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Power-Efficient Design for Secure SWIPT Relaying Systems

by

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Abstract

A model in wireless communication systems which is called energy harvesting makes it possible for batteries of terminals being recharged by environmental energy resources. This model could be applied in wireless power transfer where the resources are electromagnetic radiation. Recently, an arising scenario where simultaneous wireless information and power transfer (SWIPT) are performed is currently becoming challenging and attractive. Although SWIPT is able to extend the life-span of wireless terminals as a feasible alternative to traditional energy harvesting methods, there still exists some issues due to the characteristics of radio frequency such as the power efficiency of the whole system and some worries about the security.

In this report, an introduction of SWIPT Relaying systems will be provided in which the power efficiency and the security will be focused mainly. To ensure a power-efficient and secure system, a system mode will be proposed then. Aiming at this mode, there is a problem formulation. And this non-convex problem could be converted into a convex optimization problem by SDP relaxation so that it can be figured out quickly and efficiently. In the end, simulation results are presented as well as the performance.

Contents

1. Introduction

1.1 Background

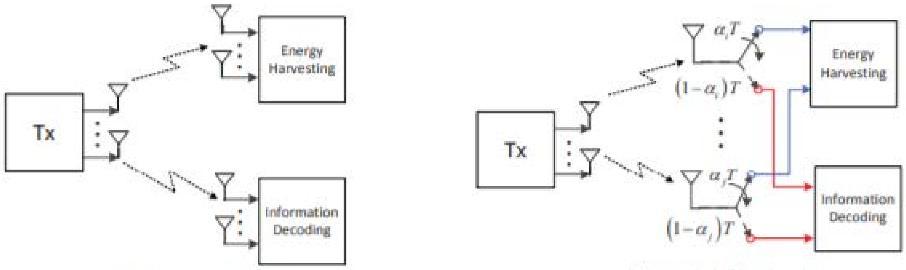
During the last decades, there is a tremendous growth of wireless communication devices because of the great progress of wireless communication technologies. Such devices are applied in various fields including e-health, environmental monitoring, energy management as well as autonomous control. A fact that about 50 billion devices will be connected together around the world with a great density of 1,000,000 devices per km^2 is predicted to come true in the coming Internet of Things (IoT) [1]. Since small devices are usually integrated at some locations which make wired recharging inaccessible, battery power seems to be a feasible style. However, the limited energy storage capacity of normal batteries leads to a frequent replacement which is cumbersome and costly. This situation becomes the bottleneck for the realizing of ubiquitous and reliable wireless communication systems. A practical method to alleviate this problem could be using renewable energy resources such as windand solar to generate electricity which could be harvested by the wireless communication devices [2]-[4]. Nevertheless, natural resources always have some disadvantages such as the dependence of location and climate and the intermittence which result in a low quality of energy harvesting.

To avoid the weakness, wireless power transfer (WPT) seems to be a feasible alternative to ensure an efficient and sustainable communication network which is able to serve the energy-limited communication devices [5]-[9]. Particularly, the electromagnetic (EM) waves used in practical communication system are in frequency (RF) band which could carry both energy and information concurrently. Hence, the receivers could harvest the energy of propagating signals radiated by transmitters to support the devices in networks and the energy consumption in information transmission. This could ensure a controllable and stable energy supple in communication devices comparing to the traditional natural renewable energy harvesting. Moreover, WPT technology makes simultaneous wireless information and power transfer (SWIPT) possible which is expected to realize the self-sustained communication systems and is able to accelerate IoT networks. Although there are some conveniences associated with SWIPT, applying SWIPT in wireless communication system also introduces some challenges two of which are energy efficiency and security.

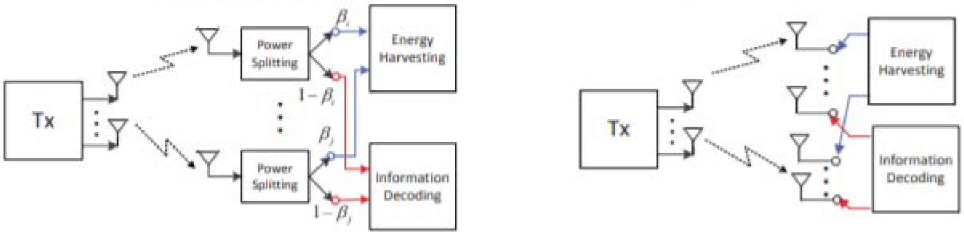
Nikola Tesla presented the initial concept of WPT in 1899 when wireless power transfer was aiming at the high-power consumption applications which caused a public health concern about serious radiation of electromagnetic wave [5]. This truth impeded the development of WPT until some recent technology advances such as multiple-antenna and silicon. Due to the fact that the application of WPT is able to reduce the high cost of power cables, WPT may be the key of the flourish of IoT. For instance, in the next decade the economic influence of IoT for logistics and transportation is expected to reach 1.9 trillion per year [10].

1.2 Receiver Structures in SWIPT

In practical SWIPT systems, the energy of the received signal is harvested directly in the radio frequency domain by existing RF-based energy harvester. Energy harvesting and information decoding are not able to perform on the same received signal because the traditional information decoding is processed in the digital baseband while the frequency down converted signals are not able to be used for energy harvesting and energy harvesting may destroy the modulated information. Hence, various kinds of receiver structures have been applied in SWIPT where the energy harvesting and information decoding should be separated. A viable solution is to separate the signal which is obtained at the receiver into two distinct parts while one is for decoding the information and another is for harvesting the energy. There are four receiver structures as shown in Fig.1.



(a) Separated Receiver (b) Time Switching Receiver



(c) Power Splitting Receiver (d) Antenna Switching Receiver

Figure 1. Separated receiver, time switching receiver, power splitting receiver and antenna switching receiver [11]

1.2.1 Separated Receiver

In the separated receiver network, a normal multiple antenna transmitter serves two receivers with separated antennas which implement an information decoding circuit and an energy harvesting circuit [12]. Since this structure could be easily accomplished by off-the-shelf components, based on the retroaction from the receivers to the transmitter and the channel state information, the balance between harvested energy and achievable information rate is able to be optimized.

1.2.2 Time Switching Receiver

In this receiver, there are a switch, a radio frequency energy harvesting and an information decoder at each receiver antenna. Particularly, each receiver antenna could switch its role between the information decoding module and the energy harvesting module according to an on/off sequence. As a result, the transmit signal and the time switching sequence are able to be optimized jointly when considering the requirements of service quality and the channel statistics.

1.2.3 Power Splitting Receiver

In the power splitting structure, the received signals will be separated into two parts by a power splitting unit with a certain power splitting ratio and then be sent to the energy harvesting and information decoding respectively [13]. By changing the value of power splitting ratios, a balance between the harvested energy and the achievable information rate is able to be made in particular. To improve the performance furtherly, a joint optimization of the power splitting ratios and the received signal should be achieved.

1.2.4 Antenna Switching Receiver

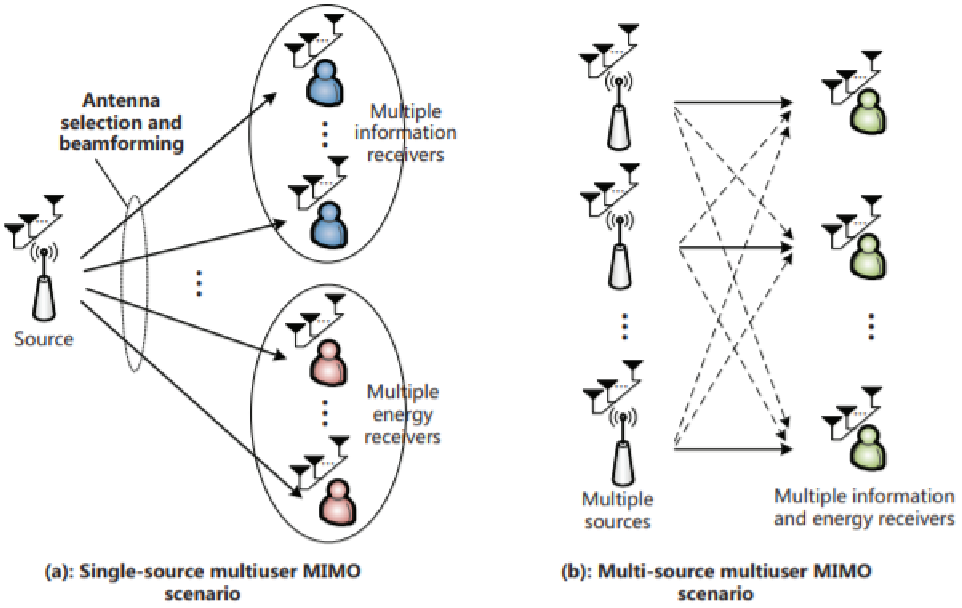
Low-complexity antenna switching with multiple antennas could be applied in SWIPT systems [14]. For example, among all antennas some will be selected for information decoding while the remaining antennas are used for energy harvesting. Comparing with the power splitting protocol where performance may be influenced by the hardware imperfections and the time switching architecture which needs stringent time synchronization, the antenna switching is more attractive for SWIPT system design because of its easier implement. In other words, antenna switching receiver is like a special case of power splitting with the half ratio.

1.3 MIMO SWIPT Networks

There are two main distinct benefits to SWIPT systems when exploiting multiple-input multiple-output. On the one hand, beamforming could be realized by exploiting extra transmit antennas which could increase the efficiency of information and energy transfer vastly. On the other hand, more antennas at the receiver could obtain more energy due to the characteristic of wireless transmission.

As shown in Fig.2a, the multiuser MIMO scenario results in the more obvious benefits when applying MIMO. A source with multiple antennas serving multiple information receivers make that possible for the radio frequency signals intended for the information decoding could also charge energy harvester wirelessly. Co-channel interference should be considered due to multiple users in the network. Hence, there are kinds of strategies to mitigate the interference to be implemented in SWIPT. For instance, block diagonalization precoding could let information be sent to receivers with no interference [15]. Moreover, user scheduling is easy to be employed in this network which makes EH and ID switching their roles according to the channel quality possible so as to extend the trade-off region between the harvested energy and the information rate.

Fig.2b illustrates the multi-source multiuser MIMO scenario where there are multiple sources sharing the same spectrum. The coordination and collaboration of interference between both signals and channels could bring new opportunities to SWIPT. For instance, as illustrated in [16], the interference alignment and antenna selection could divide the received signal space into two subspaces where one is for transferring the power and another is for transferring the information. Hence, this design could not only protect the information transfer by interference, but also utilize the discarded interference as energy source. Additionally, using RF energy harvesting will constrain the transmit beamforming design. As a result, maximum ratio transmission and zero forcing could be applied in SWIPT networks [17].



(a): Single-source multiuser MIMO scenario
(b): Multi-source multiuser MIMO scenario

Figure 2. Two scenarios of MIMO [11]

1.4 Relay Assisted SWIPT

Relay means that the transmitter or the receiver does not send signals directly to each other, but pass them after signal amplification or regeneration processing through the relay nodes. Taking a simple two-hop relay as an example, a base- mobile station link is divided into two links, namely, a base-relay node and a relay node-mobile station. In this way, a poor-quality link can be replaced by two quality links to obtain higher link capacity and better coverage. In LTE-Advanced, one method to achieve high-speed, high-capacity communication is relay technology for relaying signal transmissions between the transmitter and the receiver [18].

There are three types of technologies of relay with their merits and demerits respectively. A layer 1 relay uses the related technology which is an Amplifier and Forward type of technology. In this relay, the radio frequency signals are amplified on both the downlink and the uplink. The layer 1 relay is deployed to improve coverage in sparsely populated areas, mountain regions as well as urban areas because its simple equipment functions lead to short processing delays associated with relaying and low-cost implementation. However, the noise which is amplified simultaneously with desired signals would result in a low signal to interference plus noise power ratio. The layer 2 relay is Decode and Forward which means RF signals will be demodulated and decoded at the relay and then encoded and modulated again before being transmitted. Hence, the disadvantages of layer 1 relay could be overcome. But a delay will occur due to the process of encoding/decoding and modulation/demodulation. Moreover, radio control functions must be added between the transmitter and the receiver. The layer 3 relay adds a processing such as user-data concatenation and ciphering to retransmit user data on a radio interface between the process of demodulation/decoding and encoding/modulation. This method could not only increase throughput by removing inter-cell interference and noise, but also generate small impact on the standard specifications on implementation by incolving the same functions. Its drawback is obviously the processing delay which is similar to layer 2 relay and the delay caused by its unique processing.

Combining relay and SWIPT seems a viable solution to address some issues in single SWIPT system especially the low energy efficiency. In this architecture, a batteryless relay node could obtain both energy and information from the transmitter and the forward the signal to receiver by using the harvested energy. The performance of a layer 1 relay (AF) channel where time switching and power splitting are employed by the relay to power the link has been studied [19]. Then a similar work using a layer 2 relay (DF) is extended to analyse the throughput performance [20]. After that, a combining between dynamic decode-and-forward protocol and time switching SWIPT is studied [21]. A MIMO relay channel in which antenna switching technology is implemented in SWIPT is analysed to find a low-complexity solution for a binary knapsack problem [14]. The optimal beamforming in a full-duplex MIMO relay channel where time switching and power splitting are used is studied [22].

These studies above are mainly focused on the basic 3-node relay channel while a multiple source-destination power splitting SWIPT with decode-and-forward relay is analysed [23]. A network in which a share power splitting SWIPT MIMO relay node is applied for a two-way relay channel to exchange information by multiple communication pairs [24]. Combining multiple SWIPT relays with interference relay channel is studied when dedicated SWIPT relays are applied for multiple sources communication [25]. Apart from that, there are three main relay selection issues including distributed beamforming, relay selection depended on the Euclidean distance and the random relay selection [26].

1.5 Security in SWIPT

In SWIPT systems, signals may be received by unintended receivers because wireless channels are open which will lead to potential information leakage. A traditional solution is applying upper-layer encryption technique to ensure a secure communication which consumes much and results in a low energy efficiency. To address this problem, physical layer security has been proposed which means utilizing the physical characteristics of wireless channels such as interference, noise and fading and to guarantee a secure transmission [27]. For example, in SWIPT networks, a power signal aiming at transferring wireless power could confuse the eavesdropper. At the same time, the corresponding information signals are able to play the role of power source to enhance harvesting the energy at the receivers.

From the point of information theory, the entity of physical security is to maximize the secrecy rate which could be defined as the rate difference between the communication channel and the wiretap channel while the former means the channel from the source to the legitimate receiver and the latter means the channel from the same source to the eavesdropper [28]. So, an effective way to improve security is to increase the signals obtained by the legitimate receiver and decrease the eavesdropped signals simultaneously. Nevertheless, an important design requirement of SWIPT system is to enhance the wireless energy transfer efficiency which conflict with the objective of secure information transmission. Since the eavesdropper is unknown, the effort in increasing energy efficiency at a power receiver may lead to a loss of secrecy rate at a potential eavesdropper. If the trade-off is able to be divided into two different problems while one is to maximize the energy under a constraint of minimum required secrecy rate and another is to maximize the secrecy rate under the requirement of energy harvesting, these two could be solved jointly by applying spatial beamforming at a transmitter with multiple antennas [29]. When the channel state information is imperfect on account of limited channel state information feedback or the channels estimation errors, a robust beamforming scheme implemented in SWIPT systems with multiple antennas may be effective [30]. In addition, the combining of power signal and artificial noise to raise the amount of energy and confuse the eavesdroppers simultaneously by spatial beamforming could enhance the performance of SWIPT further [31]. Moreover, cognitive radio networks and multicarrier systems are also proved useful [32]-[33]. Generally, it is of low impossibility to come up with a universal alternative to enhance the performance for various SWIPT scenarios so applying different techniques according to kinds of scenarios with different power transfer, information transmission and signal eavesdropping schemes is necessary. There are several common effective physical-layer techniques in SWIPT networks.

1.5.1 Multiple Antenna Techniques

Multiple antennas could offer the spatial degrees of freedom to increase the received signals at both energy harvesting and information decoding and weaken the eavesdropped signals simultaneously so that the harvested energy and the secrecy rate could be improved [6]. For example, the eavesdroppers are not able to get any information if the transmitted signal is in the null space of the channels of eavesdroppers and are easily confused by the power signal.

1.5.2 Artificial Noise

Artificial noise is inspired by an idea that the secrecy performance could be improved by impairing the intercepted signal to reduce the interference [34]. Particularly in SWIPT, a friend jammer could send the artificial noise and does not need any power supply because it can harvest energy from the signal transmitted by the power transmitter. Transmitting artificial noise in the null space when the main channel state information is known. However, with unknown channel state information, adjusting transmit direction could draw a balance between the interference to the information and to the eavesdroppers.

1.5.3 Resource Allocation

Resources in SWIPT systems includes frequency, power, time and antenna, so the allocation of resources is of great significance in improving performance because it can affect the performance of eavesdroppers, energy harvesting and information decoding simultaneously. Since resource allocation depends on the channel state information heavily, designing an optimal resource allocation is hard when perfect channel state information could not be obtained [35].

2. System Mode

In this paper, a SWPIT system shown is Fig. 3 will be discussed. There is a transmitter with N_t antennas, a relay node with N_r antennas, an eavesdropper with single antenna and a user with single antenna. Power splitting technology is used at the user to separate the received signal into information decoding and energy harvesting with a splitting ratio η which means the information decoding obtains $(1-\eta)$ signal form the user while the energy harvesting gets η. In the following, the perfect channel state information is known at all nodes. In addition, the transmitter and the relay are both powered by batteries.

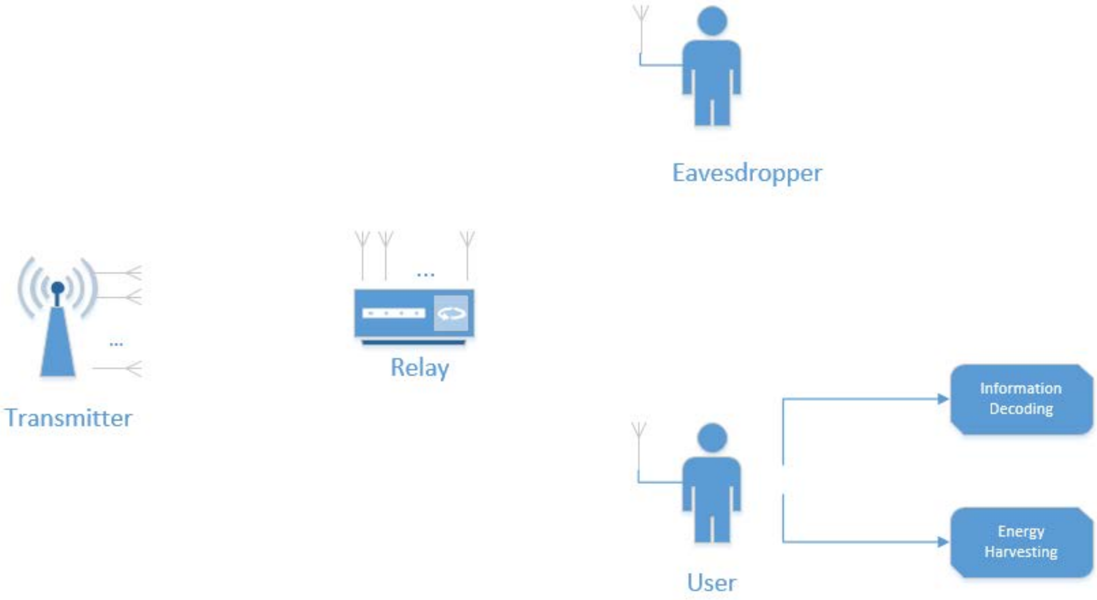


Figure 3. A SWIPT mode with a relay, a user and an eavesdropper

The transmitted signal vector is $\mathbf{w}$.

2.1 Relay Module

The received signal at relay node is given by

$$\mathbf{y} = \mathbf{H}\mathbf{w} + n \tag{1}$$

Where $\mathbf{H}$ is the channel vector between transmitter and relay and $\mathbf{n}$ is a complex Gaussian random vector with zero mean and covariance matrix **N**, i.e., $n \sim \mathbb{CN}(0, \mathrm{N})$.

The signal to noise ratio (SNR) at relay is given by

$$SNR_R = \frac{\left|\mathbf{H}^H \mathbf{w}\right|^2}{n^2} \tag{2}$$

To improve the secrecy rate, after receiving the signal from transmitter, the relay will produce an artificial noise $\mathbf{v}$ and sends it with the real signal $\mathbf{u}$ simultaneously.

2.2 Eavesdropper Module

Since there are two signals $\boldsymbol{v}$ and $\mathbf{u}$ being sent by the relay, the eavesdropper will receive two signals after wireless channel as well. So, the signal to interference and noise ratio (SINR) at eavesdropper could be given by

$$SINR_E = \frac{\left|\mathbf{t}^H \mathbf{u}\right|^2}{z^2 + |\boldsymbol{t}^H \mathbf{v}|^2} \tag{3}$$

Where $\mathbf{t}$ is the channel vector between the relay and the eavesdropper and z is additive Gaussian noises with zero mean and variance σ_1^2, i.e., $\mathrm{z} \sim \mathbb{N}(0, \sigma_1^2)$.

2.3 Energy Harvesting Module

Since there are two signals $\boldsymbol{v}$ and $\mathbf{u}$ being sent by the relay, the user will receive two signals after wireless channel as well. Additionally, there is a power splitting ratio η. So, the signal to interference and noise ratio (SINR) at information decoding could be given by

$$SINR_I = \frac{\left|\mathbf{g}^H \mathbf{u}\right|^2 (1-\eta)}{m^2 + |\mathbf{g}^H \mathbf{u}|^2 (1-\eta)} \tag{4}$$

Where $\mathbf{g}$ is the channel vector between the relay and the user and m is additive Gaussian noises with zero mean and variance σ_2^2, i.e., $\mathrm{z} \sim \mathbb{N}(0, \sigma_2^2)$.

3. Problem Formulation

The system design objective is to minimize the energy consumption while guaranteeing secure communication. Following is the resource allocation design:

Resource Allocation Design:

$$\underset{\mathbf{w},\mathbf{u},\mathbf{v}}{\text{minimize}} \quad \|\mathbf{w}\|^2 + \|\mathbf{u}\|^2 + \|\mathbf{v}\|^2$$

$$\text{s.t.} \quad \text{C1:} \quad SINR_E \leq \mu_{max}\,, \tag{5}$$

$$\text{C2:} \quad SNR_R \geq \mu_{req}\,, \tag{6}$$

$$\text{C3:} \quad SINR_I \geq \mu_{req}\,. \tag{7}$$

Where constant μ_{max} in constraint C1 is the maximum signal to interference and noise at the eavesdropper that can be accepted and μ_{req} is the minimum requirement of signal to interference and noise at the relay and the user. Since $SINR_E$, SNR_R and $SINR_I$ have been calculated in (2), (3) and (4), the resource allocation design can be rewritten as following:

Resource Allocation Design:

$$\underset{\mathbf{w},\mathbf{u},\mathbf{v}}{\text{minimize}} \quad \|\mathbf{w}\|^2 + \|\mathbf{u}\|^2 + \|\mathbf{v}\|^2$$

$$\text{s.t.} \quad \text{C1:} \quad \frac{\left|\mathbf{t}^H\mathbf{u}\right|^2}{z^2+\left|\boldsymbol{t}^H\mathbf{v}\right|^2} \leq \mu_{max}\,, \tag{8}$$

$$\text{C2:} \quad \frac{\left|\mathbf{H}^H\mathbf{x}\right|^2}{\boldsymbol{n}^2} \geq \mu_{req}\,, \tag{9}$$

$$\text{C3:} \quad \frac{|\mathbf{g}^H\mathbf{u}|^2(1-\eta)}{m^2+|\mathbf{g}^H\mathbf{u}|^2(1-\eta)} \geq \mu_{req}\,. \tag{10}$$

4. Solution for the Problem

$$\underset{\mathbf{w},\mathbf{u},\mathbf{v}}{\text{minimize}} \quad \|\mathbf{w}\|^2 + \|\mathbf{u}\|^2 + \|\mathbf{v}\|^2$$

$$\text{s.t.} \quad \text{C1:} \quad \frac{\left|\mathbf{H}^H\mathbf{w}\right|^2}{n^2} \geq \mu_{req}\,, \tag{11}$$

$$\text{C2:} \quad \frac{\left|\mathbf{t}^H\mathbf{u}\right|^2}{z^2+\left|\boldsymbol{t}^H\mathbf{v}\right|^2} \leq \mu_{max}\,, \tag{12}$$

$$\text{C3:} \quad \frac{\left|\mathbf{g}^H\mathbf{u}\right|^2(1-\eta)}{m^2+\left|\mathbf{g}^H\mathbf{v}\right|^2(1-\eta)} \geq \mu_{req}\,. \tag{13}$$

The primal problem formulation is:

Actually, this is an optimization problem with constrains. Since its objective function and three constrains are all non-convex, the primal problem is obviously non-convex optimization problem. To make solving easily, it is necessary to transform this problem to convex optimization problem. Generally, there are two mains methods for the transformation [36]-[37]. One is discards some constrains to make the new feasible region convex which contains the primal region, the another is modifying the objective function to be convex.

In this problem, it can be found that the non-convexity is caused by the beamforming vector $\mathbf{w}$. Therefore, semi-definite programming (SDP) relaxation is an efficient way to remove the non-convexity element of this problem. Firstly, rewrite $\|\mathbf{w}\|^2$:

$$\|\mathbf{w}\|^2 = \boldsymbol{w}^H\boldsymbol{w} = Tr(\boldsymbol{w}^H\boldsymbol{w}) = Tr(\boldsymbol{w}\boldsymbol{w}^H) = Tr(\boldsymbol{W}) \quad while\ Rank(\boldsymbol{W}) = 1 \tag{14}$$

That means when the rank of $\boldsymbol{W}$ equals to 1, $\|\mathbf{w}\|^2$ could be transformed to a convex expression $Tr(\boldsymbol{W})$**.**

The transformation is suitable for $\mathbf{u}$ and $\mathbf{v}$.

Hence, the problem can be converted to:

$$\underset{\mathbf{W},\mathbf{U},\mathbf{V}}{\text{minimize}} \quad Tr(\boldsymbol{W}) + Tr(\boldsymbol{U}) + Tr(\boldsymbol{V})$$

$$\text{s.t. C1:} \quad \frac{Tr(t^H \boldsymbol{U})}{z^2 + Tr(t^H \boldsymbol{V})} \leq \mu_{max} \,, \tag{15}$$

$$\text{C2:} \quad \frac{Tr(H^H \boldsymbol{W})}{n^2} \geq \mu_{req} \,, \tag{16}$$

$$\text{C3:} \quad \frac{Tr(g^H \boldsymbol{U})(1-\eta)}{m^2 + Tr(g^H \boldsymbol{V})(1-\eta)} \geq \mu_{req} \,, \tag{17}$$

$$\text{C4:} \quad \mathbf{W} \geq 0 \,, \tag{18}$$

$$\text{C5:} \quad Rank(\boldsymbol{W}) \leq 1 \,, \tag{19}$$

$$\text{C6:} \quad \mathbf{U} \geq 0 \,, \tag{20}$$

$$\text{C7:} \quad Rank(\boldsymbol{U}) \leq 1 \,, \tag{21}$$

$$\text{C8:} \quad \mathbf{V} \geq 0 \,, \tag{22}$$

$$\text{C9:} \quad Rank(\boldsymbol{V}) \leq 1 \,. \tag{23}$$

Since **u** and **v** real signal and artificial noise transmitted from the relay, the constrains (20) to (23) can be removed.

And if we remove the constrain (19), this problem would become a convex optimization problem. Its standard formulation is:

$$\underset{\mathbf{W},\mathbf{U},\mathbf{V}}{\text{minimize}} \quad Tr(\boldsymbol{W}) + Tr(\boldsymbol{U}) + Tr(\boldsymbol{V})$$

$$\text{s.t. C1:} \quad \mu_{req} n^2 - Tr(H^H \boldsymbol{W}) \leq 0 \,, \tag{24}$$

$$\text{C2:} \quad Tr(t^H \boldsymbol{U}) - \mu_{max}(z^2 + Tr(t^H \boldsymbol{V})) \leq 0 \,, \tag{25}$$

$$\text{C3:} \quad \mu_{req}\left(m^2 + (1-\eta) Tr(g^H \boldsymbol{V})\right) - (1-\eta)\, Tr(g^H \boldsymbol{U}) \leq 0 \,, \tag{26}$$

$$\text{C4:} \quad -\mathbf{W} \leq 0 \,. \tag{27}$$

To analyse and solve this problem, the KKT conditions are useful [38]-[42].

Now we can obtain the Lagrangian function as:

$$\mathcal{L} = Tr(\boldsymbol{W}) + Tr(\boldsymbol{U}) + Tr(\boldsymbol{V}) + \lambda_1 \left(\mu_{req} n^2 - Tr(H^H \boldsymbol{W})\right) + \lambda_2 (Tr(t^H \boldsymbol{U}) - \mu_{max}(z^2 + Tr(t^H \boldsymbol{V}))) + \lambda_3 (\mu_{req}\left(m^2 + (1-\eta) Tr(g^H \boldsymbol{V})\right) - (1-\eta)\, Tr(g^H \boldsymbol{U})) - Tr(\boldsymbol{Y}\boldsymbol{W}), \tag{28}$$

where $\boldsymbol{Y}$ is a dual variable related to (27).

Then, let $\frac{\partial \mathcal{L}}{\partial \boldsymbol{W}} = 0$

$$\frac{\partial \mathcal{L}}{\partial \boldsymbol{W}} = \boldsymbol{I} + \lambda_1 \left(-H^H\right) - \boldsymbol{Y} = 0 \tag{29}$$

Therefore, $\boldsymbol{Y} = -\lambda_1 H^H + \boldsymbol{I}$. (30)

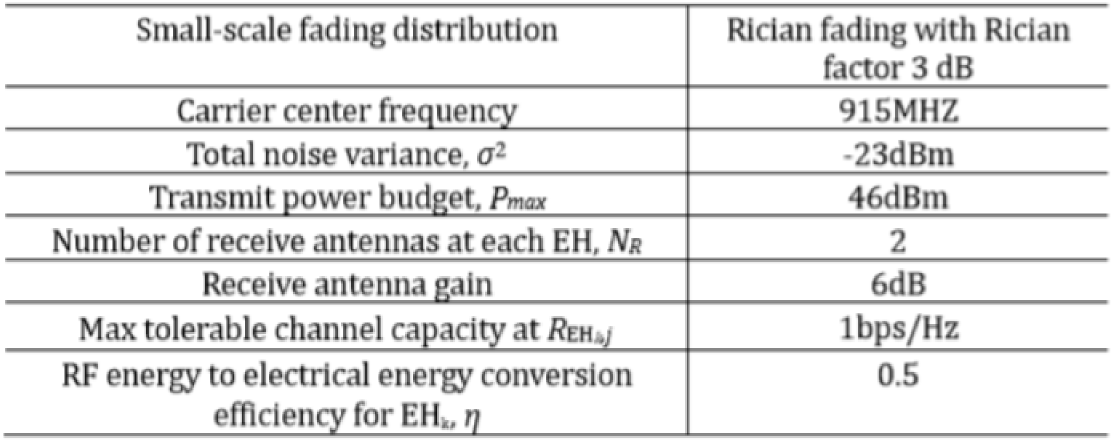
Easily we can get $rank(\boldsymbol{I}) = N_{\boldsymbol{T}}$**.** And according to the property of rank $rank(\boldsymbol{a} + \boldsymbol{b}) \leq rank(a) + rank(b)$, we could obtain

$$rank(\boldsymbol{Y}) = rank\left(-\lambda_1 H^H + \boldsymbol{I}\right) \leq rank\left(-\lambda_1 H^H\right) + rank(\boldsymbol{I}) = N_{\boldsymbol{T}} - 1\,. \tag{31}$$

Hence, $Rank(\boldsymbol{W}) \leq 1$. That means (19) could be removed. In this situation the convex optimization problem above has the same solution as the primal formulation and could be easily solved [43].

5. Simulation Results

The simulation results of this SWIPT relaying system will be analysed in this part. The simulation is running via MATLAB and some related parameters are shown in Table 1.



Small-scale fading distribution	Rician fading with Rician factor 3 dB
Carrier center frequency	915MHZ
Total noise variance, σ^2	-23dBm
Transmit power budget, P_{max}	46dBm
Number of receive antennas at each EH, N_R	2
Receive antenna gain	6dB
Max tolerable channel capacity at $R_{\mathrm{EH}_k,j}$	1bps/Hz
RF energy to electrical energy conversion efficiency for EH_k, η	0.5

Table 1. Simulation parameters

Finally, we obtain two significant figures to study. Figure 4 shows the relationship between the average total power and the minimum required. In general, with the increasing of minimum requirement of SINR, the average total transmit power will be also increased. However, due to the difference of the number of antennas of transmitter, the average power is different. That means more transmitter antennas could achieve higher energy efficiency.

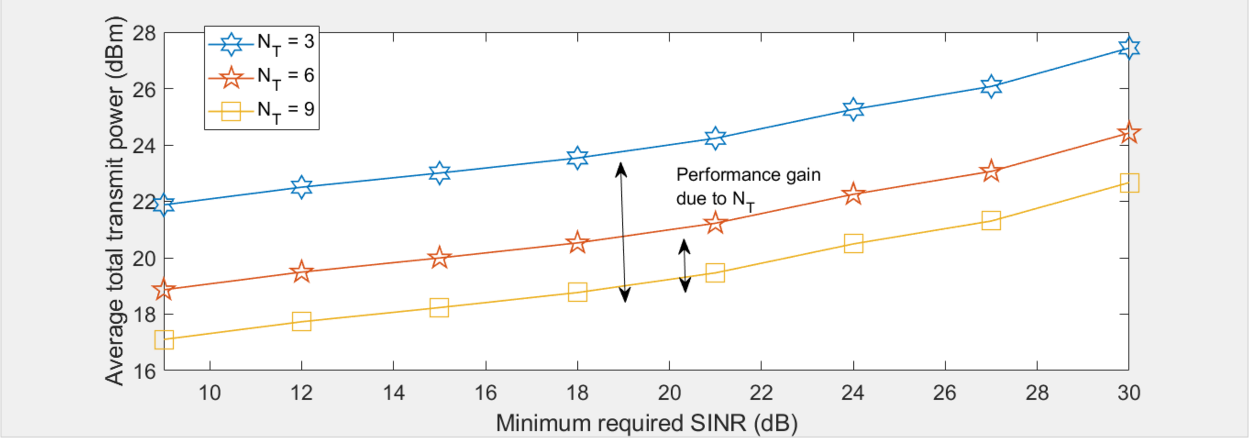


Figure 4. Average total transmit power versus minimum required SINR

Figure 5 illustrates the average total transmit power versus maximum tolerable SINR at eavesdropper. It is obvious that the average total transmit power will decrease due to the growth of maximum tolerable SINR at eavesdropper. In addition, for a given maximum tolerable SINR, we can save power if we use more transmitter antennas.

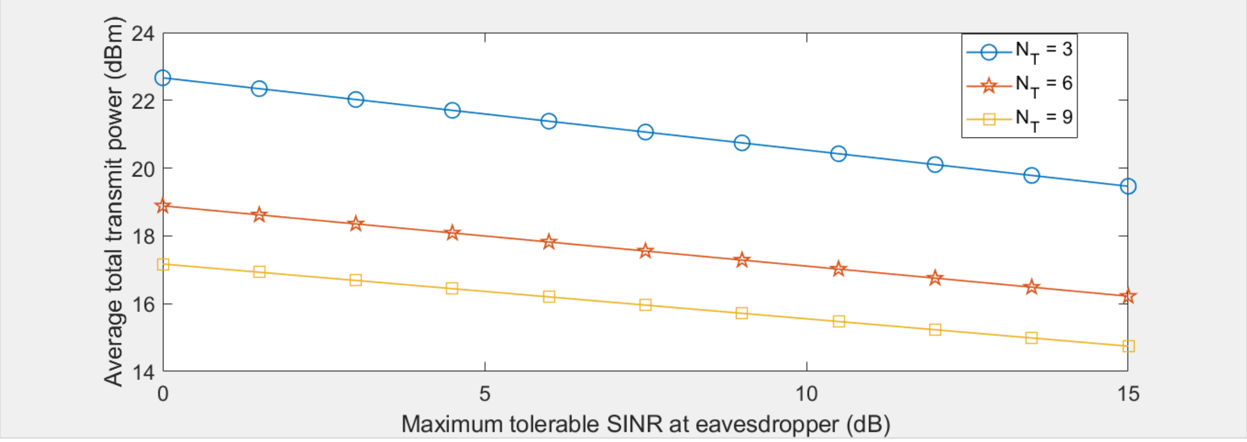


Figure 5. Average total transmit power versus maximum tolerable SINR at eavesdropper

6. Conclusion

In this paper, we discuss the power-efficient design for secure SWIPT relaying systems. The main purpose of this system is to transmit information and energy simultaneously on the premise of security and energy efficiency. Based on the system model, a problem formulation is presented. Some mathematical methods are used to solve this optimization problem. In the end the simulation is processed and some results are given to demonstrate the solution and trade-off of this system.

7. References

[1] D. Ng, T. Duong, C. Zhong, and R. Schober, Wireless Information and Power Transfer: Theory and Practice, ser. Wiley - IEEE, 2019.

[2] V. W. Wong, R. Schober, D. W. K. Ng, and L.-C. Wang, Key Technologies for 5G Wireless Systems. Cambridge, U.K.: Cambridge Univ. Press, 2017.

[3] D. W. K. Ng, E. S. Lo, and R. Schober, "Energy-efficient resource allocation in OFDMA systems with large numbers of base station antennas," vol. 11, no. 9, pp. 3292-3304, 2012.

[4] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. Schober, "An overview of sustainable green 5G networks," vol. 24, no. 4, pp. 72-80, 2017.

[5] 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," vol. 52, no. 11, pp. 104-110, 2014.

[6] X. Chen, Z. Zhang, H. Chen, and H. Zhang, "Enhancing wireless information and power transfer by exploiting multi-antenna techniques," vol. 53, no. 4, pp. 133-141, 2015.

[7] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: Opportunities and challenges," vol. 53, no. 4, pp. 117-125, 2015.

[8] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," vol. 13, no. 1, pp. 418-428, 2014.

[9] C. Boyer and S. Roy, "—Invited Paper—Backscatter Communication and RFID: Coding, Energy, and MIMO Analysis," vol. 62, no. 3, pp. 770-785, 2014.

[10] A. Marincic and Systems, "Nikola tesla and the wireless transmission of energy," no. 10, pp. 4064-4068, 1982.

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

[12] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," vol. 12, no. 5, pp. 1989-2001, 2013.

[13] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless information and power transfer: Energy efficiency optimization in OFDMA systems," vol. 12, no. 12, pp. 6352-6370, 2013.

[14] I. Krikidis, S. Sasaki, S. Timotheou, and Z. Ding, "A low complexity antenna switching for joint wireless information and energy transfer in MIMO relay channels," vol. 62, no. 5, pp. 1577-1587, 2014.

[15] W. Wang, L. Li, Q. Sun, and J. Jin, "Power allocation in multiuser MIMO systems for simultaneous wireless information and power transfer," in *Vehicular technology conference (VTC Fall), 2013 IEEE 78th*, 2013: IEEE, pp. 1-5.

[16] B. Koo and D. J. I. C. L. Park, "Interference alignment and wireless energy transfer via antenna selection," vol. 18, no. 4, pp. 548-551, 2014.

[17] S. Timotheou, I. Krikidis, G. Zheng, and B. W. C. Ottersten, "Beamforming for MISO interference channels with QoS and RF energy transfer," vol. 13, no. 5, pp. 2646-2658, 2014.

[18] M. Iwamura, H. Takahashi, and S. J. N. D. T. J. Nagata, "Relay technology in LTE-advanced," vol. 12, no. 2, pp. 29-36, 2010.

[19] Y. Sun, D. W. K. Ng, Z. Ding and R. Schober, "Optimal Joint Power and Subcarrier Allocation for Full-Duplex Multicarrier Non-Orthogonal Multiple Access Systems," in IEEE Trans. on Commun., vol. 65, no. 3, pp. 1077-1091, March 2017.

[20] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Throughput and ergodic capacity of wireless energy harvesting based DF relaying network," in *Communications (ICC), 2014 IEEE International Conference on*, 2014: IEEE, pp. 4066-4071.

[21] K. Ishibashi, "Dynamic harvest-and-forward: New cooperative diversity with RF energy harvesting," in *Wireless Communications and Signal Processing (WCSP), 2014 Sixth International Conference on*, 2014: IEEE, pp. 1-5.

[23] C. Zhong, H. A. Suraweera, G. Zheng, I. Krikidis, and Z. Zhang, "Wireless information and power transfer with full duplex relaying," vol. 62, no. 10, pp. 3447-3461, 2014.

[23] Z. Ding, S. M. Perlaza, I. Esnaola, and H. V. Poor, "Power allocation strategies in energy harvesting wireless cooperative networks," vol. 13, no. 2, pp. 846-860, 2014.

[24] F. Wang, X. Wang, Z. Fang, and R. Zhang, "Optimal beamforming design for two-way relaying with simultaneous energy harvesting," in *Communications, Control and Signal Processing (ISCCSP), 2014 6th International Symposium on*, 2014: IEEE, pp. 331-335.

[25] H. H. Chen, Y. Li, Y. Jiang, Y. Ma, and B. Vucetic, "Distributed power splitting for SWIPT in relay interference channels using game theory," vol. 14, no. 1, pp. 410-420, 2015.

[26] Z. Ding, I. Krikidis, B. Sharif, and H. V. Poor, "Wireless information and power transfer in cooperative networks with spatially random relays," vol. 13, no. 8, pp. 4440-4453, 2014.

[27] X. Chen, C. Zhong, C. Yuen, and H. H. Chen, "Multi-antenna relay aided wireless physical layer security," vol. 53, no. 12, pp. 40-46, 2015.

[28] P. K. Gopala, L. Lai, and H. El Gamal, "On the secrecy capacity of fading channels," vol. 54, no. 10, pp. 4687-4698, 2008.

[29] L. Liu, R. Zhang, and K.-C. Chua, "Secrecy wireless information and power transfer with MISO beamforming," in *Global communications conference (GLOBECOM), 2013 IEEE*, 2013: IEEE, pp. 1831-1836.

[30] R. Feng, Q. Li, Q. Zhang, and J. Qin, "Robust secure transmission in MISO simultaneous wireless information and power transfer system," vol. 64, no. 1, pp. 400-405, 2015.

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

[32] X. Huang, Q. Li, Q. Zhang, and J. Qin, "Power allocation for secure OFDMA systems with wireless information and power transfer," vol. 50, no. 3, pp. 229-230, 2014.

[33] 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," vol. 65, no. 5, pp. 3166-3184, 2016.

[34] M. Tian, X. Huang, Q. Zhang, and J. Qin, "Robust AN-aided secure transmission scheme in MISO channels with simultaneous wireless information and power transfer," vol. 22, no. 6, pp. 723-727, 2015.

[35] X. Chen, D. W. K. Ng, and H. H. Chen, "Secrecy wireless information and power transfer: Challenges and opportunities," 2015.

[36] A. B. Gershman, N. D. Sidiropoulos, S. Shahbazpanahi, M. Bengtsson, and B. Ottersten, "Convex optimization-based beamforming," *IEEE Signal Processing Magazine,* vol. 27, no. 3, pp. 62-75, 2010.

[37] S. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge university press, 2004.

[38] W. Dinkelbach, "On nonlinear fractional programming," *Management science,* vol. 13, no. 7, pp. 492-498, 1967.

[39] M. Bengtsson and B. Ottersten, "Optimal Downlink BeamformingUsing Semidefinite Optimization," in *37th Annual Allerton Conference on Communication, Control, and Computing*, 1999, pp. 987-996.

[40] W.-K. K. Ma, "Semidefinite Relaxation of Quadratic Optimization Problems and Applications," *IEEE Signal Processing Magazine,* vol. 1053, no. 5888/10, 2010.

[41] J. F. Sturm, "Using SeDuMi 1.02, a MATLAB toolbox for optimization over symmetric cones," *Optimization methods and software,* vol. 11, no. 1-4, pp. 625-653, 1999.

[42] K.-C. Toh, M. J. Todd, and R. H. Tütüncü, "SDPT3—a MATLAB software package for semidefinite programming, version 1.3," *Optimization methods and software,* vol. 11, no. 1-4, pp. 545-581, 1999.

[43] M. Grant, S. Boyd, and Y. Ye, "CVX: Matlab software for disciplined convex programming," ed, 2008.

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

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

[46] E. Boshkovska, A. Koelpin, D. W. K. Ng, N. Zlatanov, and R. Schober, “Robust beamforming for SWIPT systems with non-linear energy harvesting model,” in Signal Processing Advances in Wireless Communications (SPAWC), 2016 IEEE 17th International Workshop on. IEEE, 2016, pp. 1–5. 22

[47] E. Boshkovska, D. W. K. Ng, L. Dai, and R. Schober, “Power-Efficient and Secure WPCNs With Hardware Impairments and Non-Linear EH Circuit,” IEEE Transactions on Communications, 2017.

[48] S. Leng, D. W. K. Ng, N. Zlatanov, and R. Schober, “Multi-objective resource allocation in full-duplex SWIPT systems,” in Communications (ICC), 2016 IEEE International Conference on. IEEE, 2016, pp. 1–7.

[49] D. W. K. Ng, E. S. Lo, and R. Schober, “Dynamic Resource Allocation in MIMO-OFDMA Systems with Full-Duplex and Hybrid Relaying,” IEEE Transactions on Communications, vol. 60, no. 5, pp. 1291–1304, 2012.

[50] C. Wang, H.-M. Wang, D. W. K. Ng, X.-G. Xia, and C. Liu, “Joint Beamforming and Power Allocation for Secrecy in Peer-to-Peer Relay Networks,” IEEE Transactions on Wireless Communications, vol. 14, no. 6, pp. 3280–3293, 2015.

[51] D. W. K. Ng, Y. Wu, and R. Schober, “Power Efficient Resource Allocation for Full-Duplex Radio Distributed Antenna Networks,” IEEE Transactions on Wireless Communications, vol. 15, no. 4, pp. 2896–2911, 2016.

[52] D. W. K. Ng, E. S. Lo, and R. Schober, “Energy-efficient resource allocation in multiuser

OFDM systems with wireless information and power transfer," in Wireless Communications and Networking Conference (WCNC), 2013 IEEE. IEEE, 2013, pp. 3823–3828.

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

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

[55] H.-M. Wang, C. Wang, and D. W. K. Ng, "Artificial Noise Assisted Secure Transmission Under Training and Feedback," IEEE Transactions on Signal Processing, vol. 63, no. 23, pp. 6285–6298, 2015.23

[56] Z. Wang, D. W. K. Ng, V. W. Wong, and R. Schober, "Transmit beamforming for QoE improvement in C-RAN with mobile virtual network operators," in Communications (ICC), 2016 IEEE International Conference on. IEEE, 2016, pp. 1–6.

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

[58] C. Guo, Y. Cui, D. W. K. Ng, and Z. Liu, "Power-Efficient Multi-Quality Multicast Beamforming Based on SVC and Superposition Coding," in IEEE Global Communications Conference (GLOBECOM), 2017.

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

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