance of the optimal resource allocation. In the simulation, there are 5 ERs and 4 users located at 10 meters from the base station. Unless otherwise specified, important simulation parameters are shown in Table 6-1.

Table 6-1 Simulation parameters

System bandwidth	200 kHz
Carrier center frequency	915 MHz
Transceiver antenna gain	18 dBi
Noise power σ_s^2	-120 dBm
BS-to-ER fading distribution	Rician with Rician factor 6 dB
BS-to-IR fading distribution	Rayleigh

Figure 6.1 considers the nontrivial tradeoff relationship between the average minimum harvested energy (dBm) and Signal to Interference plus Noise Ratio (dB) of each

energy harvesting receiver with the different number of transmitting antennas under the proposed optimal beamforming scheme. In general, surrounded by a transmitting antenna number of curves of regional is achievable. In other words, all points are located in or on the curve, which can be achieved by adjusting the relevant system parameters of the optimal scheme. By comparing the intersection points of Y-axis and X-axis with the different number of transmitting antennas, it can be observed that with the same transmit power, the average minimum receiving power of energy harvested receiver decreases when the SINR is increasing. On the other hand, by comparing the different number of antennas (i.e., NT=4 , NT=6, and NT=8), it can be clearly seen that with the increase in the number of transmitter antennas, the average minimum receiving energy of each energy receiver increases.

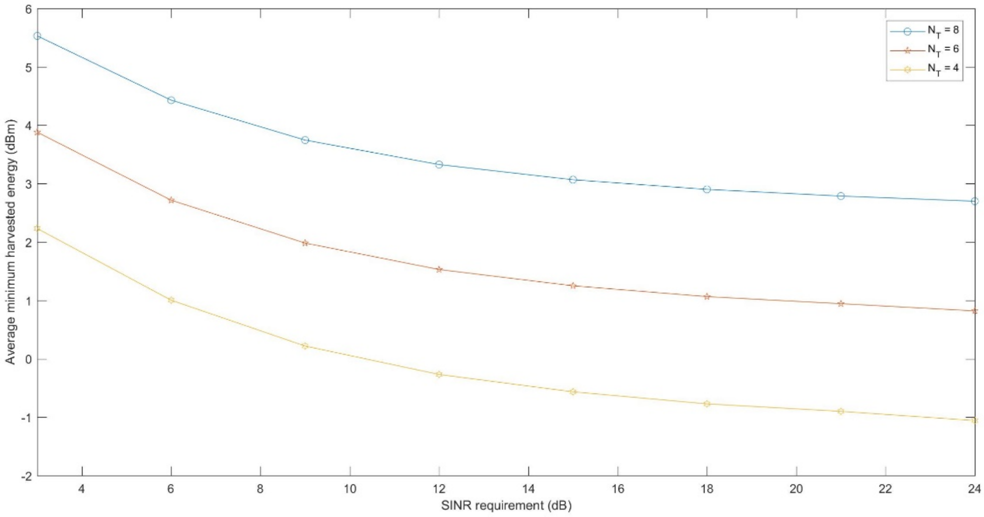

Figure 6.1

Figure 6.2 shows the relationship between the average minimum harvested energy (dBm) and the maximum transmitting power (dBm) of each energy harvesting receiver under different number of transmitting antennas. In general, the average minimum harvested energy increase with the increase of maximum transmitted power. In addition, the average minimum energy receiving power of each energy harvesting receiver increases when the number of transmitting antennas is increasing.

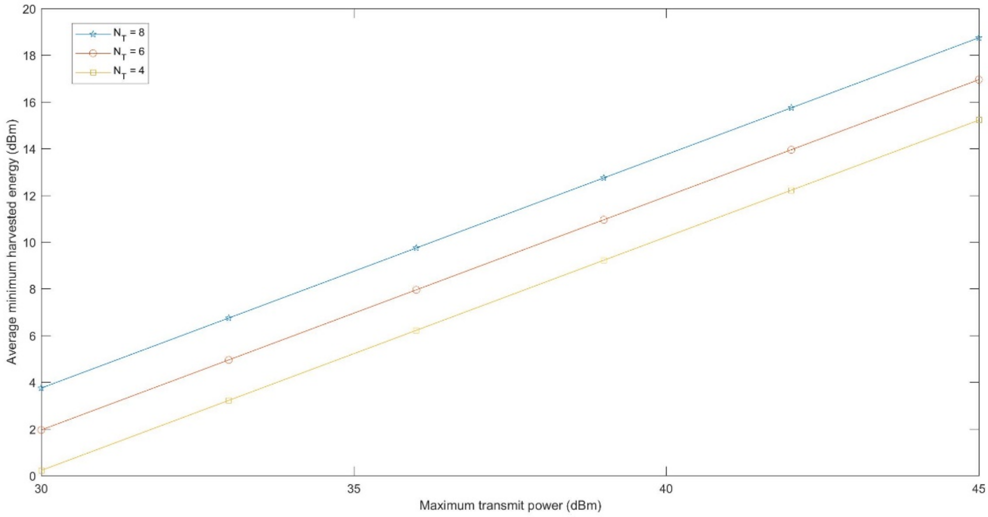

Figure 6.2

Conclusions

In this paper, we discuss the resource allocation of the SWIPT system, which transmits signal and energy simultaneously. The key of the optimisation problem is to solve a non-convex problem to maximise the minimum power received by the energy harvesting receiver under the constraints of the signal-to-interference-noise ratio (SINR) and transmission power of each user. According to SDP relaxation and KKT conditions, it is transformed into a convex problem and solved effectively. Simulation results show the optimal solution and tradeoff of the system.

Appendix — Proof of Theorem 1

It is proved that the transformation optimization problem in (5-6) is convex and satisfies Slater's constraints, so it has a strong duality. In other words, solving the dual problem is the same as solving the original problem. In this section, we intend to prove theorem 1 by first defining Lagrange function. The obtained Lagrangian function has shown follow:

$$L=\sum_{k=1}^{K} Tr\left(W_{k}\right) + \sum_{i=1}^{K} \lambda_{i}\left[\Gamma_{req}(Tr\left(H_{\mathrm{k}} W_{j}\right) + \frac{\sigma^{2}}{\rho_{k}}) - Tr\left(H_{\mathrm{k}} W_{k}\right)\right]$$
$$+ \Phi\left[\sum_{k=1}^{K} Tr\left(W_{k}\right) - P_{max}\right]- \sum_{k=1}^{K} Tr\left(Y_{\mathrm{k}} W_{k}\right)$$

(8-1)

Derivative of a Lagrange $\frac{\partial L}{\partial \boldsymbol{W}_k}$ function

$$\frac{\partial L}{\partial \boldsymbol{W}_{k}} = \boldsymbol{I}_{k} + \sum_{j\neq k} \lambda_{j} \Gamma_{req} \boldsymbol{H}_{j} - \sum_{i=1}^{K} \lambda_{i} \boldsymbol{H}_{k} + \phi \boldsymbol{I}_{k} - \boldsymbol{Y}_{k}$$
$$=0, \quad \forall k \in \left[1, K\right],$$

(8-2)

Therefore:

$$\boldsymbol{Y}_{k} = \boldsymbol{I}_{k} + \sum_{j\neq k} \lambda_{j} \Gamma_{req} \boldsymbol{H}_{j} - \sum_{i=1}^{K} \lambda_{i} \boldsymbol{H}_{k} + \phi \boldsymbol{I}_{k}\,, \quad \forall k \in \left[1, K\right],$$

(8-3)

As it can be seen that $\boldsymbol{Y}_k$ can be rearrange to a form as $\boldsymbol{Y}_{k} = - a\boldsymbol{H}_{k} + \boldsymbol{B}\ , \ \forall k \in \left[1, K\right],$

Where $$a=\sum_{i=1}^{K} \lambda_{i} \ and\ \boldsymbol{B} = \boldsymbol{I}_{k} + \sum_{j\neq k} \lambda_{j} \Gamma_{req} \boldsymbol{H}_{j} + \phi \boldsymbol{I}_{k}, \ \forall k \in \left[1, K\right],$$

Using contradiction, if matrix B is a positive semi-definite matrix, then there $\boldsymbol{V}=\boldsymbol{v}\ \boldsymbol{v}^{H}$

is at least one zero eigenvalue and we represent the associated eigenvector as **V**. Assume and multiply $\boldsymbol{Y}_k$ by **V** on the both sides, the equation becomes to

$$Tr\left(\boldsymbol{Y}_k\boldsymbol{V}\right) \leq -Tr\left(\boldsymbol{H}_k\boldsymbol{V}\right) + Tr(\boldsymbol{B}\boldsymbol{V}), \forall k \in \left[1, K\right],$$

(8-4)

Since both of H_k and $\sum_{j \neq k} \boldsymbol{H}_j$ are statistically independent, hence we can obtain that $Tr\left(\boldsymbol{H}_k\boldsymbol{V}\right) > 0$ and $Tr\left(\boldsymbol{Y}_k\boldsymbol{V}\right) < 0$. Therefore, the matrix $\boldsymbol{B}$ must be a positive semidefinite matrix and the Rank (**B**)=N_T.

According to the basic rule of inequality for the rank of matrix $Rank(\boldsymbol{a}) + Rank(\boldsymbol{b}) \geq Rank(\boldsymbol{ab})$ with the same dimension of both matrices [69-71]. Then, let $\boldsymbol{a} = \boldsymbol{Y}_k, \boldsymbol{b} = \boldsymbol{H}_k, (\forall k \in \left[1, k\right])$ we can obtain

$$\begin{aligned} Rank\left(\boldsymbol{Y}_k\right) &\geq Rank(\boldsymbol{B}) - Rank\left(\boldsymbol{H}_k\right) \\ &= N_T - 1, \ \forall k \in \left[1, K\right], \end{aligned}$$

(8-5)

Thus, we have $Rank\left(\boldsymbol{Y}_k\right) \geq N_T - 1$, and proving $Rank\left(\boldsymbol{W}_k\right) \leq 1$.

References:

[1] D. W. K. Ng, M. Breiling, C. Rohde, F. Burkhardt and R. Schober, "Energy-Efficient 5G Outdoor-to-Indoor Communication: SUDAS Over Licensed and Unlicensed Spectrum," in *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 3170-3186, May 2016.

[2] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng and R. Schober, "An Overview of Sustainable Green 5G Networks," in *IEEE Wireless Communications*, vol. 24, no. 4, pp. 72-80, Aug. 2017.

doi: 10.1109/MWC.2017.1600343

[3] S. F. Jilani, Q. H. Abbasi and A. Alomainy, "Inkjet-Printed Millimetre-Wave PET-Based Flexible Antenna for 5G Wireless Applications," *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, Dublin, 2018, pp. 1-3.

[4] B. Ó. hAnnaidh *et al.*, "Devices and Sensors Applicable to 5G System Implementations," *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, Dublin, 2018, pp. 1-3.

[5] P. Pirinen, "A brief overview of 5G research activities," *1st International Conference on 5G for Ubiquitous Connectivity*, Akaslompolo, 2014, pp. 17-22.

[6] J. Park, S. Y. Lee, Y. Kim, J. Lee and W. Hong, "Hybrid Antenna Module Concept for 28 GHz 5G Beamsteering Cellular Devices," *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*,

Dublin, 2018, pp. 1-3.

[7] Y. Huo, X. Dong, W. Xu and M. Yuen, "Cellular and WiFi Co-design for 5G User Equipment," *2018 IEEE 5G World Forum (5GWF)*, Silicon Valley, CA, 2018, pp. 256-261.

[8] K. Nakatani, Y. Yamaguchi, Y. Komatsuzaki, S. Sakata, S. Shinjo and K. Yamanaka, "A Ka-Band High Efficiency Doherty Power Amplifier MMIC using GaN-HEMT for 5G Application," *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, Dublin, 2018, pp. 1-3.

[9] S. Shinjo *et al.*, "A 28GHz-band highly integrated GaAs RF frontend Module for Massive MIMO in 5G," *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, Dublin, 2018, pp. 1-3.

[10] Z. U. Khan, Q. H. Abbasi, A. Belenguer, T. H. Loh and A. Alomainy, "Empty Substrate Integrated Waveguide Slot Antenna Array for 5G Applications," *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, Dublin, 2018, pp. 1-3.

[11] L. Aluigi, G. Orecchini and L. Larcher, "A 28 GHz Scalable Beamforming System for 5G Automotive Connectivity: an Integrated Patch Antenna and Power Amplifier Solution," *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, Dublin, 2018, pp. 1-3.

[12] S. A. Cerqueira, "Antenna development for 5G networks," *2017 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)*, Aguas de

Lindoia, 2017, pp. 1-5.

[13] I. Ahmed, A. Ikhlef, D. W. K. Ng and R. Schober, "Power Allocation for an Energy Harvesting Transmitter with Hybrid Energy Sources," in *IEEE Transactions on Wireless Communications*, vol. 12, no. 12, pp. 6255-6267, December 2013.

[14] I. Ahmed, A. Ikhlef, D. W. K. Ng and R. Schober, "Power allocation for a hybrid energy harvesting relay system with imperfect channel and energy state information," *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, Istanbul, 2014, pp. 990-995.

[15] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-Efficient Resource Allocation in OFDMA Systems with Hybrid Energy Harvesting Base Station," in *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3412-3427, July 2013.

[16] D. W. K. Ng and R. Schober, "Energy-efficient power allocation for M2M communications with energy harvesting transmitter," *2012 IEEE Globecom Workshops*, Anaheim, CA, 2012, pp. 1644-1649.

[17] E. Boshkovska, N. Zlatanov, L. Dai, D. W. K. Ng and R. Schober, "Secure SWIPT Networks Based on a Non-Linear Energy Harvesting Model," *2017 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, San Francisco, CA, 2017, pp. 1-6.

[18] E. Boshkovska, D. W. K. Ng, N. Zlatanov and R. Schober, "Practical Non-Linear Energy Harvesting Model and Resource Allocation for SWIPT Systems," in *IEEE Communications Letters*, vol. 19, no. 12, pp. 2082-2085, Dec. 2015.

[19] E. Boshkovska, A. Koelpin, D. W. K. Ng, N. Zlatanov and R. Schober, "Robust

beamforming for SWIPT systems with non-linear energy harvesting model," *2016 IEEE 17th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Edinburgh, 2016, pp. 1-5.

[20] I. Ahmed, A. Ikhled, D. W. K. Ng and R. Schober, "Optimal power allocation for a hybrid energy harvesting transmitter," *2013 IEEE International Conference on Communications (ICC)*, Budapest, 2013, pp. 4185-4190.

[21] I. Ahmed, A. Ikhlef, D. W. K. Ng and R. Schober, "Optimal resource allocation for energy harvesting two-way relay systems with channel uncertainty," *2013 IEEE Global Conference on Signal and Information Processing*, Austin, TX, 2013, pp. 345-348.

[22] R. Morsi, E. Boshkovska, E. Ramadan, D. W. K. Ng and R. Schober, "On the performance of wireless powered communication with non-linear energy harvesting," *2017 IEEE 18th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Sapporo, 2017, pp. 1-5.

[23] R. Morsi, V. Jamali, D. W. K. Ng and R. Schober, "On the Capacity of SWIPT Systems with a Nonlinear Energy Harvesting Circuit," *2018 IEEE International Conference on Communications (ICC)*, Kansas City, MO, 2018, pp. 1-7.

[24] D. W. K. Ng and R. Schober, "Secure and Green SWIPT in Distributed Antenna Networks With Limited Backhaul Capacity," in *IEEE Transactions on Wireless Communications*, vol. 14, no. 9, pp. 5082-5097, Sept. 2015.

[25] S. Leng, D. W. K. Ng, N. Zlatanov and R. Schober, "Multi-objective resource allocation in full-duplex SWIPT systems," *2016 IEEE International Conference on*

Communications (ICC), Kuala Lumpur, 2016, pp. 1-7.

[26] R. Morsi, V. Jamali, D. W. K. Ng and R. Schober, "On the Capacity of SWIPT Systems with a Nonlinear Energy Harvesting Circuit," *2018 IEEE International Conference on Communications (ICC)*, Kansas City, MO, 2018, pp. 1-7.

[27] F. Jameel, A. Ali and R. Khan, "Optimal time switching and power splitting in SWIPT," *2016 19th International Multi-Topic Conference (INMIC)*, Islamabad, 2016, pp. 1-5.

[28] S. Leng, D. W. K. Ng, N. Zlatanov and R. Schober, "Multi-objective beamforming for energy-efficient SWIPT systems," *2016 International Conference on Computing, Networking and Communications (ICNC)*, Kauai, HI, 2016, pp. 1-7.

[29] E. Boshkovska, A. Koelpin, D. W. K. Ng, N. Zlatanov and R. Schober, "Robust beamforming for SWIPT systems with non-linear energy harvesting model," *2016 IEEE 17th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Edinburgh, 2016, pp. 1-5.

[30] E. Boshkovska, X. Chen, L. Dai, D. W. K. Ng and R. Schober, "Max-Min Fair Beamforming for SWIPT Systems with Non-Linear EH Model," *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*, Toronto, ON, 2017, pp. 1-6.

[31] E. Boshkovska, D. W. K. Ng, N. Zlatanov and R. Schober, "Practical Non-Linear Energy Harvesting Model and Resource Allocation for SWIPT Systems," in *IEEE Communications Letters*, vol. 19, no. 12, pp. 2082-2085, Dec. 2015.

[32] E. Boshkovska, N. Zlatanov, L. Dai, D. W. K. Ng and R. Schober, "Secure SWIPT Networks Based on a Non-Linear Energy Harvesting Model," *2017 IEEE Wireless*

Communications and Networking Conference Workshops (WCNCW), San Francisco, CA, 2017, pp. 1-6.

[33] T. A. Le, Q. Vien, H. X. Nguyen, D. W. K. Ng and R. Schober, "Robust Chance-Constrained Optimization for Power-Efficient and Secure SWIPT Systems," in *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 3, pp. 333-346, Sept. 2017.

[34] T. A. Le, Q. Vien, H. X. Nguyen, D. W. K. Ng and R. Schober, "Robust Optimization with Probabilistic Constraints for Power-Efficient and Secure SWIPT," *2016 IEEE Global Communications Conference (GLOBECOM)*, Washington, DC, 2016, pp. 1-7.

[35] M. Ishiba, J. Ishida, K. Komurasaki and Y. Arakawa, "Wireless power transmission using modulated microwave," *2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications,* Uji, Kyoto, 2011, pp. 51-54.

[36] Y. Miyazaki, "Image reconstruction theory of electromagnetic wave CT based on spatial beam sampling characteristics," *2012 International Symposium on Antennas and Propagation (ISAP)*, Nagoys, 2012, pp. 423-426.

[37] C. Montzka et al., "Investigation of SMAP Fusion Algorithms With Airborne Active and Passive L-Band Microwave Remote Sensing," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 54, no. 7, pp. 3878-3889, July 2016.

[38] P. E. Glaser, "An overview of the solar power satellite option," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 40, no. 6, pp. 1230-1238,

June 1992.

[39] G. Oliveri, P. Rocca, F. Viani, F. Robol and A. Massa, "Latest advances and innovative solutions in antenna array synthesis for microwave wireless power transmission," *2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications,* Kyoto, 2012, pp. 71-73.

[40] J. Choi, J. Cho and C. Seo, "Analysis on transmission efficiency of wireless energy transmission resonator based on magnetic resonance," *2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications*, Uji, Kyoto, 2011, pp. 199-202.

[41] L. R. Varshney, "Transporting information and energy simultaneously," *2008 IEEE International Symposium on Information Theory*, Toronto, ON, 2008, pp. 1612-1616.

[42] P. Grover and A. Sahai, "Shannon meets Tesla: Wireless information and power transfer," *2010 IEEE International Symposium on Information Theory*, Austin, TX, 2010, pp. 2363-2367.

[43] Y. Ren, T. Lv, H. Gao and S. Yang, "Wireless information and energy transfer in multi-cluster MIMO uplink networks through opportunistic interference alignment," in *IEEE Access*, vol. 4, pp. 3100-3111, 2016.

[44] O. Ozel, K. Tutuncuoglu, J. Yang, S. Ulukus and A. Yener, "Transmission with Energy Harvesting Nodes in Fading Wireless Channels: Optimal Policies," in *IEEE*

Journal on Selected Areas in Communications, vol. 29, no. 8, pp. 1732-1743, September 2011.

[45] X. Chen, X. Wang and X. Chen, "Energy-Efficient Optimization for Wireless Information and Power Transfer in Large-Scale MIMO Systems Employing Energy Beamforming," in *IEEE Wireless Communications Letters*, vol. 2, no. 6, pp. 667-670, December 2013.

[46] S. Zhao, Q. Li, Q. Zhang and J. Qin, "Antenna Selection for Simultaneous Wireless Information and Power Transfer in MIMO Systems," in *IEEE Communications Letters*, vol. 18, no. 5, pp. 789-792, May 2014.

[47] B. K. Chalise, Y. D. Zhang and M. G. Amin, "Energy harvesting in an OSTBC based amplify-and-forward MIMO relay system," *2012 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Kyoto, 2012, pp. 3201-3204.

[48] A. M. Fouladgar and O. Simeone, "On the Transfer of Information and Energy in Multi-User Systems," in *IEEE Communications Letters*, vol. 16, no. 11, pp. 1733-1736, November 2012.

[49] J. Wu, W. Lu, H. Peng, X. Liu and J. Hua, "Simultaneous wireless information and power transfer in OFDM systems based on subcarrier allocation," *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*, Paphos, 2016, pp. 926-929.

[50] Z. Yun, C. Xiang and L. Wang, "A hybird red blood cell model based on the linear spring network model and worm-like-chains model," *2017 10th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics*

(CISP-BMEI), Shanghai, 2017, pp. 1-5.

[51] E. Boshkovska, R. Morsi, D. W. K. Ng and R. Schober, "Power allocation and scheduling for SWIPT systems with non-linear energy harvesting model," 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, 2016, pp. 1-6.

[52] Z. Ding et al., "Application of smart antenna technologies in simultaneous wireless information and power transfer," in IEEE Communications Magazine, vol. 53, no. 4, pp. 86-93, April 2015.

[53] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," in IEEE Communications Magazine, vol. 52, no. 11, pp. 104-110, Nov. 2014.

[54] X. Chen, D. W. K. Ng and H. Chen, "Secrecy wireless information and power transfer: challenges and opportunities," in IEEE Wireless Communications, vol. 23, no. 2, pp. 54-61, April 2016.

[55] Derrick Wing Kwan Ng; Trung Q. Duong; Caijun Zhong; Robert Schober, "The Era of Wireless Information and Power Transfer," in Wireless Information and Power Transfer: Theory and Practice , , Wiley, 2019, pp.1-16

[56] M. Chynonova, R. Morsi, D. W. K. Ng and R. Schober, "Optimal multiuser scheduling schemes for simultaneous wireless information and power transfer," 2015 23rd European Signal Processing Conference (EUSIPCO), Nice, 2015, pp. 1989-1993.

[57] B. Clerckx, R. Zhang, R. Schober, D. W. K. Ng, D. I. Kim and H. V. Poor, "Fundamentals of Wireless Information and Power Transfer: From RF Energy

Harvester Models to Signal and System Designs," in IEEE Journal on Selected Areas in Communications, vol. 37, no. 1, pp. 4-33, Jan. 2019.

[58] Q. Wu, W. Chen, D. W. K. Ng and R. Schober, "Spectral and Energy-Efficient Wireless Powered IoT Networks: NOMA or TDMA?," in IEEE Transactions on Vehicular Technology, vol. 67, no. 7, pp. 6663-6667, July 2018.

[59] Q. Wu, M. Tao, D. W. Kwan Ng, W. Chen and R. Schober, "Energy-Efficient Resource Allocation for Wireless Powered Communication Networks," in IEEE Transactions on Wireless Communications, vol. 15, no. 3, pp. 2312-2327, March 2016.

[60] Q. Wu, W. Chen, D. W. Kwan Ng, J. Li and R. Schober, "User-Centric Energy Efficiency Maximization for Wireless Powered Communications," in IEEE Transactions on Wireless Communications, vol. 15, no. 10, pp. 6898-6912, Oct. 2016.

[61] Q. Wu, M. Tao, D. W. K. Ng, W. Chen and R. Schober, "Energy-efficient transmission for wireless powered multiuser communication networks," 2015 IEEE International Conference on Communications (ICC), London, 2015, pp. 154-159.

[62] E. Boshkovska, D. W. K. Ng and R. Schober, "Power-Efficient and Secure WPCNs with Residual Hardware Impairments and a Non-Linear EH Model," GLOBECOM 2017 - 2017 IEEE Global Communications Conference, Singapore, 2017, pp. 1-7.

[63] Q. Wu, G. Zhang, D. W. K. Ng, W. Chen and R. Schober, "Generalized Wireless-Powered Communications: When to Activate Wireless Power Transfer?," in IEEE Transactions on Vehicular Technology.

[64] E. Boshkovska, D. W. K. Ng, L. Dai and R. Schober, "Power-Efficient and Secure

WPCNs With Hardware Impairments and Non-Linear EH Circuit," in IEEE Transactions on Communications, vol. 66, no. 6, pp. 2642-2657, June 2018.

[65] D. W. K. Ng, E. S. Lo and R. Schober, "Multiobjective Resource Allocation for Secure Communication in Cognitive Radio Networks With Wireless Information and Power Transfer," in IEEE Transactions on Vehicular Technology, vol. 65, no. 5, pp. 3166-3184, May 2016.

[66] D. W. K. Ng, E. S. Lo and R. Schober, "Wireless Information and Power Transfer: Energy Efficiency Optimization in OFDMA Systems," in IEEE Transactions on Wireless Communications, vol. 12, no. 12, pp. 6352-6370, December 2013.

[67] D. W. K. Ng, E. S. Lo and R. Schober, "Robust Beamforming for Secure Communication in Systems With Wireless Information and Power Transfer," in IEEE Transactions on Wireless Communications, vol. 13, no. 8, pp. 4599-4615, Aug. 2014.

[68] X. Chen, D. W. K. Ng and H. Chen, "Secrecy wireless information and power transfer: challenges and opportunities," in IEEE Wireless Communications, vol. 23, no. 2, pp. 54-61, April 2016.

[69] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," in IEEE Communications Magazine, vol. 52, no. 11, pp. 104-110, Nov. 2014.

[70] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-efficient resource allocation in multiuser OFDM systems with wireless information and power transfer," 2013 IEEE Wireless Communications and Networking Conference (WCNC), Shanghai, 2013, pp. 3823-3828.

[71] D. W. K. Ng, E. S. Lo and R. Schober, "Energy-efficient power allocation in OFDM systems with wireless information and power transfer," 2013 IEEE International Conference on Communications (ICC), Budapest, 2013, pp. 4125-4130.