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Power-Efficient Resource Allocation of SWIPT-Relaying Systems

By

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Abstracts

The new challenge in the era of wireless communication networks nowadays is that enabling charging terminals from external energy sources in the ambient environment instead of replacing batteries. A promising method to harvest energy is wireless power transfer (WPT) which becomes feasible because of the nature of electromagnetic radiation. In this case, a particularly new and interesting challenge triggers people's attention on the situation that source performs simultaneous wireless information and power transfer (SWIPT).For example, not only strong signals will enhance the efficiency in power transfer but it also increases the possibility of being eavesdropped and interfered. It is thus been seen that SWIPT technology will be treated as a crucial technology in the development of Internet-of-things (IoT) in the next generation of communication system

In this paper, we introduce a beamforming design for simultaneous wireless information and power transfer (SWIPT) system. The objective of the design is to minimize the energy consumption of the system. This design will be formulated as a non-convex optimization problem with the consideration of the quality of service (QoS) and security as well as the minimum power consumption. The secrecy performance in this paper is maintained by injecting an artificial noise which performs as one method of jamming. We used semidefinite programming relaxation (SDR) to achieve the optimal solution of problem formulation. The simulation results indicates that how the changes of certain requirements such as tolerable SINR at eavesdropper or minimum required harvested power affects the power consumption.

Keywords: SWIPT, Beamforming, Relay Network, Physical layer security

Abbreviation

SWIPT	Simultaneous Wireless Information and Power Transfer
WIT	Wireless Information Transfer
WET	Wireless Energy Transfer
RF	Radio Frequency
EM	Electromagnetic Wave
PS	Power Splitting
TS	Time Splitting
SNR	Signal to Noise Ratio
SINT	Signal to Interference and Noise Ratio
BS	Base Station
AN	Artificial Noise
CSI	Channel State Information
IoT	Internet of Things
QoS	Quality of Service
MIMO	Multiple-Input Multiple-Output
PHY	Physical Layer
IR	Information decoding receiver
ER	Energy harvesting receiver

Introduction

In recent decades, the rapid growth of wireless communication technology continually causes increasingly evolutions in wireless communication devices and sensors. There are varies related practical applications developing furtherly such as in building smart city, making proper management in era of energy or safety, even in inventing e-health system. Sensor modules in terms of wireless communication have been widely used in various areas especially in the field of the Internet of Things (IoT). As it can be intangibly integrated into some objectives such as clothing, vehicles, or even human being for medical purposes, the demand for energy-supplied and proper energy-management methods significantly increases. However, the traditional battery-powered charging method seems not to be applied because of limited energy storage capacity. In addition, not only the cost of frequent replacement of the battery is relatively high, but also wired or manual recharging sometimes is difficult to access or even impossible to some wireless communication devices such as a biomedical implant. Thus, to provide a self-sustainable and secure as well as high-speed communication with the guarantee of the quality of service (QoS) becomes a considerable problem waiting to be solved to the next generation of the communication system.

As the performance of wireless communication devices is seriously restricted by its finite energy. Solar, geothermal heat and wind are the environmental source of harvesting energy which becomes a promising method to ensure the performance and extend the lifetime of wireless communication system. Although using renewable energy to generate electricity is self-sustainable and environmental-friendly, another limitation from this approach cannot be ignored is that conventional natural energy sources are not manageable since it usually varies with the change of climate and location. This will lead to serious problems on mobile devices such as discontinuous communication and restricted mobility. In addition, it is unlikely to maintain the stability of communication networks and guarantee the quality of service (QoS) as the energy of devices origin from uncontrollable natural sources.

Comparing with harvesting energy from renewable sources, wireless power transfer (WPT) provides another approach to harvest energy for energy-limited devices aiming to build stable and efficient communication networks [1-3]. Electromagnetic (EM) radiation in radio frequency (RF) band in the ambient background around antennas is a potential source for energy harvesting. RF signals carry both information and energy simultaneously, which enables the possibility of simultaneous wireless information and power transfer (SWIPT). Therefore, SWIPT as a new technology attracts attention from both academia and industry to have continuous and unstoppable study [4-20].

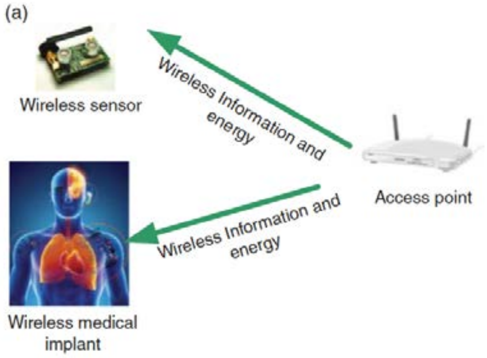

Figure1: Simple operation of SWIPT system

Background

The concept of wireless power transfer (WPT) was first introduced by Nikola Tesla in 1900s. It aimed to address problems in high-power-consumption applications. But the processes of development of WPT was interrupt as it imposed adverse impacts on public health due to the radiation of electromagnetic (EM) waves. It attracts people's attention again because of the development of silicon technology and the wide use of IoT products. WPT networks make it possible to overcome the huge obstacles of IoT technology via wireless powered sensors for the purpose of further development of smart cities.

There are three existing technologies of supplying energy which are magnetic resonant coupling inductive coupling and RF-based WPT.. Inductive coupling and magnetic resonant coupling are dependent on near-field EM waves which cannot ensure the mobility and stability of wireless communication devices because of limited charging distance. However, RF-based WPT rely on the far-field characteristics of EM waves, which aims to relative long distance of wireless power charging and data transfer. In practice, RF energy can be harvested by receivers from ambient background of transmitter such as base station, Wi-Fi access points with the regulation of radiation of RF signal to meet the standardized safety level of people. Moreover, the power of RF signals can not only supply small wireless sensor but also able to power some relatively large power application such as digital clocks, which can reduce the replacement of battery. In practice, designers and researchers make efforts to design system model and algorithms of resource allocation and hence boost the efficiency and performance. The tradeoff between wireless power transfer and wireless information transfer lead to various optimization algorithms. Traditional techniques might not be suitable to new technology as introduced. An urgent requirement for the improvement of both grand new hardware such as circuit design and software such as new signal processing algorithms and system model for the purpose of obtaining potential possibility of SWIPT system of wireless communication networks.

Receivers Structure of SWIPT

The process of information decoding and energy harvesting in SWIPT have to be separated, which means that these two processes cannot be operated in same received signal in order to enable SWIPT. In practice, energy is harvested by energy harvesting circuits as received signals in RF domain which means that the process of energy harvesting will have negative impacts on modulated information. Also the signal processing of information decoding always happens in the digital baseband, which cannot facilitate energy harvesting process. Particularly in SWIPT system, the receiver is supposed to separate the energy harvesting and information decoding processes. There are existing some viable techniques to split RF signal into two parts, one for energy harvesting and the other one for information decoding. In the following, several techniques will be proposed to achieve signal-splitting in different domains (time, power, antenna, space).

Time Switching Receiver

Time Switching (TS) receiver structure enable the receiver switches process between information decoding and energy harvesting in time. In this case, the process of TS will be either information decoding or energy harvesting. As the signal splitting is occurred in time domain, the requirement of the implementation of hardware of TS is less complex whilst the higher requirement of data selecting in time synchronization and information scheduling.

Power Splitting Receiver

The power splitting (PS) technique enable SWIPT by splitting signals in two streams in one time slot. The power will be received and divided into two streams with different power level dominating by power splitting ratio before active analog or digital signal processing. Then energy harvester and information decoder will receive splitting power at each antenna respectively. PS technique can achieve instantaneous SWIPT as the signal it receives will be used for both information decoding and power transfer in the same time. The power splitting ratio can be optimized at antennas individually thus to balance the achievable information rate and energy harvesting efficiency. In conclusion, PS receiver structure is likely to apply with signal with delay constraints and it has higher complexity in hardware implementation comparing to TS receiver structure.

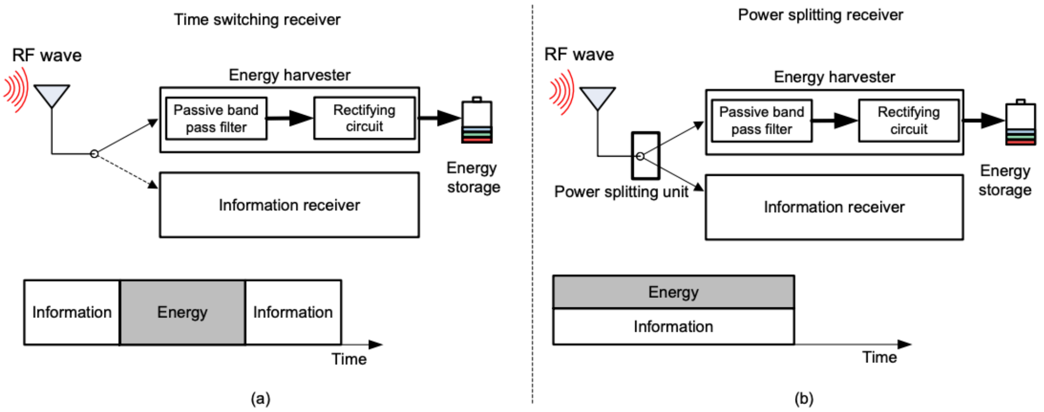

Figure2: (a) shows the detailed structure of time switching receiver (b) shows the detailed structure of power splitting receivers

Separated Receiver

In separated receiver structure, information decoder and energy harvester are implemented with individual receiver with different antennas. Therefore, separated receiver structure are easier to be implemented via using off-the-shelf components for each receiver. The optimization of separated receiver will mainly focus on the tradeoff between WIT and WPT depending channel state information (CSI) and feedback from receivers to the joint multiple-antennas transmitters. In other words, minimum required amount of energy received by energy harvesting receiver will determined the working operation of information decoder.

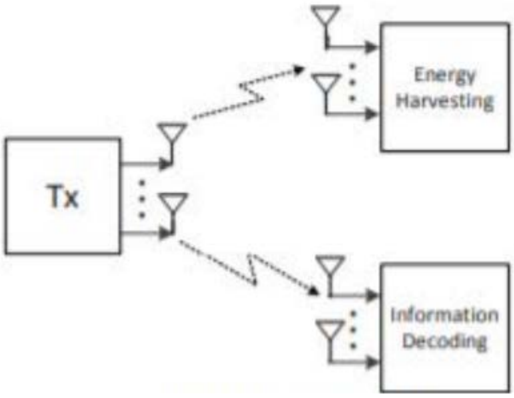

Figure3: Receiver structure of separate receiver

Challenges in SWIPT

Despite the fact that SWIPT brings tangible convenience to energy harvesting technology, there are some challenges that could not be ignored when integrating SWIPT technology into wireless communication system. In [21] and [22] show that the basic perspective about the tradeoff of WET and WIT in the consideration of channel fading and frequency selection. The author in [23-26] shows the tradeoff regions on rate-energy for Multiple-input multiple-output (MIMO) system. Although considerable investigation has been explored before, the efficiency of wireless power transfer remains low. Significantly, the path loss of channels attenuates wireless signals obviously which causes only small fraction of total power will be harvested at end-users. Hence, people start to combine other technology cooperating with SWIPT system in order to improve the power transfer efficiency. Multiple antenna is the most frequently used technology for this purpose. Especially, to increase spatial degree of freedom in multiple antennas, system will obtain larger wireless energy which can be transferred more accurately and specifically into desired receivers, which improves the efficiency of energy transferring. Additionally, existing technology such as network protocols, resource allocation algorithms and receiver structures were designed for conventional communication system as it serves and optimizes for pure data communication. The related technologies will not sufficiently meet the standard requirement to implement SWIPT practically due to the nature of beamforming.

Security in SWIPT

In SWIPT system, in order to enable energy harvesting at power-limited receiver, one approach is to enhace the energy of the information carrying signals. Another fact of improving efficiency is that energy harvesting receivers are normally situated closer distance to transmitter than information decoding receivers. Both of those method will increase the possibility of eavesdropping due to the relatively high transmit power and the characteristics of broadcasting. Furthermore, the increasing number of devices used for wireless energy harvesting also exerts negative impacts on communication networks as it exceeds the capacity of channel [26-36]. Generally, cryptographic encryption algorithms are exploiting at the application layer to ensure the security of communication networks. In spite of that, traditional algorithms were designed with the basic idea of perfect key management and distribution while not applicable in future SWIPT system as massive wireless sensor nodes will be applied in the future wireless communication networks. There comes to an alternative solution named physical (PHY) security to assist with cryptographic encryption algorithms to guarantee secure communication. PHY security is usually operated with exploring unique physical characteristics of wireless channels such as fading, noise and interference to prevent communication between wireless devices from eavesdropping. It has been revealed that in wiretap channel, perfectly secure information with one source and one destination if the conditions of source-to-destination channel overweight source-to-eavesdropper channel [37]. This triggers the researches on multiple-antenna beamforming design in SWIPT system by taking PHY security into account [38-44]. In [45], author analysis scenarios of perfect CSI and imperfect CSI with subjective of minimizing total transmit power in secure communication system. Additionally, a beamforming design for maximize secrecy rate in SWIPT system has been shown in [46]. Although there are several evidences show that the process of energy harvesting is non-linear because of the rectifying circuit process during RF energy-to-direct current power conversion, I assume the process of energy harvesting is linear for simplification. Maximize the energy efficiency under a constraint of minimum required secrecy rate or maximize secrecy rate with constraint of minimum harvesting energy could be solved together by applying spatial degree of freedom at transmitter with multiple antennas with beamforming design [47].

Secrecy Rate

Then definition of secrecy rate representing actual data rate received at IR is given by

$$\text{Secrecy Rate} = [A - B]^{+} \qquad (1)$$

Where A is the capacity of the channel between transmitter and targeted IR while B denotes the capacity between the common transmitter and the eavesdropper.

As what has been mentioned in introduction, due to the high carrier frequency of RF signal, path loss will attenuate the power and quality of received signal. One means to avoid this is to control the size of transmit antennas in a reasonable range. Hence, increasing the power of information signal on purpose to compensate the path loss for more efficient WPT, which will lead to an increase of susceptibility of eavesdropping by ERs as the nature of broadcast between channels and channels will raise security problems. Communication security issues have become the main challenge when implementing wireless communication systems. In order to address the problem with this, large amount of approaches have been proposed such as energy beamforming and artificial jamming. The key to ensure a secure communication with the considering of treating energy harvesting receiver as potential eavesdropper is to inject ideal artificial noise (AN) via multiple antennas to attenuate the quality of channel between transmitter and potential eavesdropper.

Artificial Noise

Interference Management

In traditional communication system, it is highly recognized that co-channel interference (CCI) is the major obstacle which limit the overall performance of system and efficient resources allocation. But it seems to have positive effects on SWIPT system since the interference can act as a supportive source of energy and can be accepted by receivers. Therefore, injecting artificial interference to wireless communication system sometimes is beneficial to overall system performance in particular when there is insufficient energy supporting the basic operations for receivers. At that time, one compromise is to have less quality of information decoding but better performance on energy harvesting.

It is thus been seen that jamming can be applied when potential eavesdropper tries to intercept confidential information. In many cases, jammers will cause the loss of power of wireless devices while in SWIPT system it will be encouraged for the reason that jammer as additional nodes in entire network can be powered wirelessly by RF signals at the ambient environment of receivers. Then system engineers can concentrate on optimizing the efficiency of jam-and-harvest by adjusting node position of jammer and energy harvester aiming to boost entire performance of system.

Artificial noise (AN) is one of the possible solutions to improve the secrecy performance [48]. As jamming is an important means to interfere with eavesdroppers. Optimized AN will not make negative influence on users' information although it will be treated as an interference to information decoder. This is because the energy of AN will be harvested together with the energy of signal and if we control the direction of beamforming of AN, signal to interference and noise ratio will remain large. Thus, the quality of channel state information will be maintained.

MIMO SWIPT System

Because of the nature of broadcasting, low power transfer efficiency becomes a major issue in wireless power transfer. Multiple-input and multiple-output (MIMO) can be exploited making up to SWIPT system. First of all, MIMO enjoys the higher degree of freedom as multiple antennas could be used in both transmitters and receivers, which will cause more energy harvested at receivers. Secondly, applying extra antennas can be used for more combinations of beamforming and resource allocation algorism which will improve the efficiency of both WIT and WPT. In [49], consequences are shown with MIMO SWIPT scenario including one source and one IR as well as one ER with the consideration of tradeoff between information rate and power transfer. Figure2.6.1 shows several benefits of MIMO system regarding multiple users. In figure2.6.1(a), a multiple-antennas source serves multiple information decoding receivers and energy harvesting receivers continuously which RF signals are not only transferring information but charging energy harvesting receivers wirelessly. The fact that CCI existing in MIMO system cannot be ignored in practical implementation and it could be optimized in system designs. The author in [50] illustrates a way of users scheduling to enlarge the tradeoff region between information rate and energy harvesting by allowing ER and IR switch each other. In figure2.6.1(b) shows the scenario equipped with multiple sources and multiple users, which is another vital application of SWIPT system. In this model, same spectrum and related interference are shared between source and destination specifically, which is another challenge in achieve well-operated system model. Additionally, the new opportunities come to SWIPT in this situation with the collaboration and coordination of interference. There are an example illustrating in [51] that exploiting two subspaces at received signal space. One subspace contains the targeted signals preparing for information decoding and the other subspace contains the interference alignment which is used for energy harvesting. In this way, the desired information storing signal will be protected when transferring with interference as well as the management of interference with energy transferring. This kind of approach introduces modifications in conventional technology design method in order to face the new constraints raised by information beamforming.

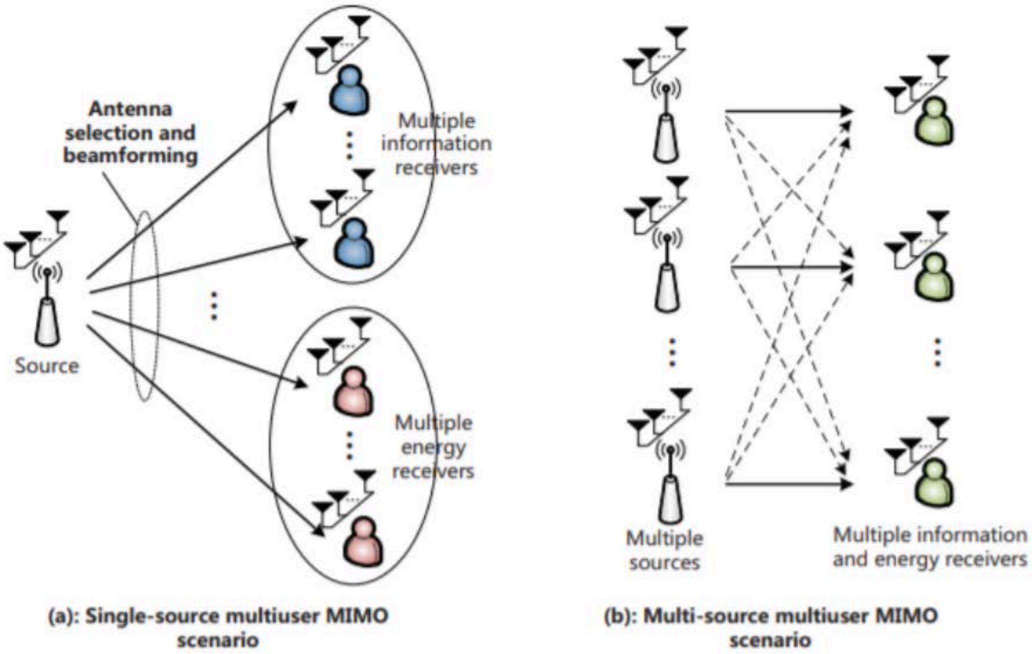

Figure4: Two different scenarios of beamforming

Relay Assisted SWIPT System

Relay will be used when signal from transmitters cannot directly be achieved to receivers. It will be sent to receivers after signal amplification or re-encoding processing.

Over the past decades, using cooperative techniques has aroused people's attention significantly in order to enhance the performance of the communication system. Cooperative communication networks mean that multi-single-antenna terminals and multi-users share antennas from the MIMO system. There are three types of cooperation using frequently in SWIPT system including user cooperation, base station cooperation and relaying. Significantly, when considering diversity gains, throughput gains, cooperative relaying provide low-cost implementation comparing to user cooperation and base station cooperation. When MIMO is hard to apply to the practical system due to constraints of reality such as size of wireless charging devices, cooperative relaying will be used for the SWIPT network. Relay could be powered by energy harvested in the receiver and hence extend the lifetime of battery powering relays. The advantages of using relay will be shown in the following example which compares the system performance of relay assisted SWIPT system with direct transmission SWIPT system. It is observed that the outage probability decreases whilst the reception reliability increases ten times than direct transmission in relaying networking system including a single source-destination pair with decode and forward (DF) relay. Different types of relay will have various impacts on power efficiency base on different resource allocation algorism. The detailed analysis of applying amplify-and-forward relays and DF relays are shown in [52]. Moreover, the outage probability and reception reliability are varying with the different charging methods of the relay. Performance loss on power transmission also depends on the conditions of the source-relay channel. This might be compensated by other methods of cooperation such as user cooperation.

Key Notation

Key Mathematical notations are given in table 1.1 below. Boldface lower letters used to denote vector while boldface capital case letters stand for matrices. $\mathbb{C}^{N\times M}$ represents all N x M sets with complex entries. $\mathbb{CN}$ (**m**,**N**) represents circularly symmetric complex Gaussian distribution with mean vector m and covariance matrix **N**. Rank(A) and Tr(A) represent the rank and trace of matrix **A** as well as $\mathbf{A}^{\mathrm{H}}$ stands for Hermitian transpose of matrix **A**. $\mathbf{A} \succcurlyeq 0$ shows that **A** is semi-definite positive matrix.

Notation	Description
$\mathbf{H}$	Channel vector between BS and relay H$\in \mathbb{C}^{N\times N}$
$\boldsymbol{g_j}$	Channel vector between relay and users j
$\boldsymbol{w_j}$	Information beamforming vector between relay and user j
$\boldsymbol{v}$	Artificial noise vector between relay and eavesdropper
$\mathbf{f}$	Channel vector between relay and eavesdropper
σ^2, σ_{eve}^2, σ_{n}^2	Signal processing noise power
η_j	power splitting ratio of user j
λ_i	channel gain between BS and relay
μ_{req}	minimum requirement of signal to interference and noise ratio
μ_{total}^{max}	maximum signal to interference and noise ratio at eavesdropper
$P_{min}.$	minimum required harvested power at users

System Model

My SWIPT system is assumed that the communication channels are slow time-varying fading and frequency flat. This system model includes a base station (BS), a relay, N information receivers (IRs), N + 1 energy harvesting receivers (ERs) where one of ERs acting as an eavesdropper. I assume that there exists a block between BS and users thus relay in this model is to enable the communication between transmitter and receivers. This model is symmetric system as the base station is equipped with N antennas and single relay equipped with N antennas, serving N users where each user has single-antenna IR and ER. Power splitting technology is used at users to separate received signal in process of information decoding and energy harvesting with power splitting ratio η_n, which represents that at user N the information decoding receiver (IR) will receive η_n of signal information from the user N while the energy harvesting receivers (ER) will have $1-\eta_n$ of signal energy. The broadcast nature of RF channel will cause that the signal received by IRs is likely to be eavesdropped by ERs. Another fact is that the location of ERs in practice is usually closer to BS than IRs for gathering more energy. Therefore, SWITP systems have larger risk of being overheard than traditional communication system. In the following, we assume that both transmitter and receivers know the perfect channel state information (CSI) in resource allocation. In addition, base station and the relay are both powered by battery. Pure energy beamforming and pure information beamforming will be considered in the following part.

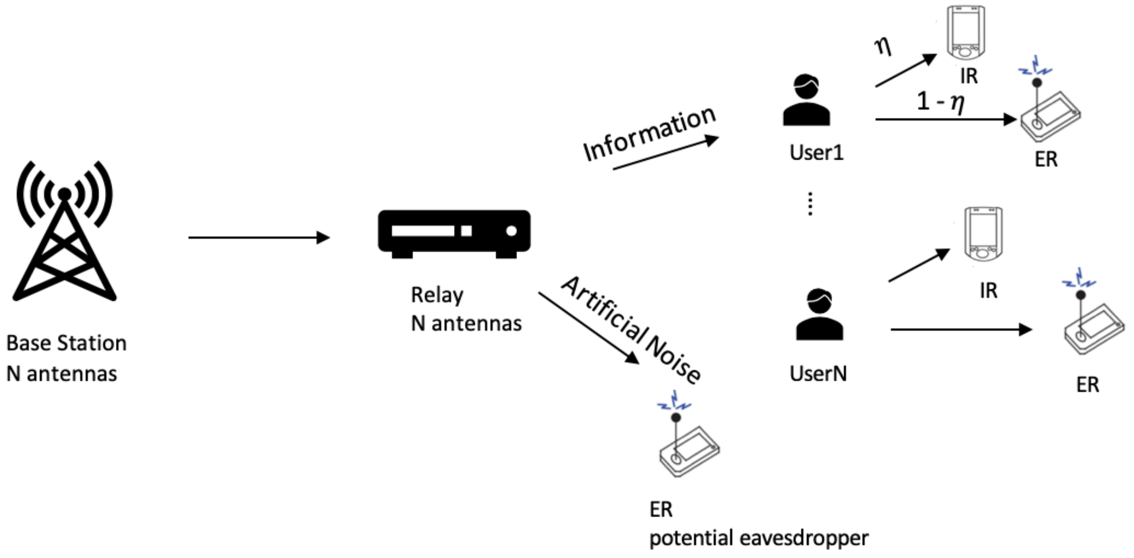

Figure5: A SWIPT system model with relay, users and eavesdropper.

The process will be discussed in two time slots

In time slot τ_1

From base station to relay, the channel sum capacity is given by:

$$\mathrm{C} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \log_2(1 + \frac{\mathrm{P_i}\lambda_\mathrm{i}}{\sigma^2}) \qquad (2)$$

where P_i is transmit power of the transmitter $\forall i \in \{1,2,\ldots,i\}$, λ_i is channel gain between BS and relay $\forall i \in \{1,2,\ldots,i\}$ and σ^2represents the power of additive Gaussian noises generated at relay. In order to ensure security of entire system, secrecy rate need to be improved to some extent. Therefore, after receiving signal from transmitter, an artificial noise **v** will be produced by relay and deliver with real signal **w** to the users simultaneously. In particularly, v is modeled as random vector with circularly symmetric complex Gaussian distribution.

$$\mathbf{v} \sim \mathbb{CN}\ (0, \mathbf{V}) \qquad (3)$$

where $\mathbf{V} \in \mathbf{H^N}$, **V** represents covariance matrix of AN.

Time slot τ_2 will have two processes, one is from relay to users and another one is from relay to eavesdropper. Both users and eavesdropper will receive two signals **v** and **w** which is sent by relay. Therefore, the signal to interference noise signal to information decoding receiver n can be expressed as

$$SINR_n = \frac{|\mathbf{g}_\mathrm{n}^\mathbf{H}\mathbf{w}_\mathrm{n}|^2\eta_\mathrm{n}}{\sum_{\mathrm{j}\neq\mathrm{n}}^{\mathrm{N}}|\mathbf{g}_\mathrm{n}^\mathbf{H}\mathbf{w}_\mathrm{j}|^2\eta_\mathrm{n}+\sigma_\mathrm{n}^2+|\mathbf{g}_\mathrm{n}^\mathbf{H}\mathbf{v}|^2\eta_\mathrm{n}} \qquad (4)$$

Channel capacity between relay to user N can be expressed as follow

$$C_n = log_2(1 + \frac{|\mathbf{g}_\mathrm{n}^\mathbf{H}\mathbf{w}_\mathrm{n}|^2\eta_\mathrm{n}}{\sum_{\mathrm{j}\neq\mathrm{n}}^{\mathrm{N}}|\mathbf{g}_\mathrm{n}^\mathbf{H}\mathbf{w}_\mathrm{j}|^2\eta_\mathrm{n}+\sigma_\mathrm{n}^2+|\mathbf{g}_\mathrm{n}^\mathbf{H}\mathbf{v}|^2\eta_\mathrm{n}}) \qquad (5)$$

And the power harvested at user n is given by

$$P_{ER,n} = (1-\eta_\mathrm{n})[\sum_{\mathrm{j}=1}^{\mathrm{N}}|\mathbf{g}_\mathrm{j}^\mathbf{H}\mathbf{w}_\mathrm{j}|^2 + |\mathbf{g}_\mathrm{n}^\mathbf{H}\mathbf{v}|^2] \qquad (5)$$

Where $\mathbf{H} \in \mathbb{C}^{N\times N}$is the channel vector between BS and relay, $\boldsymbol{g_j} \in \mathbb{C}^{N\times 1}$ is the channel vector between relay and users, η_n is power splitting ratio of receivers. v is the vector representing artificial noise and $\mathbf{w}_\mathrm{j}$ stands for the information beamforming vector between relay and user j. Additionally, σ_n^2 is the power of additive Gaussian noise (AWGNs).

Also, as eavesdropper can receive signal as well. Assume it will try to decode user n. The signal to interference and noise ratio at eavesdropper could be given by

$$SINR_{eve,n} = \frac{|\mathbf{f}^{\mathbf{H}}\mathbf{w}_{\mathrm{n}}|^2}{\sum_{\mathrm{j}\neq \mathrm{n}}^{\mathrm{N}}|\mathbf{f}^{\mathbf{H}}\mathbf{w}_{\mathrm{j}}|^2+\sigma_{\mathrm{eve}}^2+|\mathbf{f}^{\mathbf{H}}\mathbf{v}|^2} \qquad (6)$$

Where $\mathbf{f} \in \mathbb{C}^{N\times 1}$ is the channel vector between relay and eavesdropper, $\sigma_{\mathrm{eve}}^2$is the power of additive Gaussian noise generating at eavesdropper.

Then the capacity between relay and eavesdropper is given by

$$C_{eve,n} = log_2(1 + \frac{|\mathbf{f}^{\mathbf{H}}\mathbf{w}_{\mathrm{n}}|^2}{\sum_{\mathrm{j}\neq \mathrm{n}}^{\mathrm{N}}|\mathbf{f}^{\mathbf{H}}\mathbf{w}_{\mathrm{j}}|^2+\sigma_{\mathrm{eve}}^2+|\mathbf{f}^{\mathbf{H}}\mathbf{v}|^2}) \qquad (7)$$

Remark: Expression of channel capacity follows the Shannon-Hartley Capacity Theorem

Problem Formulation

The problem statement of this system model is to minimize energy consumption of entire system with the guarantee of secure communication in WPT. In this case, we formulate the resource allocation algorithm design as the following optimization problem:

Robust Resource allocation for SWIPT-Relaying system

$$\underset{\mathrm{P_n}, \eta_n, \mathbf{w}_n, \mathbf{v}}{\text{Minimize}} \quad \sum_{n=1}^{N} \mathrm{P_n} + \sum_{n=1}^{N} \|\mathbf{w}_n\|^2 + \|\mathbf{v}\|^2 \qquad (8)$$

Subject to

$$\text{C1:} \quad \mathrm{P_n} \geq 0, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$$

$$\text{C2:} \quad \mathrm{SINR_n} \geq \mu_{\mathrm{req}}, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$$

$$\text{C3:} \quad \mathrm{SINR}_{\mathrm{n}}^{\text{first hoop}} \geq \mu_{\mathrm{req}}, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$$

$$\text{C4:} \quad \mathrm{SINR_{eve,n}} \leq \mu_{\mathrm{total}}^{\mathrm{max}}, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$$

$$C5: \quad P_{ER,n} \geq P_{min}, \forall n \in \{1,2,\dots,n\}$$

Constraint C1 denotes transmit power of each antenna is always positive. μ_{req} . Constraint C2 and C3 stands for minimum requirements of signal to interference and noise ratio at relay and users respectively. In constraints C4, maximum signal to interference and noise ratio at eavesdropper cannot exceed a constant μ_{total}^{max}. Last constraint C5 ensures that minimum required harvested power at user n should larger than a constant, P_{min}. If any of the above constraints is not achieved, the entire system will not operate correctly. Since $SINR_n$, $SINR_r$, $SINR_{eve,n}$ and $P_{ER,n}$ have already been calculated, the resource allocation design can be rewritten as following:

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$$\underset{\mathrm{P_n}, \eta_n, \mathbf{w}_n, \mathbf{v}}{\text{Minimize}} \quad \sum_{n=1}^{N} \mathrm{P_n} + \sum_{n=1}^{N} \|\mathbf{w}_n\|^2 + \|\mathbf{v}\|^2 \qquad (8)$$

Subject to

C1: $\mathrm{P_n} \geq 0, \forall n \in \{1,2,\dots,n\}$

C2: $\dfrac{\left|\mathbf{g}_n^{\mathbf{H}}\mathbf{w}_n\right|^2 \eta_n}{\sum_{j\neq n}^{N}\left|\mathbf{g}_j^{\mathbf{H}}\mathbf{w}_j\right|^2 \eta_n + \sigma_n^2 + \left|\mathbf{g}_n^{\mathbf{H}}\mathbf{v}\right|^2 \eta_n} \geq \mu_{req}$

C3: $\dfrac{\mathrm{P_i}\lambda_i}{\sigma^2} \geq \mu_{req}$

C4: $\dfrac{\left|\mathbf{f}^{\mathbf{H}}\mathbf{w}_n\right|^2}{\sum_{j\neq n}^{N}\left|\mathbf{f}^{\mathbf{H}}\mathbf{w}_j\right|^2 + \sigma_{eve}^2 + \left|\mathbf{f}^{\mathbf{H}}\mathbf{v}\right|^2} \leq \mu_{total}^{max}, \forall n \in \{1,2,\dots,n\}$

C5: $(1-\eta_n)\left[\sum_{j=1}^{N}\left|\mathbf{g}_n^{\mathbf{H}}\mathbf{w}_j\right|^2 + \left|\mathbf{g}_n^{\mathbf{H}}\mathbf{v}\right|^2\right] \geq \mathrm{P_{min}}, \forall n \in \{1,2,\dots,n\}$

z

Remark:

Secrecy Rate reflects the security of system.

In my system, the achievable secrecy rate of IR can be expressed as

$$\mathrm{R} = [A - B]^{+} \qquad (1)$$

Where A represents End-to-end channel capacity from transmitter to user and B represent channel capacity from relay to eavesdropper.

End to end capacity from end to end can be expressed as

min {capacity from transmitter to relay, Capacity from relay to users}

In my system, as we already calculated capacity between transmitter and relay C, capacity between relay and eavesdropper $\mathrm{C_{eve,n}}$ as well as the channel capacity between relay to users $\mathrm{C_n}$.

In my problem formulation, the minimum secrecy rate can be expressed as

$$R_{min} = log_2(1 + \mu_{req}) - log_2(1 + \mu_{total}^{max}) \qquad (9)$$

Evaluation

In this problem, we could find non-convexity constraints C2, C4, C5, as it is simple to see C1, C3 and objective function are convex. Firstly, we will use semi-definite programming (SDP) relaxation to convert non-convexity element into convex function. For example, rewrite $\|\boldsymbol{w_n}\|^2$:

$\|\boldsymbol{w_n}\|^2 = \boldsymbol{w^H w} = Tr(\boldsymbol{w^H w}) = Tr(\boldsymbol{w w^H}) = Tr(\boldsymbol{W})$ while Rank(W) =1

Also, we could rewrite $\left|\boldsymbol{g}_n^{\boldsymbol{H}}\boldsymbol{w}_j\right|^2$:

$$\left|\boldsymbol{g}_n^{\boldsymbol{H}}\boldsymbol{w}_j\right|^2 = \boldsymbol{g}_n^{\boldsymbol{H}}\boldsymbol{w}_j\boldsymbol{w}_j^{\boldsymbol{H}}\boldsymbol{g}_n = Tr\left(\boldsymbol{g}_n^{\boldsymbol{H}}\boldsymbol{w}_j\boldsymbol{w}_j^{\boldsymbol{H}}\boldsymbol{g}_n\right) = Tr\left(\boldsymbol{w}_j\boldsymbol{w}_j^{\boldsymbol{H}}\boldsymbol{g}_n\boldsymbol{g}_n^{\boldsymbol{H}}\right) = Tr(\boldsymbol{W}_j\boldsymbol{G}_n)$$

This transformation is also suitable for other non-convexity elements in problem formulation. Thus, problem formulation could be transformed to:

Robust Resource allocation for SWIPT-Relaying system

$$\underset{P_n, \eta_n, \mathbf{w}_n, \mathbf{v}}{\text{Minimize}} \quad \sum_{n=1}^{N} P_n + \sum_{n=1}^{N} \mathrm{Tr}(\mathbf{W}_n) + \mathrm{Tr}(\mathbf{V}) \qquad (10)$$

Subject to

C1: $P_n \geq 0$

C2: $\dfrac{\mathbf{Tr}(\mathbf{W}_n\mathbf{G}_n)\eta_n}{\sum_{j\neq n}^{N} \mathbf{Tr}(\mathbf{W}_j\mathbf{G}_j)\eta_n + \sigma_n^2 + \mathbf{Tr}(\mathbf{V}\mathbf{G}_j)\eta_n} \geq \mu_{req}$

C3: $\dfrac{P_i\lambda_i}{\sigma^2} \geq \mu_{req}$

C4: $\dfrac{\mathrm{Tr}(\mathbf{F}\mathbf{W}_{\mathbf{n}})}{\sum_{j\neq n}^{N} \mathrm{Tr}(\mathbf{F}\mathbf{W}_j) + \sigma_{eve}^2 + \mathrm{Tr}(\mathbf{F}\mathbf{V})} \leq \mu_{total}^{max}$

C5: $(1-\eta_n)\left[\sum_{j=1}^{N} \mathrm{Tr}\left(\mathbf{G}_n\mathbf{W}_j\right) + \mathrm{Tr}(\mathbf{G}_n\mathbf{V})\right] \geq P_{min}$

C6: $\mathbf{W}_j \succcurlyeq 0$

C7: $\mathbf{V} \succcurlyeq 0$

C8: $0 < \eta_n < 1$

C9: $\mathrm{Rank}(\mathbf{W}_j) = 1$

Rearrange it into proper form:

Robust Resource allocation for SWIPT-Relaying

$$\underset{\mathrm{P_n}, \eta_n, \mathbf{w}_n, \mathbf{v}}{\text{Minimize}} \quad \sum_{n=1}^{N} \mathrm{P_n} + \sum_{n=1}^{N} \mathrm{Tr}(\mathbf{W}_n) + +\mathrm{Tr}(\mathbf{V}) \qquad (10)$$

Subject to

C1: $\mathrm{P_n} \geq 0$

C2: $\mu_{req}\left(\sum_{j\neq n}^{N} \mathbf{Tr}(\mathbf{W}_j\mathbf{G}_j) + \frac{\sigma_n^2}{\eta_n} + \mathbf{Tr}(\mathbf{V}\mathbf{G}_j)\right) - \mathbf{Tr}(\mathbf{W}_n\mathbf{G}_n) \leq 0$

C3: $\mu_{req} - \frac{P_i\lambda_i}{\sigma^2} \leq 0$

C4: $\mathrm{Tr}(\mathbf{F}\mathbf{W}_{n)} - \mu_{total}^{max}(\sum_{j\neq n}^{N} \mathrm{Tr}(\mathbf{F}\mathbf{W}_{j)} + \sigma_{eve}^2 + \mathrm{Tr}(\mathbf{F}\mathbf{V})) \leq 0$

C5: $\mathrm{P_{min}} - (1-\eta_n)\left[\sum_{j=1}^{N} \mathrm{Tr}(\mathbf{G}_n\mathbf{W}_{j)} + \mathrm{Tr}(\mathbf{G}_n\mathbf{V})\right] \leq 0$

C6: $\mathbf{W}_j \succcurlyeq 0$

C7: $\mathbf{V} \succcurlyeq 0$

C8: $0 < \eta_n < 1$

C9: $\mathrm{Rank}(\mathbf{W}_j) = 1$

In order to find optimal solution, Slater's condition and KKT conditions as well as Lagrangian function will be used. According to KKT conditions include four conditions which are primal constraints, dual constraints, complementary slackness as well as that the gradient of Lagrangian with respect to target vanishes.

Slater's condition introduces that one value is optimal if and only if they satisfy KKT conditions.

As the reason that the objective of my project is to find the structure of beamforming vector **W**, I will only express Lagrangian with the terms that relevant to **W** whilst Δ is the rest of other terms which is not relevant to **W**.

Recall the original problem formulation:

Robust Resource allocation for SWIPT-Relaying system

$$\underset{\mathrm{P_n},\eta_{\mathrm{n}},\mathbf{w}_{\mathrm{n}},\mathbf{v}}{\text{Minimize}} \quad \sum_{\mathrm{n=1}}^{\mathrm{N}} \mathrm{P_n} + \sum_{\mathrm{n=1}}^{\mathrm{N}} \|\mathbf{w}_{\mathrm{n}}\|^2 + \|\mathbf{v}\|^2$$

Subject to

C1: $\mathrm{P_n} \geq 0, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$

C2: $\mathrm{SINR_n} \geq \mu_{\mathrm{req}}, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$

C3: $\mathrm{SINR}_{\mathrm{n}}^{\text{first hoop}} \geq \mu_{\mathrm{req}}, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$

C4: $\mathrm{SINR_{eve,n}} \leq \mu_{\mathrm{total}}^{\mathrm{max}}, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$

C5: $\mathrm{P_{ER,n}} \geq \mathrm{P_{min}}, \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$

We could see that all constraints are considered for all n, $\forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\}$, representing every user are under those constraints

Rearrange and simplify above to obtain formula as following

$$\mathrm{L} = \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{P_n} + \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{Tr}(\mathbf{W}_{\mathrm{j}}) + \mu_{\mathrm{req}} \sum_{\mathrm{j \neq n}}^{\mathrm{N}} \mathrm{a_n} \mathrm{Tr}(\mathbf{W}_{\mathrm{j}}\mathbf{G}_{\mathrm{j}}) - \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{a_n}\, \mathrm{Tr}(\mathbf{W}_{\mathrm{n}}\mathbf{G}_{\mathrm{n}}) + \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{b_n}\, \mathrm{Tr}(\mathbf{F}\mathbf{W}_{\mathrm{n}}) - \mu_{\mathrm{total}}^{\mathrm{max}} \sum_{\mathrm{j \neq n}}^{\mathrm{N}} \mathrm{b_n} \mathrm{Tr}\left(\mathbf{F}\mathbf{W}_{\mathrm{j}}\right) - \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{c_n} \mathrm{Tr}\left(\mathbf{G}_{\mathrm{n}}\mathbf{W}_{\mathrm{j}}\right) - \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{Tr}\left(\mathbf{Y}_{\mathrm{j}}\mathbf{W}_{\mathrm{j}}\right) + \Delta, \quad \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\} \qquad (11)$$

Δ represents the rest of terms which are not contain matrix **W**

Rearrange and simplify above to obtain formula as following

$$\mathrm{L} = \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{P_n} + \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{Tr}(\mathbf{W}_{\mathrm{j}}) + \mu_{\mathrm{req}} \sum_{\mathrm{j \neq n}}^{\mathrm{N}} \mathrm{a_n} \mathrm{Tr}(\mathbf{W}_{\mathrm{j}}\mathbf{G}_{\mathrm{j}}) - \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{a_n}\, \mathrm{Tr}(\mathbf{W}_{\mathrm{n}}\mathbf{G}_{\mathrm{n}}) + \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{b_n}\, \mathrm{Tr}(\mathbf{F}\mathbf{W}_{\mathrm{n}}) - \mu_{\mathrm{total}}^{\mathrm{max}} \sum_{\mathrm{j \neq n}}^{\mathrm{N}} \mathrm{b_n} \mathrm{Tr}\left(\mathbf{F}\mathbf{W}_{\mathrm{j}}\right) - \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{c_n} \mathrm{Tr}\left(\mathbf{G}_{\mathrm{n}}\mathbf{W}_{\mathrm{j}}\right) - \sum_{\mathrm{j=1}}^{\mathrm{N}} \mathrm{Tr}\left(\mathbf{Y}_{\mathrm{j}}\mathbf{W}_{\mathrm{j}}\right) + \Delta \quad \forall \mathrm{n} \in \{1,2,\dots,\mathrm{n}\} \qquad (12)$$

Then if we take the derivative of Lagrangian with the respect to $\mathbf{W}_{\mathrm{j}}$, we could obtain that

$$\frac{\partial \mathrm{L}}{\partial \mathbf{W}_{\mathrm{j}}} = \mathrm{I} + \sum_{\mathrm{n} \neq \mathrm{j}}^{\mathrm{N}} \mathrm{a}_{\mathrm{n}} \mu_{\mathrm{req}} \mathbf{G}_{\mathbf{j}} - \mathrm{a}_{\mathrm{n}} \mathbf{G}_{\mathbf{n}} + \mathrm{b}_{\mathrm{n}} \mathbf{F} - \sum_{\mathrm{j} \neq \mathrm{n}}^{\mathrm{N}} \mathrm{b}_{\mathrm{j}} \mu_{\mathrm{total}}^{\mathrm{max}} \mathbf{F} - \sum_{\mathrm{j}=1}^{\mathrm{N}} \mathrm{c}_{\mathrm{j}} \mathbf{G}_{\mathbf{n}} - \sum_{\mathrm{j}=1}^{\mathrm{N}} \mathbf{Y}_{\mathrm{j}}$$

(13)

$$\frac{\partial \mathrm{L}}{\partial \mathbf{W}_{\mathrm{j}}} = \mathbf{I} + \sum_{\mathrm{j} \neq \mathrm{n}}^{\mathrm{N}} \mathrm{a}_{\mathrm{j}} \mu_{\mathrm{req}} \mathbf{G}_{\mathbf{j}} - \mathrm{a}_{\mathrm{n}} \mathbf{G}_{\mathbf{n}} + \mathrm{b}_{\mathrm{n}} \mathbf{F} - \sum_{\mathrm{j} \neq \mathrm{n}}^{\mathrm{N}} \mathrm{b}_{\mathrm{j}} \mu_{\mathrm{total}}^{\mathrm{max}} \mathbf{F} - \mathrm{c}_{\mathrm{j}} \mathbf{G}_{\mathbf{n}} - \mathbf{Y}_{\mathrm{j}} \qquad (14)$$

In order to satisfy conditions of using KKT conditions, the gradient of Lagrangian with respect to target should be vanished, which means that

$$\frac{\partial \mathrm{L}}{\partial \mathbf{W}_{\mathrm{j}}} = 0 \qquad (15)$$

Thus, we could represent $\mathbf{Y}_{\mathrm{j}}$ in this form

$$\mathbf{Y}_{\mathrm{j}} = \mathbf{I} + \sum_{\mathrm{j} \neq \mathrm{n}}^{\mathrm{N}} \mathrm{a}_{\mathrm{n}} \mu_{\mathrm{req}} \mathbf{G}_{\mathbf{j}} - \mathrm{a}_{\mathrm{n}} \mathbf{G}_{\mathbf{n}} + \mathrm{b}_{\mathrm{n}} \mathbf{F} - \sum_{\mathrm{j} \neq \mathrm{n}}^{\mathrm{N}} \mathrm{b}_{\mathrm{n}} \mu_{\mathrm{total}}^{\mathrm{max}} \mathbf{F} - \mathrm{c}_{\mathrm{j}} \mathbf{G}_{\mathbf{n}} \qquad (16)$$

Furthermore, KKT conditions also indicates the complementary slackness

$$\mu_{\mathrm{req}} \sum_{\mathrm{j} \neq \mathrm{n}}^{\mathrm{N}} \mathrm{a}_{\mathrm{j}} \mathbf{Tr}(\mathbf{W}_{\mathrm{j}} \mathbf{G}_{\mathrm{j}}) - \sum_{\mathrm{j}=1}^{\mathrm{N}} \mathrm{a}_{\mathrm{j}} \mathbf{Tr}(\mathbf{W}_{\mathrm{n}} \mathbf{G}_{\mathrm{n}}) = 0 \qquad (17)$$

$$\sum_{\mathrm{j}=1}^{\mathrm{N}} \mathrm{b}_{\mathrm{j}} \mathrm{Tr}(\mathbf{F}\mathbf{W}_{\mathrm{n}}) - \mu_{\mathrm{total}}^{\mathrm{max}} \sum_{\mathrm{j} \neq \mathrm{n}}^{\mathrm{N}} \mathrm{b}_{\mathrm{j}} \mathrm{Tr}\left(\mathbf{F}\mathbf{W}_{\mathrm{j}}\right) = 0 \qquad (18)$$

$$\sum_{\mathrm{j}=1}^{\mathrm{N}} \mathrm{c}_{\mathrm{j}} \sum_{\mathrm{j}=1}^{\mathrm{N}} \mathrm{Tr}\left(\mathbf{G}_{\mathrm{n}} \mathbf{W}_{\mathrm{j}}\right) = 0 \qquad (19)$$

$$\sum_{\mathrm{j}=1}^{\mathrm{N}} \mathrm{Tr}\left(\mathbf{Y}_{\mathrm{j}} \mathbf{W}_{\mathrm{j}}\right) = 0 \qquad (20)$$

From (20) we could see that $\mathbf{Y}_{\mathrm{j}} \mathbf{W}_{\mathrm{j}} = 0$, which means that the structure of $\mathbf{W}_{\mathrm{j}}$ is influenced by the structure of $\mathbf{Y}_{\mathrm{j}}$.

If we concentrate on Karush-Kuhn-Tucker (KKT) conditions, we could conclude the proof as following

$$\sum_{j=1}^{N} a_j, \boldsymbol{Y}_j \sum_{j=1}^{N} b_j, \sum_{j=1}^{N} c_j \geq 0 \quad (21)$$

$$\boldsymbol{Y}_j \boldsymbol{W}_j = 0 \qquad (22)$$

$$\boldsymbol{Y}_j = \mathbf{I} - \Xi \qquad (23)$$

$$\Xi = -a_j \mu_{req} \mathbf{G}_{\mathbf{j}} + a_n \mathbf{G}_{\mathbf{n}} - b_n \mathbf{F} + b_j \mu_{total}^{max} \mathbf{F} + c_j \mathbf{G}_{\mathbf{n}} \qquad (24)$$

From (24) we could see that $\mathbf{Y}_{\mathrm{j}}\mathbf{W}_{\mathrm{j}} = 0$, which means that the structure of $\mathbf{W}_{\mathrm{j}}$ is influenced by the structure of $\mathbf{Y}_{\mathrm{j}}$. $\mathbf{Y}_{\mathrm{j}}$ could be found via matrix Ξ, as $\mathbf{Y}_{\mathrm{j}} = \mathbf{I} - \Xi$, where $\Xi = -\mathrm{a}_{\mathrm{j}}\mu_{\mathrm{req}}\mathbf{G}_{\mathbf{j}} + \mathrm{a}_{\mathrm{n}}\mathbf{G}_{\mathbf{n}} - \mathrm{b}_{\mathrm{n}}\mathbf{F} + \mathrm{b}_{\mathrm{j}}\mu_{\mathrm{total}}^{\max}\mathbf{F} + \mathrm{c}_{\mathrm{j}}\mathbf{G}_{\mathbf{n}}$. Suppose Ξ is a negative definite matrix, then

from $\mathbf{Y}_{\mathrm{j}}\mathbf{W}_{\mathrm{j}} = 0$, we see that the columns of $\mathbf{W}_{\mathrm{j}}$ located in the null space of $\mathbf{Y}_{\mathrm{j}}$. In order to identify the rank of $\mathbf{W}_{\mathrm{j}}$, we could firstly investigate the structure of $\mathbf{Y}_{\mathrm{j}}$.

$\mathbf{Y}_{\mathrm{j}}$ could be found via matrix Ξ, as

$$\mathbf{Y}_{\mathrm{j}} = \mathbf{I} - \Xi \qquad (23),$$

where $\Xi = -\mathrm{a}_{\mathrm{j}}\mu_{\mathrm{req}}\mathbf{G}_{\mathbf{j}} + \mathrm{a}_{\mathrm{n}}\mathbf{G}_{\mathbf{n}} - \mathrm{b}_{\mathrm{n}}\mathbf{F} + \mathrm{b}_{\mathrm{j}}\mu_{\mathrm{total}}^{\max}\mathbf{F} + \mathrm{c}_{\mathrm{j}}\mathbf{G}_{\mathbf{n}}$ (24).

Suppose Ξ is a negative definite matrix, then Y has to be full-rank and positive definite matrix, which will lead to Rank($\mathbf{W}$) = 0. If Ξ is semi positive definite matrix, since $\mathbf{Y}_{\mathrm{j}} = \mathbf{I} - \Xi$ is defined to positive semi-definite, therefore the inequality holds as following

$$1 \geq \lambda_{\Xi}^{\max} \geq 0 \qquad (25)$$

Where $\lambda_{\Xi}^{\max}$ is the maximum eigenvalue of matrix Ξ . If $\lambda_{\Xi}^{\max} < 1$, matrix Y will be a positive definite matrix with full rank thus Rank($\mathbf{W}$) = 0. Meanwhile if $\lambda_{\Xi}^{\max} = 1$, the null space of Y could be spanned by unit vector $\mathbf{u}_{\Xi} \in \mathbb{C}^{N\times 1}$, w. Thus Rank($\mathbf{W}$) = 1 and could be represented by

$$\mathbf{W} = \mathbf{u}_{\Xi}\mathbf{u}_{\Xi}{}^{H}. \qquad (26)$$

Where $\mathbf{u}_{\Xi}$is the unit eigenvector of matrix Ξ with eigenvalue $\lambda_{\Xi}^{\max}$

Thus we can see that the only non-convex constraint Rank($\mathbf{W}_{\mathrm{j}}$) = 1 could be removed as the structure of W is discovered. The rest parts in problem formulation are all convex so that we could use software technique to simulate the results.

Simulation Results

In this section, the simulation results will be presented and discussed to determine if proposed resource allocation algorithm design has expected system performance or not. We assume that carrier center frequency is 915MHz. There are three users and one eavesdropper located 10 meters and 5 meters from the relay respectively. Relay is located 100 meters for BS and minimum required harvested power at users is Pmin= 1 W.

Simulation parameters

Carrier Frequency	915MHz
Distance between BS to relay	100 meters
Distance between relay to user	10 meters
Distance between relay to eavesdropper	5 meters
Number of users	3
Minimum required harvested power	1W

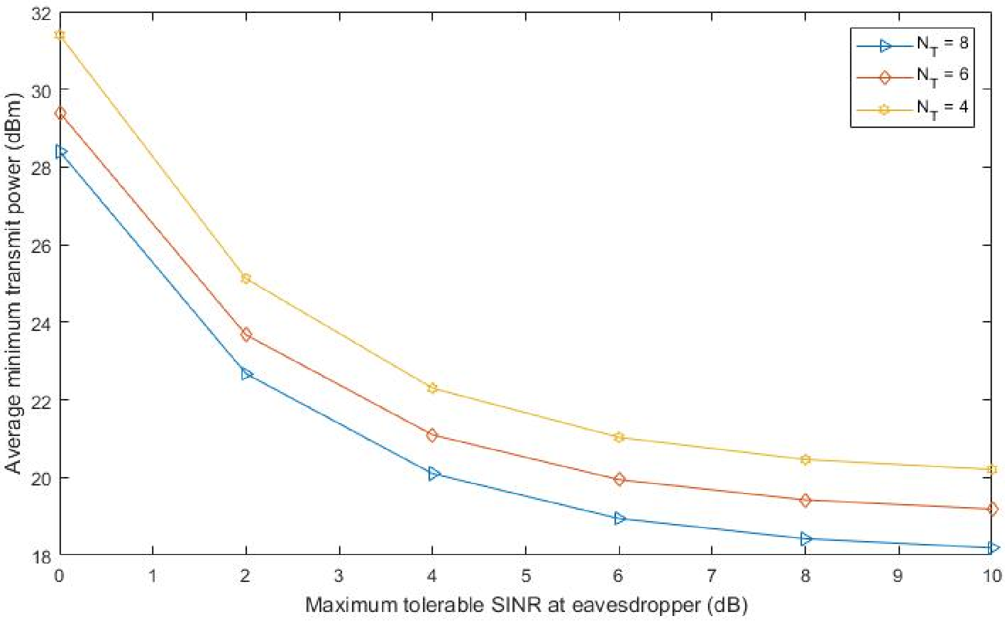

Figure6 discovers the average minimum transmit power versus the maximum tolerable SINR at eavesdropper and three different numbers of antennas at the transmitter side. It could be seen that the average minimum transmit power is decreasing which means the average total power consumption is decreasing with increasing maximum tolerable SINR at eavesdropper

(μ_{total}^{max}). Particularly, to obtain a larger maximum SINR requirement, the relay is supposed to control the direction of beamforming towards the users which will cause lower RF energy towards eavesdropper. Meanwhile, given consistent maximum tolerable SINR, the total power consumption decreases for increasing numbers of transmit antennas NT as more antennas lead to larger degrees of freedom which could facilitate more efficient power resource allocation.

Figure7 depicts the average minimum transmit power versus the minimum harvested power for maximum tolerable SINR at eavesdropper of 0dB and three different numbers of transmit antennas NT. It could be observed that the average power consumption decreases with an increasing number of antennas as well as that the total average power consumption decreases with decreasing minimum required harvested power.

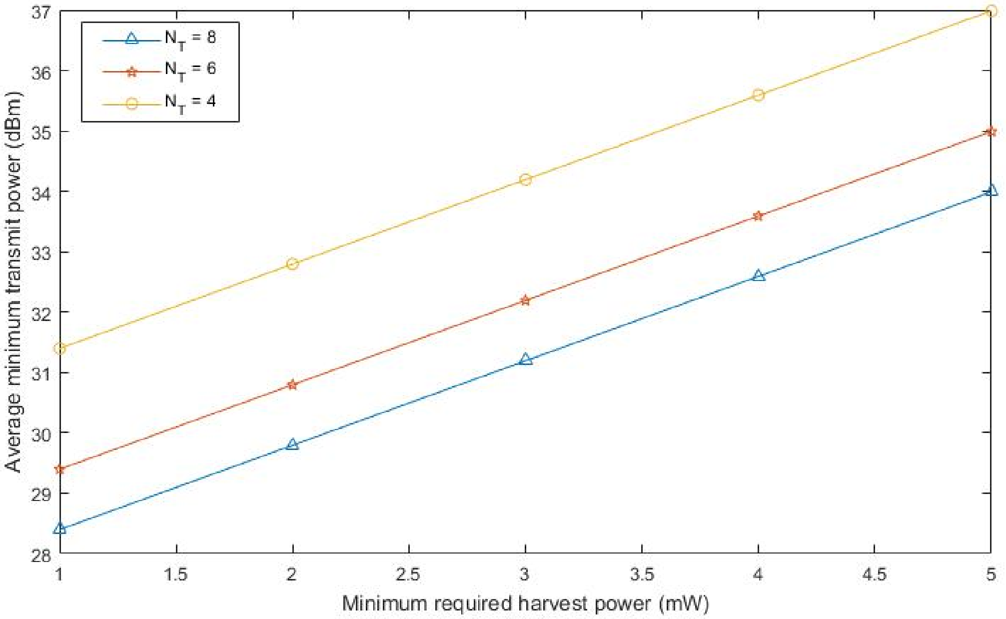

Figure7: Average minimum transmit power (dBm) versus the minimum required harvest power (mW).

Conclusion

In conclusion, this thesis applies a resource allocation algorithm that is established to optimize the power consumption of a SWIPT system. This algorithm particularly concentrates on solving the non-convex problem for obtaining the minimum of the power consumption with the consideration of QoS of an efficient system and communication security. With the use of SDP relaxation and the CVX technique, the non-convex optimization problem is solved optimally. Results show how total power consumption varies with the minimum required harvested power and maximum tolerable SINR at eavesdropper numerically. In the future, more complicated conditions could be considered in my system model for example that I could consider imperfect channel state information of signal which is practically received by users rather than assuming perfect CSI between BS and users. Moreover, we can compare system performance of different types of receivers in the future.

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