ENERGY-EFFICIENT RESOURCE ALLOCATION FOR BACKSCATTER COMMUNICATIONS

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A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Electronic and
Communications
Engineering with Honours

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May 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"ENERGY-EFFICIENT RESOURCE ALLOCATION FOR BACKSCATTER COMMUNICATIONS"** was prepared by **Lum Hui Tian** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Electronic and Communications Engineering with Honours at Universiti Tunku Abdul Rahman.

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ABSTRACT

Wireless-powered backscatter communication (WP-BC) networks have emerged as a low-power technology for supporting massive Internet of Things. Backscatter networks are environmentally friendly and low power communication systems. In WP-BC networks, backscatter transmitters modulate the information received from the power beacon (PB) and reflect the modulated signals to the intended backscatter receivers in radio frequency (RF) signals without external power consumption. To jointly optimize the transmit power from the PB and reflection coefficient of the backscatter transmitter, an interference-aware resource allocation scheme that aims to fairly maximize the individual energy efficiency performance of the backscatter devices in WP-BC networks is proposed. In this scheme, a nonconvex joint reflection coefficient and transmit power allocation optimization problem that maximizes a proportional utility function of energy efficiency is formulated subject to energy-harvesting constraints. A new resource allocation algorithm based on a swarm intelligence approach is developed for the problem. The simulation results have verified that the proposed scheme has outperforms the baseline schemes in terms of energy efficiency and Jain's fairness index.

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LIST OF SYMBOLS / ABBREVIATIONS

6G	Sixth generation
AmBC	Ambient backscatter communication
BER	Bit error rate
BC	Backscatter communication
BTRP	Backscatter transmitter-receiver pair
gBest	Global best
IoT	Internet of Things
IoV	Internet of Vehicle
NOMA	Non-orthogonal multiple access
OFDMA	Orthogonal frequency-division multiple access
PB	Power beacon
pBest	Personal best
PSO	Particle swarm optimization
QoS	Quality of Service
RF	Radio frequency
RSU	Roadside unit
SIC	Successive interference canceller
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-Noise ratio
WP	Wireless-powered
WP-BC	Wireless-powered backscatter communication

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Communication is referring to the transmission of information from one location to another. Every communication involves a sender, a message and a recipient which can be seen in Figure 1.1. Although it sounds straightforward, communication is a complex process. There are a wide variety of factors that can affect the signal quality during the transmission process. These include the communication method and geographic location.

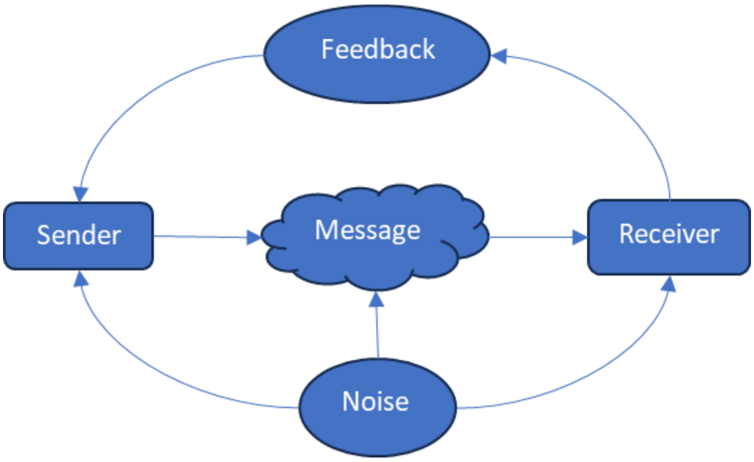


Figure 1.1 Communication Process (Wisconsin Technical College System)

Backscatter is a technique of transmitting data using radio frequency (RF) signals without a dedicated battery or power source. The incoming RF signal is passively reflected, modulated, and converted into tens or hundreds of microwatts of electricity that can be coded for data transfers by equipping the RF backscattering capability into a transmitter device (Moumita, 2020). Backscatter communications (BC) are unique, innovative and different from other wireless communication systems as it is half duplex in nature which the transmitter and receiver cannot send the signal at the same time or simultaneously. Instead of actively emitting their own signals, it enables devices to communicate with their intended receivers by harvesting a portion of energy of the received RF signal while modulating and reflecting the existing RF signals using the remaining portion of the energy. This has become the key benefit for supporting massive Internet of Things (IoT) which is low energy consumption and low complexity of implementation (Lee et al., 2021).

1.2 Importance of the Study

In today's wireless communication environment with the accelerated growth of communication technology and mobile devices, efficient resource allocation for backscatter communications is crucial. This is due to the fact that the IoT will permeate many facets of our daily lives. Besides that, one of the major challenges for IoT is the short network lifetime due to the enormous IoT devices' use of batteries with finite capacity.

BC is one of the communication techniques which rely on passive reflection and modulation of RF. It transmits data by reflecting existing RF signals and provides immense potential for energy conservation and long-term sustainability. There are some limitations for the BC thus bistatic and ambient BC have been proposed to tackle the problems. The associated signal modulation, interference cancellation and resource allocation can be further studied to enhance the current communication system. Furthermore, efficient resource allocation can ensure reliable transmission of data in challenging environments and empower the growth of the IoT by enabling large-scale and energy-efficient deployments.

In smart city initiatives, backscatter technology plays a pivotal role in enabling efficient and sustainable urban development. In severe or remote locations with limited or impracticable access to power sources, backscatter communications also play an important role as they can reflect RF signals without a power source. With resource allocation strategies, it can be scalable and can accommodate the growing number of devices in IoT deployments without devoting energy efficiency to BC.

A greener, more connected future where gadgets can communicate easily, energy saving, and contribute to a more sustainable society is made possible through optimizing resource allocation tactics. At the same time, a reliable and stable energy supply has been ensured as the energy harvesting from ambient sources has been maximized. The data rate and latency can be improved, and the devices can be ensured to meet their performance expectations. Hence, proper and efficient resource allocation strategies can maximize the amount of energy harvested by the backscatter receiver and reducing power consumption to the minimum in the wireless-powered backscatter communication (WP-BC) system.

1.3 Problem Statement

When deploying a smart city, we face the problem of maximizing energy efficiency while maintaining Quality of Service (QoS) standards where thousands of sensors and devices rely on BC for data transmission. The main issue is how to efficiently contribute transmit power levels across a large number of backscatter devices respectively in order to maintain energy efficiency and ensure reliable data transmission of the network. The energy usage should be as minimal as feasible at the same time. Some devices may experience suboptimal performance while resulting in excessive energy use without efficient resource allocation. Hence, efficient resource allocation is critical for ensuring the reliability of data collection in a smart city environment. Failure of efficient resource allocation may lead to an increase in energy consumption and compromised data quality.

It can be observed that energy efficiency among backscatter links has been mostly studies but fairness among the links has been leave out. Due to this, backscatter links may perform unfairly in terms of individual energy efficiency, and some backscatter transmitters may only be able to achieve very low data rates even with high power consumption. This is an important issue for WP-BC networks as there is the presence of co-channel interference which makes the process more challenging. Some of the studies have considered energy efficiency fairness for WP-BC networks. However, it is not scalable with large numbers of backscatter links.

The primary aim of this project is to develop an algorithmic solution for resource allocation that can fairly maximize energy efficiency performance of the individual backscatter receiver in each backscatter link while still meeting the QoS constraints. The solution has included the fairness of the transmit power levels among the devices, reflection coefficient of the transmitter, interference such as noise, minimization of energy waste and enhanced reliability of data transmission. When transmitting the signals to a receiver, the fairness among the backscatter transmitter-receiver pair needs to be considered which include dynamic transmit power control at the PB and flexible adjustment of reflection coefficient at the backscatter transmitters while enhancing the energy efficiency performance of each backscatter link.

1.4 Aim and Objectives

The major goal of this project is to develop an energy-efficient and proportionally fair resource allocation scheme for WP-BC networks that consists multiple backscatter links. Besides, this project aims to optimize the transmit power level at PB and reflection coefficients at backscatter transmitters which can maximize the energy efficiency fairness of the network with the minimum power consumption.

1. **To develop a mathematical resource allocation model for a backscatter communication network**

   From the model, this study aims to understand the network behavior and performance. Besides that, this study also targets to maximize the overall network data rate while ensuring that each node can successfully transmit data to the receiver.

2. **To devise a proportionally fair resource allocation algorithm that maximizes the network energy efficiency**

   In order to handle the nonconvex resource allocation problem, a metaheuristic algorithm will be used to develop the resource allocation algorithm. This type of algorithm is particularly useful when dealing with high computational complexity or optimization problems. It can find near-optimal solutions using an iterative searching process.

3. **To evaluate the effectiveness of the resource allocation algorithm**

   This study aims to implement and assess the algorithm by considering scenarios with various factors such as the number of backscatter links, transmit power levels and environmental constraints. Computer simulation experiments will be implemented to analyze the network performance in terms of energy efficiency and Jain’s fairness index for backscatter communications.

1.5 Scope and Limitation of the Study

A resource allocation algorithm for backscatter communications will be developed in this project. In the design of the resource allocation scheme, the jointly optimization of reflection coefficients of backscatter channels among the backscatter devices and transmit power levels needs to be taken into consideration while ensuring that the minimum requirement data rate of each device is satisfied. This is because co-channel interference between multiple backscatter transmission links may occur, and its severity depends on the transmit power levels. Also, the performance of backscatter communications can be affected by external factors such as environmental conditions and interference sources that cannot be controlled. To model these scenarios, the current study adopts existing channel models available in the literature and implements these scenarios using computer simulations in order to evaluate the performance in terms of energy efficiency and fairness of the proposed resource allocation algorithm. It is noteworthy that this study does not consider real-world implementation of resource allocation algorithm due to the costly real-world experimental setup and limited budget.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Recently, wireless communications have become an integral part of modern society with the increasingly interconnected world. The demand for low-power, cost-effective and efficient communication technologies has never been greater than the continuous expansion of the IoT. Hence, backscatter communication emerges as a groundbreaking approach that challenges the conventional paradigms of wireless data transmission.

According to Wu et al. (2022), BC can be categorized into three: Monostatic, bistatic and ambient. Monostatic BC refers to a type of BC where the reader and the backscatter device are collocated or share the same physical location. In monostatic BC, the backscatter transmitter receives the incoming signal from the signal source and uses it as an excitation signal. The backscatter transmitter then modulates the data and reflects it to the backscatter receiver where the signal is transmitted from (Niu and Li, 2019). Both the backscatter receiver and the signal source are roles of the signal source. In bistatic BC, the backscatter transmitter and the backscatter receiver are located in separate physical locations. It enables two-way communications between them, but it may incur round-trip path loss. Lastly, ambient BC is a communication paradigm that utilizes existing RF signals from the environment as carriers for communications.

2.2 Interference of Bi-static Communication

In the paper by Biswas et al. (2021), it has introduced the concept of bistatic BC and highlighted the growing significance of interference analysis in ensuring reliable communication in the real world. The paper identifies various sources of interference that could affect the communications between the backscatter receiver and the backscatter transmitter. This includes self-interference and cross-interference. The presence of interference will cause the signal to follow multipaths after bouncing between the two backscatter devices.

Firstly, they consider an ambient backscatter scenario where several backscatter tags share the same spectrum with non-orthogonal multiple access (NOMA). A receiver antenna is located at a distance of 150 m from the antenna then a backscatter device (BD) is placed at a distance of 15 m from the receiver antenna. The signal-to-noise ratio (SNR) is computed with the receiver power and thermal noise power. Another backscatter device is then deployed in another location in the same environment. The interference is induced due to the introduction of the second backscatter device in the environment.

Lastly, the SNR is used to analyse the efficiency of power transmission when only one backscatter device and two backscatter devices have been deployed at different distances from each other. It has been found that the area around the transmitter and receiver antennas constitutes a higher SNR compared to other areas. As the second backscatter device has been deployed, the signal follows three different paths when travelling from the transmitter to the receiver due to the occurrence of interference. However, the authors have introduced and utilized the successive interference canceller (SIC) at the receiver antenna. The interference caused by the second backscatter device can be suppressed by SIC, except when it is located too close to the first backscatter device.

2.2.1 Interference Cancellation Scheme

A stable and controllable bistatic communication system needs to be established since ambient RF signals are dynamic and unpredictable, which can lead to unstable performance (Tao et al., 2021). The system model takes a bistatic BC technology into account. An information signal is transmitted from the emitter (E) to tags (T) and followed by the receiver (R) and from the emitter to the receiver. The signal from the E-T-R link is weaker as it has double fading. At the same time, the receiver can hardly decode the received signal as the signal is weak with the presence of strong interference. Hence, they proposed a scheme which jointly designed carrier and tag coding structures to remove the direct link interference. Furthermore, optimal detectors and coherent detectors are proposed to employ specific block length channel codes and present an analysis of the bit error rate (BER) performance. To increase the SNR, they also created a data smoothing technique that can contain two phases of filtering.

2.3 Energy-Efficient Resource Allocation

Many studies have been carried out to address the challenge of resource allocation for WP-BC networks. Some of them were focused for single link whereas some of them were multiple backscatter transmitters sharing a common backscatter receiver or unique pair of the backscatter receiver. Both of these studies below are mainly focused on resource allocation for single link WP-BC networks. The paper by Ye et al. (2019) utilizes RF signals for energy harvesting and backscatter communication, which presents an innovative approach for energy-constrained devices.

The central goal is to optimize the resource allocation such as time slots and transmit power in the networks to enhance energy efficiency while maintaining its reliability (Long et al., 2021). Devices can reflect the existing RF signals by taking into account the characteristics of BC to enable the coexistence of energy harvesting and data transmission.

2.3.1 Max-Min Energy Resource Allocation

In the article by Yang, Ye and Chu (2020), resource allocation within WP backscatter networks and fairness among devices has been studied. The authors propose an algorithm which grounded in the concept of max-min fairness. The study has considered WP-BC network architecture which each backscatter transmitter is paired with a unique backscatter receiver. This architecture has also been considered in the study of Chong et al. (2023). This approach can ensure that the device with a low harvesting capability can also be provided with equitable opportunity for communications. At the same time, the energy efficiency of the WP-BC network can be maximized.

The problem of max-min energy efficiency is divided into two. One is the convex optimization problem which can be resolved using the Lagrange dual decomposition and Karush-Kuhn-Tucker (KKT) conditions and the second is a non-convex problem which can be resolved by utilizing the attribute of related constraints. The authors propose an algorithm that involves iteratively adjusting the allocation of resources such as increasing transmit power or allocating more time slots to the device with low energy efficiency. By dynamically adapting these allocations, the algorithm aims to maximize the minimum achievable energy efficiency across all devices thus enabling energy-constrained devices to participate in the network.

From the simulation result, the energy efficiency of the worst user has been improved with the proposed algorithm. Additionally, it can be observed that when the difference of channel power gain between gi,1 and gj,1 increases, where gi,1 and gj,1 refers to the power gains in the channel from the power beacon (PB) to the backscatter transmitters in Figure 2.1, the achievable extent of max-min fairness is decreased. This is because it is challenging to accomplish fairness as the difference in energy efficiency between the best user and the poorest user grows due to the channel gain gap widening. Hence, when the throughput demand is low, the channel gain difference is small, the max-min energy effectiveness of resource allocation is greater.

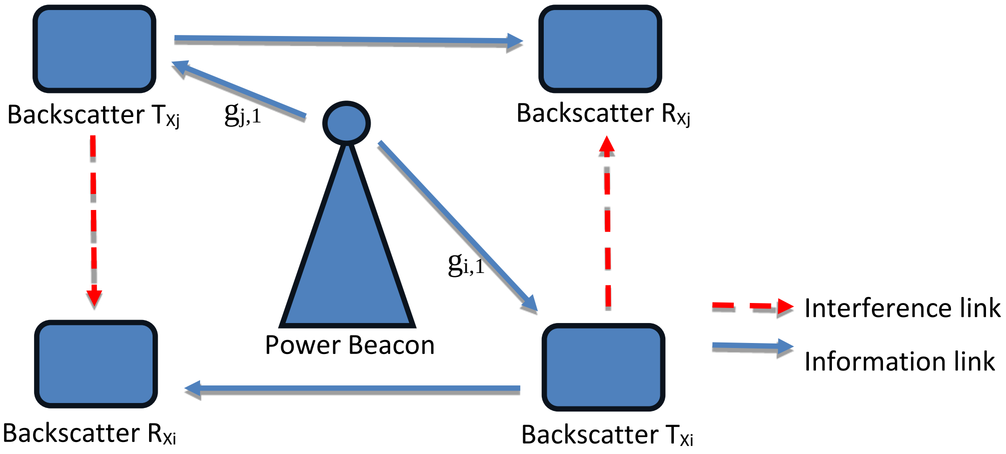


Figure 2.1 WP Backscatter Networks (Yang, Ye and Chu, 2020)

Besides that, the energy efficiency resource scheme with fairness can prolong the worst user’s lifetime in the BC network. This is because each backscatter receiver’s performance can be balanced due to the fairness index which is a crucial component. In the article by Wang et al. (2022), a joint power and backscatter coefficient allocation algorithm depends on convex optimization with the max-min criteria using Non-orthogonal Multiple Access (NOMA) is investigated. By adjusting transmission power and backscatter equipment coefficient, the BC system's minimum energy efficiency is maximized while taking user fairness into account. From the results obtained, the users’ fairness index increases gradually to 1 with the increase of power. This means that the users are obtaining nearly identical energy efficiency.

2.3.2 6G Backscatter-Enable NOMA IoV Networks

In the article by Khan et al. (2022), the concept of sixth-generation (6G) networks has been introduced. The advantages and reasons of 6G will be the foundation of wireless technology in the coming years are discussed. One of the advantages is the enhanced reliability on secure, connectivity and transmission in a high data rate. It can minimize transmission loss and enhance the packet delivery ratio. The challenge for connecting the 6G Internet of Vehicles (IoVs) is the limited spectrum resources and energy reservoirs. NOMA is chosen as it allows an accommodating number of IoVs across similar spectrum resources to enhance spectral efficiency and exploit channel dynamics (Yang, Xu and Liang, 2020). It uses SIC at the receiver to decode the signals and superimposing coding at the transmitter side to encrypt the signals. Hence, energy efficiency in a NOMA-based backscatter IoV network is crucial.

The proposed resource allocation solution is a framework of an ambient BC (AmBC)-enabled NOMA IoV and the framework without AmBC. Both can be affected by the cooperation of the power budget of roadside units (RSU) and power coefficients for each RSU work along with the reflection power of BackTag located in each RSU’s geographical area. The higher the transmit power required to reach the minimum data rate, the greater interference between RSUs which in turn decreases the energy efficiency of IoV networks. From the simulation, the IoV framework with AmBC that is proposed achieves higher energy efficiency. Hence, the transmit power of RSUs and BackTags reflection are simultaneously adjusted to increase the network’s energy efficiency.

2.3.3 OFDMA-based Wireless Powered Backscatter Communications

The concept of WP-BC is introduced by Gu et al. (2021). It highlights the importance of energy efficiency in communication systems and the role of OFDMA as a communication technique. They make use of the application of OFDMA in backscatter communication. It explains how effective resource allocation is made by OFDMA to split up frequency resources into orthogonal subcarriers.

Some optimal resource allocation algorithms with Dinkelbach's method by Karl Dinkelbach have been adopted. Some transformations need to be included to implement the algorithm. The first is optimal transmit power during data transmission time followed by optimal energy harvest coefficient and transformation of the convex optimization problem. They integrate the harvest-then-transmit (HTT) mode and the backscattering mode as complementary transmission modes in their approach, which differs from the use of a single transmission mode. Under the energy-harvesting paradigm, switching between the two transmission modes is thought to increase user data rates. After the simulation, a comparison of system energy efficiency with only one mode and both are done. The energy efficiency of the system is improved when the number of subcarriers increases as more subcarriers can provide more spectrum resources for data transmission. This is a result of their utilization of the advantages of both transmission modes and implementation. Hence, it can minimize wireless energy waste, increase utilization of time effectively, and increase users' data rates.

2.4 Energy-Efficiency Maximization

As the data consumption of communication systems has increased, the energy consumption and interference in the systems would also increase. The user equipment quality of service (QoS) constraints needs to be considered. There are two approaches to optimize the energy efficiency of BC systems while maintaining the desired level of quality of service.

The first approach is in bistatic backscatter communication. According to the research done by Liu et al. (2019), the bistatic nature of the communication system adds complexity to the optimization process or protocol. It also focuses on dynamically adjustable communication parameters. Even if the backscatter node power is relatively low, it significantly affects energy efficiency. With QoS necessities, the energy-efficient network can operate as intended, using the maximum permitted power in the dedicated energy source at all times without the need for scheduled sleep periods.

The second approach is implementation of non-orthogonal multiple access (NOMA) technology. Numerous wireless terminals can benefit from greater chances offered by NOMA, which enables the terminals to share the same frequency with different power levels and interference levels to each user. System capacity and spectrum efficiency can be further increased by combining NOMA and backscatter communication (Xu *et al.*, 2021). This can minimize waste of energy and QoS is achieved through transmission diversity and power allocation. In the paper of Xu et al. (2023), the authors have integrated NOMA and beamforming technologies into WP-BC networks and developed a joint time, beamforming, transmit power and reflection coefficient optimization scheme to maximize the network throughput. In this study, multiple backscatter transmitters are sharing a common backscatter receiver in the WP-BC networks. Similar to the paper of Zhou (2020), the authors have incorporated NOMA into the network ad jointly optimize the transmit power and reflection coefficients to achieve max-min throughput fairness.

The third approach is the joint optimization of relay selection with source and relay power allocation. According to Li (2020), multiple decode and forward relays are taken into account for the BC system throughout the two-time slots, and only a single relay is chosen. The backscatter receiver will harvest the transmit power from the source in the first time slot. The harvested power is utilized to compensate for the power usage of the tag circuit while the transmit power of the relay is used to backscatter and reflect the receiver's signal in the second time slot. This can maximize the performance and QoS of the backscatter receiver where no harsh interference will affect the BC system.

2.5 Summary

Different communication modes between transmitter and receiver based on QoS are compared in Table 2.1 below.

Aspect	NOMA	OFDMA-based	Max-Min Fairness
Resource Allocation	Different power levels to users sharing the same frequency resource.	Each user transmits on its allocated subcarriers without interference.	Allocate resources to maximize minimum utility among users.
Spectral Efficiency	Typically higher due to simultaneous transmission on the same frequency resource.	High due to orthogonal subcarrier allocation and simultaneous transmission.	Suboptimal spectral utilization and may sacrifice due to fairness.
Fairness	Not inherently. Users with better channel conditions may have advantages.	Achieved through orthogonal subcarrier allocation.	Achieved through energy efficiency as each user will receive the minimum resources.
Complexity	High as sophisticated power allocation and decoding schemes.	A simple implementation which only orthogonal subcarrier allocation.	Moderate complexity which has computationally intensive algorithms.

Table 2.1 Comparison of Different Communication Modes

Channel characteristics of bistatic backscatter communication and NOMA have been compared below Table 2.2.

Aspect	Single Link	Multi-link with A Common Receiver	Multi-link with A Unique Receiver
Interference Mitigation	Limited interference	Potential interference among multiple transmitters sharing a common receiver	Reduced interference as each transmitter is paired with a unique receiver
Resource Sharing	Dedicated to a single link	Need to be shared among multiple transmitter	Allocated separately for each backscatter link
Scalability	Limited as dedicated resources	Scalable but limited by interference and resource availability	Scalable with dedicated resources for each transmitter-receiver pair
Complexity	Simple	Requires coordination and interference management	Intermediate complexity with coordination

Table 2.2 Comparison between Links of WP-BC Networks

Resource allocation optimization in the literature review may not inherently ensure fairness among backscatter links and potentially resulting in unequal resource distribution. This can lead to unfair energy efficiency performance among backscatter links thus multi-link with unique pair of transmitter-receiver is chosen. Max-Min fairness algorithms prioritize fairness in the resource allocation scheme, but it is developed based on two backscatter links and unscalable with large number of backscatter link. Therefore, the energy efficiency fairness issue for WP-BC network with unique pair of backscatter links is proposed.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In this project, an algorithm is developed to solve the resource allocation problem that maximizes energy efficiency and fairness for WP-BC systems. It is worth noting that the resource allocation problem consists of several constraints, which are challenging to address using conventional methods. Metaheuristics algorithms are often chosen as an alternative to solve such problems with multiple constraints. They have been adopted to find near-optimal solutions to an increasing range of challenging real-world issues. It can efficiently explore the search space to find solutions that are close to optimal based on imperfect or incomplete information in the real world or sparse resources. Besides, they also can balance exploration and exploitation in the solution search and adapt to various problem characteristics for solving optimization problems with multiple constraints. Thus, compared to conventional optimization algorithms, adopting metaheuristic algorithms can frequently offer a suitable solution with less computational work (Balan).

3.2 Problem Modelling

A bistatic WP-BC network architecture which consists of a PB and multiple backscatter links denoted by $D=\{1,2,3,\ldots,i,\ldots,D\}$, where $D=|D|$ refers to the cardinality of the set (i.e., number of backscatter links), as described in Figure 3.1 is considered. Each backscatter link i comprises a single backscatter transmitter i and a single receiver i. In every time interval of T, the PB would broadcast an RF signal to all the backscatter transmitters. While passively reflecting the RF signal and backscattering information to their intended backscatter receivers, the transmitters will utilize the energy from the RF signal to power their operations. Hence, assume that all the backscatter links are operating in the same frequency band at which the RF signal is transmitted by the PB.

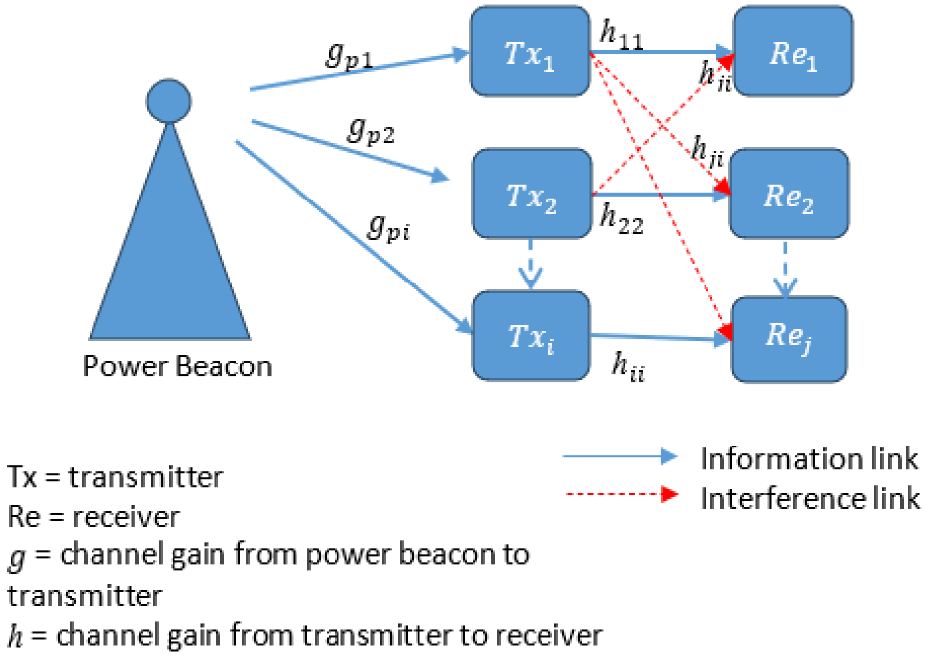


Figure 3.1 A WP-BC Network with Multiple Backscatter Links

3.2.1 Communication Model

The received power at the receiver i can be expressed as

$$P_i = P_t g_{pi} h_{ii} \beta_i + N_o + \sum_{j\epsilon\mathcal{D}\setminus\{i\}} P_t g_{pj} h_{ji} \beta_j + P_t k_{pi} \qquad (3.1)$$

where g_{pi} is referring to the channel gains between PB and backscatter transmitter i, h_{ii} represents the channel gain of the backscatter link i and h_{ji} refers to the channel gains from the transmitter of backscatter link i to the receiver of backscatter link j where $j \neq i$. k_{pi} is the channel gains between PB and respective receiver of the backscatter link i, P_t is the power transmit of the PB, N_o is additive white Gaussian noise power (AWGN) and $\beta_i \epsilon\ [0,1]$ is the reflection coefficient of the transmitter of backscatter link i. $P_t g_{pi} h_{ii} \beta_i$ is the signal power received at the receiver from the intended transmitter in backscatter link I, whereas $\sum_{j\epsilon\mathcal{D}\setminus\{i\}} P_t g_{pj} h_{ji} \beta_j$ is the aggregate interference from backscatter transmitters of other backscatter links $j \neq i$ and $P_t k_{pi}$ is the interference from the PB to the receiver of backscatter link i. Since the PB is usually located far from the backscatter receiver therefore the interference between them can be neglected (Xu and Gui, 2020). It can be removed by assuming that the PB delivers a standard RF signal with predefined patterns that is recognized by all the receivers using SIC techniques (Ye *et al.*, 2019). Besides, the signal-to-interference-plus-noise ratio (SINR), γ_i at the receiver from its desired transmitter for backscatter link *i* is determined as

$$\gamma_i = \frac{P_t g_{pi} h_{ii} \beta_i}{N_o + \sum_{j \epsilon \mathcal{D} \setminus \{i\}} P_t g_{pj} h_{ji} \beta_j} \tag{3.2}$$

The transmission rate for backscatter link *i* (in bits/Hz) can then be obtained as

$$R_i = T \log_2(1 + \gamma_i) \tag{3.3}$$

3.2.2 Energy-Harvesting Model

For WP-BC networks, a linear energy harvesting model is adopted to estimate the harvested energy level at the backscatter transmitters. With this model, the energy harvested by the transmitter of backscatter link i from the PB can be obtained with this model as

$$E_i = (1 - \beta_i) T_\eta P_t g_{pi} \tag{3.4}$$

where $\eta \epsilon [0,1]$ is the energy conversion efficiency. Since the energy harvested from thermal noise is low, so neglected. The energy harvested by the backscatter transmitter is used to preserve the operation of the transmitter circuit for backscatter transmissions which is denoted as PC_t and has been assumed to be similar for all transmitters. Therefore, the amount of the harvested energy needs to be sufficient to meet energy consumption requirement of the transmitter circuit operation which is $E_i \geq P_{Ct} T$. The total power usage for the backscatter link *i* is composed of power consumption at the PB, PC_s; transmitter circuit power, PC_t; receiver circuit power, PC_r (which are assumed to be the same for all the receivers); and transmission power, *Pt*. Therefore, the energy efficiency of the backscatter link *i* can be calculated as

$$EE_i = \frac{R_i}{P_{cr,i} + P_{cs} + P_t} \tag{3.5}$$

The transmitter power consumption has been taken into account in the energy efficiency as the consumption is drawn from the transmit power of the PB received at the transmitter in the WP-BC network. The overall energy efficiency of the WP-BC network can be obtained as the ratio of the sum rate of all backscatter links to the total power usage in the WP-BC network:

$$EE = \frac{\sum_{i \in \mathcal{D}} R_i}{\sum_{i \in \mathcal{D}} P_{cr,i} + PCs + Pt} \tag{3.6}$$

Note that PC_t is harvested from the transmit power of the PB, therefore it is not counted in the total network power usage.

3.2.3 Optimization Framework

The current study formulates the resource allocation issue for WP-BC networks that aims to achieve fair individual energy efficiency among backscatter links in WP-BC network by joint allocation of reflection coefficients of the backscatter transmitters and the transmit power at the PB. The natural logarithmic function which has a diminishing return property and designate the utility function of each backscatter link i. The maximizing of the sum utility function across all backscatter links can make the achievable energy efficiency of individual backscatter links distributed evenly. The maximization of the sum logarithmic utility function can lead to proportional fairness which strikes a good balance between energy efficiency and fairness (Pu et al., 2020). The resource allocation problem can be formulated as follows:

$$P1: \max_{P_t, \beta} \zeta(P_t, \beta) = \sum_{i \in \mathcal{D}} \log(EE_i) \tag{3.7}$$

subject to

$$0 \leq P_t \leq P_{max} \tag{3.8}$$

$$E_i \geq P_{ct} \quad \forall i \in \mathcal{D} \tag{3.9}$$

$$0 \leq \beta_i < 1 \quad \forall i \in \mathcal{D} \tag{3.10}$$

where $\beta = \{\beta_i\}_{i \epsilon D}$. Constraint (3.8) enforces that the P_t does not exceed the maximum transmit power of the PB, P_{max}. As required by constraint (3.9), the amount of energy harvested by the backscatter transmitter must be sufficient to meet the power consumption requirements of the transmitter circuit. The final constraint (3.10) ensures that the reflection coefficient for the backscatter transmitter is restricted within the range of [0,1].

3.3 Proposed Resource Allocation Scheme

Problem P1 is a mixed-integer programming problem in which P_t and β are continuously valued. This problem is challenging due to its non-convex nature. Thus, a metaheuristics algorithm is adopted. It can provide an efficient solution for complicated and multidimensional optimization problems in a shorter time. Here, a swarm intelligence algorithm is leveraged to solve the problem stated in (3.7). The algorithm is also known as the Particle Swarm Optimization (PSO) algorithm. It is an optimization metaheuristic algorithm proposed by Kennedy and Eberhart (Ser, Villar and Osaba 2019). It is developed based on the social behavior of observed in bird flocking and simulated depends on the concept of swarm intelligence capable of solving mathematics problems existing in engineering. It is also a population-based stochastic approach that repetitive solves continuous and discrete optimization problems (Rhim, 2023).

The fundamental idea of the PSO algorithm is to model the optimization process as a swarm particle moving through a multidimensional search space to find the optimal solution to a problem. PSO is inspired by the social behavior of birds flocking and is based on the principles of cooperation and information sharing among individuals in a group. Details of PSO can be referred to below.

3.3.1 Particle Swarm Optimization (PSO)

In PSO, it starts with initializing a population of particles in a multidimensional search space. The group of particles represents the potential solutions to the problem. Each particle's position is randomly initialized and its velocity is set to random value; both are set within predefined bounds. The fitness or objective function has been used to evaluate the quality of each particle's position. It can quantify how well a particular solution satisfies the problem's objective and constraint. Hence, each particle offers a potential answer to the optimization puzzle.

In each iteration, each particle will keep track of two positions. One is the personal best position (pBest), and the other is the global best position (gBest). The pBest represents the best-known position of the particle itself while the gBest position refers to the best-known position among all the particles in the swarm. The initial setting of the gBest is the arbitrary pBest of one of the particles.

In each iteration, each particle updates its velocity based on these three components: Cognitive component, social component and inertia component. The cognitive component refers to the self-learning factor while the social component is the swarm learning factor. Both of them determine the movement of particles, whereby the particles' trajectories are attracted toward the pBest position and gBest position. Each particle is also allowed to maintain some of its current velocity which helps to balance the solution exploration and exploitation. Besides that, particles in PSO may alter their movement mode to adapt to environmental changes while still maintaining their steady movement in the search space. The movement of the swarm particle is determined by a set of mathematical equations that include the consideration of the current particle position, its pBest solution and the gBest solution (Rhim, 2023). The particle velocity equation can be determined as follows once the position of the particles has been defined:

$$V_i(t+1) = w * V_i(t) + C_1 r_1\big(pBest - X_i(t)\big) + \; C_2 r_2\big(gBest - X_i(t)\big) \quad (3.11)$$

where $V_i(t+1)$ is referring to the particle i velocity at time t+1, $V_i(t)$ represents the current particle *i* velocity and $X_i(t)$ is the current particle position. w is referring to inertia weight, C_1 and C_2 represent the acceleration coefficient and r_1 and r_2 are the random vectors that falls between 0 to 1. The term of the acceleration coefficients and the random vectors govern the stochastic impact of cognitive and social components on the particle's overall velocity. C_1expresses the own confidence level of a particle whereas C_2 expresses the confidence level of a particle has in its neighbours.

After updating the particles' velocity, particles will proceed to adjust their positions in the search space according to the newly updated particles' velocity. In each iteration, each particle will update its position according to the environment and velocity changes. Each particle will search for the best position within its neighbourhood by updating its position and moving to it. The new positions of the particle *i* are calculated as:

$$X_i(t+1) = X_i(t) + V_i(t+1) \tag{3.12}$$

where $X_i(t+1)$ represents the updated particle i position, $X_i(t)$ refers to the current particle i position, and $V_i(t+1)$ is the updated particle i velocity. The new position of each particle will undergo evaluation based on the optimization problem's objectives and constraints. This fitness function can be used to assess the quality of the particle in the search space. The particle will update its pBest if its new position has a better fitness value than the previous pBest. The same goes for gBest if any particle in the swarm fields has finds a better fitness quality than the current gBest.

PSO will continue iterating through velocity and position updates until a termination criterion is met. The termination criterion of PSO can include reaching the maximum number of iterations, convergence where particles no longer significantly change their positions or achievement of satisfactory solutions. The best-known position or solution, which also represents an ideal or near-optimal solution to the problem during the optimization process, is returned by PSO at the end.

3.3.2 PSO-Based Resource Allocation

In the current study, the PSO algorithm is implemented as follows to solve problem P1. In the PSO, each swarm represent a search agent to find the solution for the given problem. The position vector for particle *m* is given as

$$X_m = \left\{P_{t,m}, \{\beta_{i,m}\}_{i\epsilon D}\right\} = \{P_{t,m}, \beta_{1,m}, \dots, \beta_{i,m}, \dots, \beta_{|D|,m}\} \tag{3.13}$$

where $P_{t,m}$ and $\beta_{i,m}$ represent the transmit power of the particle *m* from the PB and the corresponding reflection coefficient of the particle *m* of the transmitter of backscatter link *i*. The variables in the position vector will be randomly placed within the search space defined by constraints (3.8) and (3.10). The following equations have been introduced to update each element in the position vector of each particle after its velocity and position updates in Eq. (3.11) and (3.12).

$$P_{t,m} = \begin{cases} P_{t,m} & 0 \leq P_{t,m} \leq P_{max} \\ P_{max} & P_{t,m} > P_{max} \\ 0 & P_{t,m} < 0 \end{cases} \tag{3.14}$$

$$\beta_{i,m} = \begin{cases} \beta_{i,m} & 0 \leq \beta_{i,m} \leq 1 \\ 1 & \beta_{i,m} > 1 \\ 0 & \beta_{i,m} < 0 \end{cases} \tag{3.15}$$

Once the position vector has been defined, we determine the solution quality by evaluating its position vectors based on the fitness function. For the design of the fitness function, the feasibility of the particles' positions with regard to constraint (3.9) and the optimality of the particles' positions based on the sum utility function defined in Eq. (3.7) need to be ensured. Since the ultimate goal in problem P1 is to maximize the energy efficiency of the backscatter link, let the fitness function of each particle m, $F(X_m)$ defined as:

$$F(X_m) = \sum_{i \in D} \langle \log(EE_i) \rangle |_{P_t = P_{t,m}, \boldsymbol{\beta} = \{\beta_{i,m}\}_{i \in D}} \tag{3.16}$$

where

$$\langle \log(\mathrm{EE}_i) \rangle = \begin{cases} \log(\mathrm{EE}_i) & E_i > P_{ct}T \\ -\rho & E_i \leq P_{ct}T \end{cases} \tag{3.17}$$

Note that ρ is a very large number. Eq. (3.17) reflects constraint (3.9) in such a way that if the constraint is violated for backscatter link i, it indicates that the energy is insufficient to power up the transmitter circuit. Thus, the transmission rate is zero due to the failure of backscattering transmission. This also applies to the case when $E_i = P_{ct}T$ since there will be no energy remained for backscatter transmission therefore $R_i = 0$ and $\mathrm{EE}_i = 0$ is implied. Note that $\log(\mathrm{EE}_i) \rightarrow -\infty$ when $\mathrm{EE}_i \rightarrow 0$. As such, we set $\log(\mathrm{EE}_i)$ to $-\rho$ which is large in magnitude in the algorithm if $\Gamma_i = 0$ for simplicity. This way, the fitness of the particle becomes lower when constraint (9) is not satisfied.

Algorithm 1 summarizes the proposed PSO-based resource allocation algorithm for the WP-BC network, where M is the swarm population size and T_{max} represents maximum iterations number. The P_t and reflection coefficient of the transmitters will be set accordingly to the boundaries defined in (3.8) and (3.10) which can be expressed in [V_{min}, V_{max}]. The entire PSO process is repeated until $t = T_{max}$. Therefore, Algorithm 1 can be shown to have a linear computational complexity of $O(T_{max}M|D|)$, which reasonable for practical implementation.

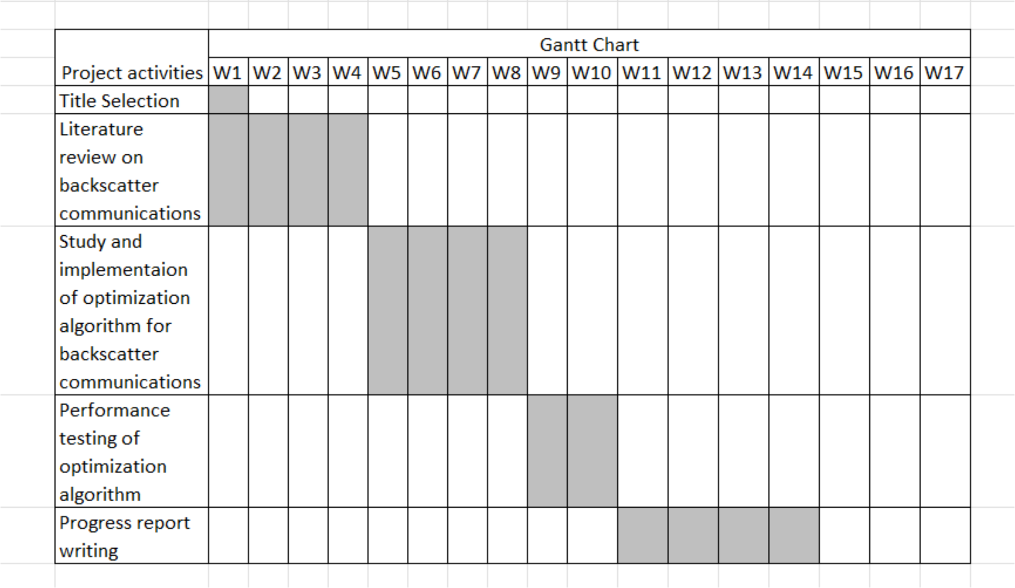
Algorithm 1: PSO-based resource allocation algorithm

```
Initialize $M$, $T_{max}$, $V_{max}$, $V_{min}$, $t = 0$;
for particle $m = 1$ to $M$
    Randomly initialize $\mathbf{V}_m^{(t)} \in [V_{min}, V_{max}]^{1+|D|}$.
    Randomly initialize $\mathbf{X}_m^{(t)}$ with $P_{t,m}$ and $\beta_{i,m}$ being respectively set within $[0, P_{max}]$ and $[0, 1]$ for all $i \in D$.
    Evaluate $F\left(\mathbf{X}_m^{(t)}\right)$ using (21).
    Set $\mathbf{X}_{p,m}^{(t)} = \mathbf{X}_m^{(t)}$.
end for
Set $\mathbf{X}_g^{(t)} = \arg \max_{\left\{\mathbf{X}_m^{(t)}\right\}_{m=1}^{M}} F\left(\mathbf{X}_m^{(t)}\right)$.
while $t < T_{max}$
    for particle $m = 1$ to $M$
        Update $\mathbf{V}_m^{(t+1)}$ using (16).
        Set $\mathbf{V}_m^{(t+1)} = \max\left(\mathbf{V}_{min}, \min\left(\mathbf{V}_{max}, \mathbf{V}_m^{(t+1)}\right)\right)$ to enforce velocity limits.
        Update $\mathbf{X}_m^{(t+1)}$ using (17).
        Enforce the boundary conditions for $\mathbf{X}_m^{(t+1)}$ using (19) and (21).
        Evaluate $F\left(\mathbf{X}_m^{(t+1)}\right)$ using (21).
        if $F\left(\mathbf{X}_m^{(t+1)}\right) > F\left(\mathbf{X}_m^{(t)}\right)$
            Set $\mathbf{X}_{p,m}^{(t+1)} = \mathbf{X}_m^{(t+1)}$.
        else
            Set $\mathbf{X}_{p,m}^{(t+1)} = \mathbf{X}_{p,m}^{(t)}$.
        end if
        if $F\left(\mathbf{X}_m^{(t+1)}\right) > F\left(\mathbf{X}_g^{(t)}\right)$
            Set $\mathbf{X}_g^{(t+1)} = \mathbf{X}_m^{(t+1)}$.
        else
            Set $\mathbf{X}_g^{(t+1)} = \mathbf{X}_g^{(t)}$.
        end if
    end for
    Set $t \leftarrow t + 1$.
end while
```

3.4 Summary

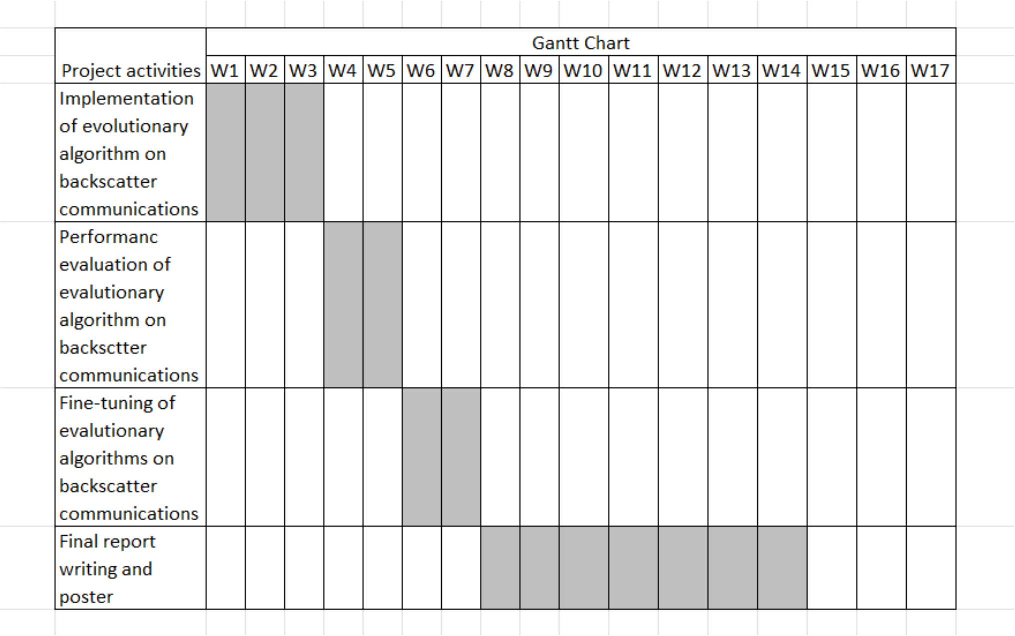
In summary, the PSO algorithm is proposed to optimize energy efficiency for BC while ensuring fairness among BTRPs. PSO can efficiently explore the complex search space, balance exploration and exploitation and adapt to problem characteristics. The algorithm iteratively updates particle velocity and positions based on the objective functions and constraints to seek the optimal solutions. In the current phase, the study of backscatter communications and energy efficiency resource allocation has been done. At the same time, an analysis of PSO algorithms to obtain maximization functions is conducted. The fitness function for constrained optimization using the penalty function method has been implemented to obtain better results.

The project timeline can be observed as below in Figure 3.4.



	Gantt Chart																
Project activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17
Title Selection	▨																
Literature review on backscatter communications	▨	▨	▨	▨													
Study and implementaion of optimization algorithm for backscatter communications					▨	▨	▨	▨									
Performance testing of optimization algorithm									▨	▨							
Progress report writing											▨	▨	▨	▨			

Figure 3.4 Gantt Chart for Semester 1



	Gantt Chart																
Project activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17
Implementation of evolutionary algorithm on backscatter communications	■	■	■														
Performanc evaluation of evalutionary algorithm on backsctter communications				■	■												
Fine-tuning of evalutionary algorithms on backscatter communications						■	■										
Final report writing and poster								■	■	■	■	■	■	■			

Figure 3.5 Gantt Chart for Semester 2

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Performance Evaluation

Simulation results are presented in this section to demonstrate the performance of the proposed resource allocation scheme which include fairness. The performance is evaluated with the consideration of the bistatic WP-BC network shown in Figure 3.1, with a distance dependent pathloss as large-scale fading. The path loss model is $(\frac{d}{d_o})^{2.5}$, where the reference distance of d_o= 1 m and d is referring the distance between the PB and transmitter.

The environment is set as follows which mainly follow from the study of Chong et al. (2023), Ye et al. (2019) and, Yang, Ye and Chu (2020): All backscatter transmitters are located randomly in a maximum 30 m radius from the PB while a 15 m of maximum distance between the backscatter transmitter and backscatter receiver of corresponding backscatter link. The parameters of energy conversion efficiency, η = 0.6, AWGN, N_o = -114 dBm, transmitter circuit power consumption, PC_t = 0.1 mW, power consumption at the PB, PC_s = 100 mW, receiver circuit power consumption, $PC_{r,i}$ = 10 mW for $i \in \mathcal{D}$, and time interval, T of 1 s. Numerical computing based on the Monte-Carlo approach is adopted and with the number of realizations being set to 100 (Chong et al.,2023).

Next, the reflection coefficients of the backscatter transmitters are set within 0 to 1 respectively, while for Pt are set from 20 to 40 dBm respectively. The population size of the swarm is set to 30 and the number of iterations, $MaxIt$ is set to 100. The cognitive learning factor, C_1 and social learning factor, C_2 are set to 1.5 and the inertia weight, w is 0.72.

The performance metrics used for evaluations are the overall network energy efficiency defined in Eq. (3.6) and Jain’s fairness index function (Jain, 1990). It is adapted in the proposed scheme which is a fairness metric for static resource allocation between the backscatter receivers that ensure that the transmission rate is fairly distributed to each other. Thus, the user fairness index in the context of study can be defined as

$$\mathcal{J}(EE_1, EE_2, \dots, EE_n) = \frac{(\sum_{i=1}^{n} EE_i)^2}{|D| \cdot \sum_{i=1}^{n} {EE_i}^2} \tag{3.5}$$

where EE_i is referring to the energy efficiency of the link i and $|D|$ is representing the number of backscatter receivers in WP-BC network. The outcome of the Jain's fairness index will lie within [0,1]. A higher value indicates a higher degree of fairness in the performance. As performance benchmarks, two baseline schemes are adopted which are the Max-Min resource allocation scheme and the Max Power resource allocation scheme where the transmit power is always set to the maximum allowed power with random reflection coefficient of backscatter transmitters.

4.2 Scenario with Two Backscatter Links

In this section, we evaluate the average energy efficiency and fairness performance of the WP-BC network with two backscatter links and varying P_{max} over 100 realizations. In Figure 1, it can be observed that the proposed scheme has demonstrated superior performance in energy efficiency over the two baseline schemes. The proportional fairness utility function has enabled the maximization of energy efficiency in the WP-BC network. In Max-Min scheme, it mainly focuses on maximizing the energy efficiency of the worst channel condition which may not maximize the overall network energy efficiency.

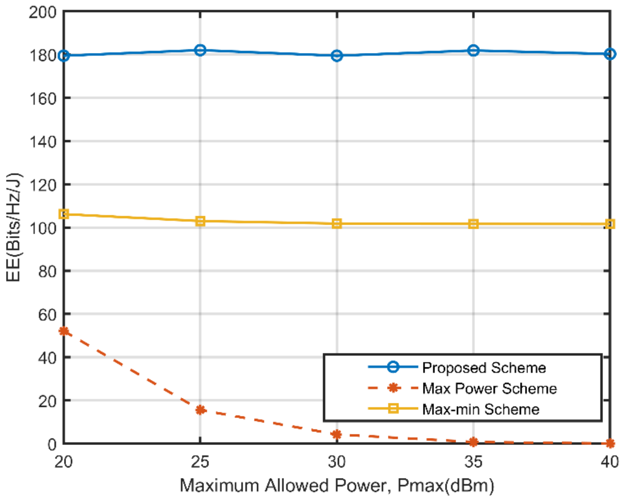


Figure 4.1 Energy Efficiency Performance of the WP-BC Network with Two Backscatter Links

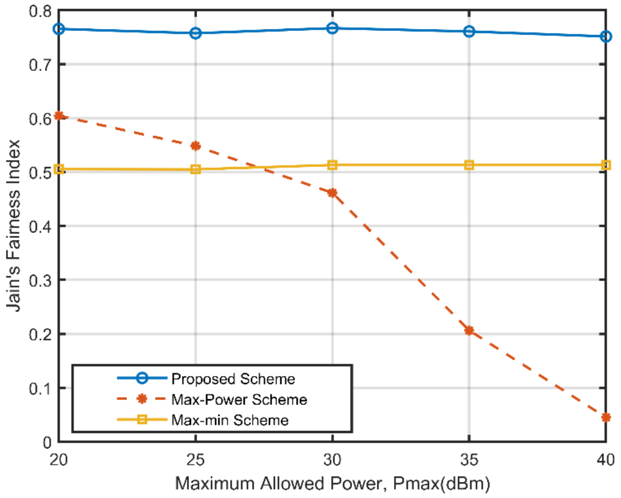


Figure 4.2 Fairness Performance of the WP-BC Network with Two Backscatter Links

Jain’s fairness index results can be observed in Figure 4.2. In the proposed scheme, the fairness index of the backscatter receiver achieves the value beyond 0.7. This has shown that there is high degree of energy efficiency fairness among the backscatter links. On the other hand, the fairness performance of the Max Power scheme degrades with increasing P_{max} as energy efficiency fairness is not taken into account.

4.3 Scenario with More Than Two Backscatter Links

Performance of average energy efficiency and fairness of the WP-BC networks with more than two backscatter links over 100 realizations have been evaluated in this section. The Max-Min scheme is excluded from the evaluation as it is only applicable to the scenarios with only two BTRPs.

Figure 4.3 shows the energy efficiency performance of WP-BC networks with more than two backscatter links. It can be observed that the proposed scheme has outperformed the baseline scheme across all numbers of backscatter links. From the observation, the proposed scheme has a high degree of scalability as it can maintain high energy efficiency with the increasing numbers of backscatter links.

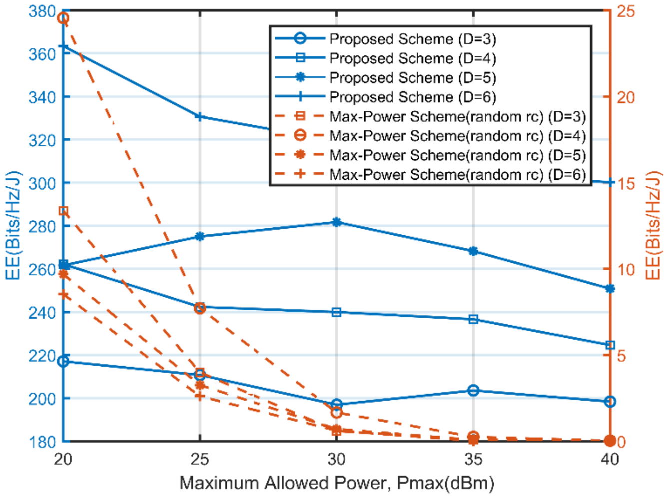


Figure 4.3 Energy Efficiency Performance of the WP-BC Network with Multiple Backscatter Links

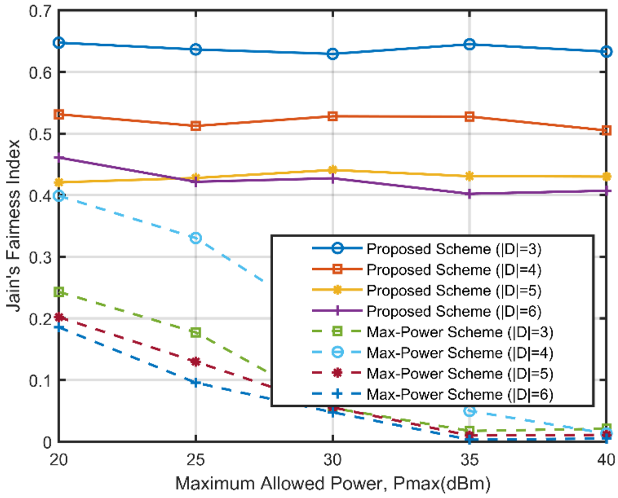


Figure 4.4 Fairness Performance of the WP-BC Network with Multiple Backscatter Links

Figure 4.4 illustrates that the fairness index of the proposed resource allocation scheme outperforms the Max Power scheme due to consideration of proportional fairness in the optimization problem defined in Eq. (3.7). The performance declines with the increasing numbers of backscatter links due to the co-channel interference between backscatter links become stronger which can substantially limit the transmission rates of backscatter links.

4.4 Scenario with Increasing Maximum Distance Between Transmitters and Receivers

This section is investigating the impact of varying maximum distance between the backscatter transmitter and their paired receivers on the energy efficiency and fairness performance of WP-BC networks. The evaluation is done by considering the maximum distance between backscatter transmitters and receivers is varying from 5 m to 15 m.

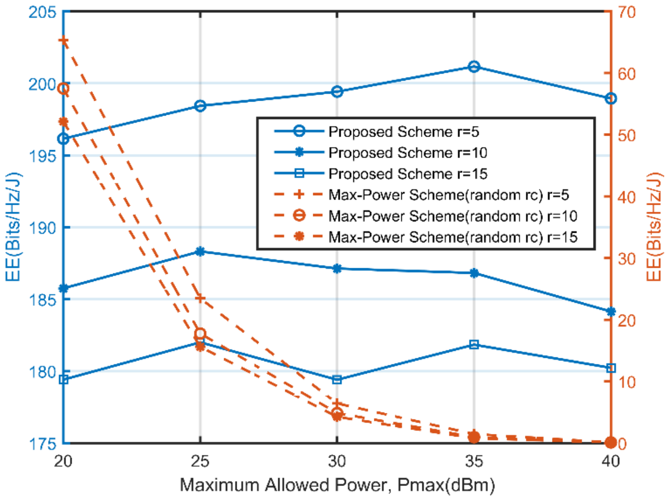


Figure 4.5 Energy Efficiency Performance of the WP-BC Network with Varying Maximum Distance Between the Backscatter Transmitters and Receivers.

Figure 4.5 has illustrated that energy efficiency performance of the proposed scheme performs better than the Max Power scheme regardless of the maximum distance between backscatter transmitter and receiver of each backscatter link. When the maximum distance between each backscatter link increases, the energy efficiency performance deteriorates. This is due to path loss between backscatter transmitters and receivers increase which limits the achievable data rate of backscatter links. Max Power scheme has the similar performance trend with the proposed scheme.

In Figure 4.6, the performance in terms of fairness of the proposed scheme remains superior over the Max Power scheme. A slight decline in the fairness index of the proposed scheme with the increasing maximum distance between backscatter transmitters and receivers. This is because the increasing path loss between each backscatter link limits the achievable data rates which will indirectly limits the achievable energy efficiency of each backscatter link.

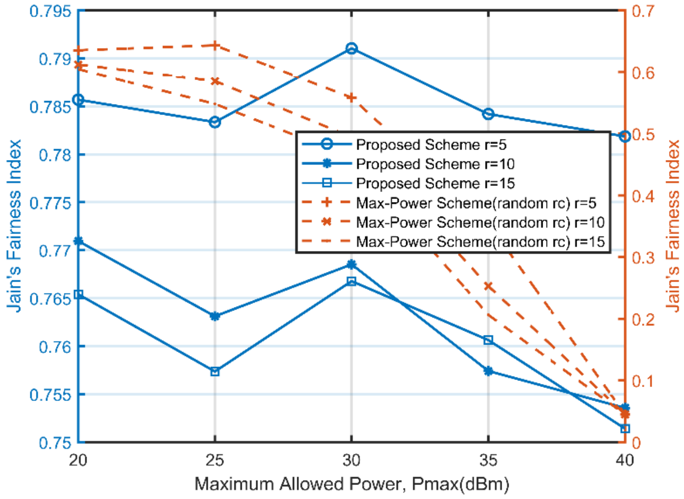


Figure 4.6 Fairness Performance of the WP-BC Network with Varying Maximum Distance Between the Backscatter Transmitters and Receivers.

4.5 Summary

In summary, a near-optimal interference-aware and efficient resource allocation scheme that strives for the maximization of the energy efficiency performance of WP-BC networks has been proposed. An iterative algorithm that jointly optimizes the reflection coefficient of backscatter transmitter and transmit power of the PB has been proposed. The superior performance of the proposed scheme has been shown under different scenarios with varying the numbers of backscatter links and maximum distance between backscatter transmitters and receivers. Fairness awareness has been shown to be significant in efficiently utilizing the transmit power from the PB and the channel gain to provide high energy efficiency for the users in the WP-BC networks which has been demonstrated in the simulation results in terms of energy efficiency and fairness performance.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The resource allocation problem for WP-BC networks with multiple backscatter links by taking into account energy efficiency fairness and co-channel interference between backscatter links has been studied. On the precondition of user fairness, the reflection coefficient of the backscatter transmitter and the transmit power of the PB have been jointly optimized based on PSO for the maximization of the energy efficiency performance of the BC network. Fairness awareness is crucial in the network management of BC. It can efficiently provide a fair share of resources to the users and ensures good energy efficiency for the individual backscatter receivers. The proposed resource allocation for the BC scheme has successfully demonstrates that it achieves substantial performance gains over the baseline schemes in energy efficiency and Jain's fairness index.

5.2 Recommendations for future work

Further investigation on this topic can be done to enhance the user experience with the increasing demand for high data rates and capacity in wireless networks. One of the recommendations is to tackle the resource allocation problem for multi-carrier WP-BC networks. Multi-carrier operation allows backscatter devices to utilize multiple frequency channels or carriers to harvest energy. This has enhanced spectral efficiency and improve throughput of the networks. However, it has increase resilience of the network to interference and backscatter transmitter may harness the RF energy from the different channels. Therefore, multi-carrier stands out as a promising approach for improving energy efficiency and performance of WP-BC networks which well-suited for applications such as IoT and smart infrastructure.

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APPENDICES

Publication List

Lum, H. T., Chong, W. S., Lee, Y. L., Tee. Y. K., Sheraz, M., Chuah, T. C., and Feng, K., 2024. Fair Resource Allocation for Energy-Efficient Wireless-Powered Backscatter Communications: A Swarm Intelligence Approach. *ETRI Journal, Wiley*. (Submitted for review)