Optimal Time Splitting in Wireless Energy Harvesting-Enabled Sensor Networks

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Abstract. This research paper presents a study on wireless energy harvesting (WEH) protocols and their impact on the performance of sensor networks. A time switching (TS)-based WEH protocol is proposed, which allows sensor nodes to switch between energy harvesting and data transmission modes. The primary objective of this research is to maximize the uplink (UL) sum throughput while considering the constraint of a minimum downlink (DL) throughput. To achieve this, an optimization problem is formulated, and the Karush-Kuhn-Tucker (KKT) conditions and Lagrangian multiplier are employed to solve the optimization problem. Additionally, a UL-DL channel gain-based unequal sensor node operating time scheme is introduced. The results of the study demonstrate that increasing the DL threshold data rate enhances UL performance in terms of sum throughput and outage. Moreover, the proposed channel gain-based unequal operating time scheme outperforms the equal sensor node operating time approach.

Keywords: Wireless energy harvesting · Sensor networks · Sum throughput · Outage

1 Introduction

Wireless energy harvesting (WEH) has been recognized as a critical element of modern communication systems, particularly in the context of 5G and beyond. With the expansion of wireless devices and services, energy consumption has become a major challenge for sustainability, and WEH furnishes a potential solution [1]. WEH can indeed be implemented in various applications, including the

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Internet of Things (IoT), Wireless Sensor Networks (WSNs), and cognitive radio (CR) systems. In the IoT, WEH can power small devices and sensors, empowering them to operate without the need for batteries or wired power sources. This allows for increased flexibility and mobility in IoT deployments [2]. In WSN, WEH can be used to power the sensors, eliminating the need for frequent battery replacements. This enhances the sustainability and maintenance-free operation of the sensor network [3]. Wireless energy harvesting also plays a significant role in the field of CR, offering significant advantages and addressing critical challenges [4]. The CR, as a technology that enables intelligent and adaptive wireless communication, requires a continuous and reliable power source to operate efficiently. However, WEH is crucial as it overcomes the limitations of traditional battery power, enhancing the scalability, flexibility, and lifespan of CR devices. This technology allows devices to extract energy from the environment, such as from ambient sources like RF signals, light, or vibrations. Radio Frequency (RF) WEH involves harvesting energy from ambient RF signals that already exist in the environment, such as from Wi-Fi, cellular, or other wireless communication networks. The energy can then be used to power the device or recharge its battery, reducing reliance on external power sources and improving the device's lifespan.

Power splitting (PS) and time switching (TS) are the two most popular energy harvesting protocols used to manage the harvested energy [5,6]. The PS protocol divides energy into two parts, where one part is directly used to power the device, and another part is stored for information transmission. This makes a balance between immediate energy requirements and energy storage. On the other hand, TS involves switching between two different time periods for energy utilization. During the first time period, the harvested energy fulfills immediate power requirements. In the second time period, the harvested energy is stored in a battery for transmission. A comprehensive analysis of Simultaneous Wireless Information and Power Transfer (SWIPT) is Demonstrated in [7]. The authors cover a wide range of features related to SWIPT, including TS, PS, and antenna beamforming. It examines the advantages, limitations, and tradeoffs associated with each technique, providing a comprehensive understanding of their capabilities. The recent developments in materials, wireless power transfer standards, and integration with other technologies are expected to drive the growth of WEH techniques.

1.1 Related Work

Hosein et al. proposed a Time Division Multiple Access (TDMA) based protocol in WEH networks, where each time slot is divided into two intervals: one for energy absorption and the other for data transmission by the sensors [8]. In their proposed model, a sensor can transmit its information if the amount of energy it has harvested surpasses its power consumption requirements. They focus on achieving energy-efficient resource allocation while considering constraints on time scheduling parameters and transmission power consumption. Another protocol, named TSAPS, is introduced for EH relay networks. It combines elements from the Traditional TS and adaptive power splitting (APS) techniques [6]. The study aims to derive a closed-form outage probability expression of the TSAPS protocol and analyze its effective transmission rate in scenarios involving random relay selection and opportunistic relay selection. Saman *et al.* propose a new hybrid protocol that combines PS and TS EH protocols [9]. An optimization problem is formulated to determine the optimal PS and TS ratios, aiming to maximize throughput in information transfer from the source to the destination for both decode-and-forward (DF) and amplify-and-forward (AF) relaying schemes [9]. Chao *et al.* implement EH in cooperative spectrum sharing within CR systems. Primary users (PUs) harvest energy from their access points (APs), while APs and secondary users (SU) are powered by a stable power supply [10]. Cooperation from SUs in wireless energy transfer enhances EH efficiency for PUs, and SU assistance in primary data transmission improves link robustness. Nguyen *et al.* analyze the impact of relay transceivers in terms of outage probability and throughput of cognitive network with an energy-harvesting relay. Two wireless power transfer policies and two bidirectional relaying protocols are considered in the network configuration [11]. In a proposed protocol for an underlay cognitive relay network, secondary nodes harvest energy from the primary network while sharing its licensed spectrum. Outage probability expression is derived, considering constraints on maximum transmit power, peak interference power, and interference power from primary users to the secondary network [12]. An integrated model is proposed for cooperative dual-hop DF relay transmission, combining information relay and wireless power supply through a TS protocol based on RF energy harvesting [13]. The relay node assists communication between an energy-constrained source and destination while supplying power to them. In a WEH relay sensor network, Nirati *et al.* aim to maximize system throughput using DF relaying and TS for energy harvesting and transmission. The harvested energy charges the battery of a common control unit, which is then distributed among the relay nodes for transmission [14].

1.2 Motivations and Contributions

In the above-mentioned article, TS-based protocol is implemented to perform two operations; UL and DL operations. However, in this study, a TS protocol is considered to operate three operations. Along with UL and DL, an additional dedicated EH mode exists. The importance of optimal EH time for UL sum throughput maximization under the constraint of guaranteed DL quality of service (QoS) also was not addressed previously. Furthermore, the literature commonly assumes equal time for the operation of sensor nodes, which may not be a suitable approach considering the frequent variation of channel gain. The key contributions of this research paper are as follows:

- Proposal of a TS-based WEH protocol that allows sensor nodes to efficiently switch between energy harvesting and data transmission modes, optimizing the utilization of available energy resources.

- An optimization problem is formulated to maximize the UL sum throughput of the sensor network. The problem considers the constraint of a minimum DL throughput, ensuring a balance between UL and DL performance.
- A channel gain-based approach is proposed to allocate operating time among sensor nodes unequally. This approach utilizes the variations in channel gains to enhance the overall throughput performance of the sensor network compared to an equal operating time allocation.

The rest of the paper is organized as follows: Sect. 2 presents the system model for wireless energy harvesting (WEH) and introduces the equal time-based operating time as well as the proposed channel gain-based unequal operating time under the problem formulation in Sect. 3. Section 4 discusses the simulation results. Finally, Sect. 5 concludes the research work.

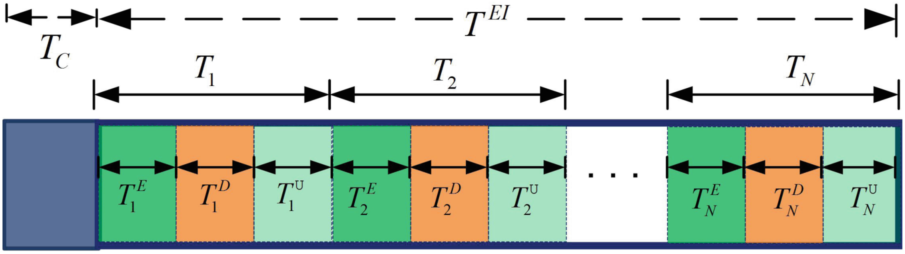

Fig. 1. Operating time frame for energy harvesting, UL, and DL transmission for each sensor node.

2 System Model

A typical multi-user wireless-powered communication system has been considered to analyze the proposed work. The system consists of one base station (BS) and N sensor nodes (SNs) uniformly distributed within the transmission range of BS. The BS is connected to a reliable power supply and maintains continuous communication with the SNs. However, the SNs have limited energy resources, meaning their ability to transmit information and perform regular operations is constrained by the available battery power. To overcome this limitation, the SNs first harvest energy from the BS and then utilize a portion of that harvested energy for information transmission. The surplus energy is stored in a supercapacitor, which is used to sustain regular operations. For energy harvesting and information transmission, a time switching (TS) based protocol is employed. The BS is equipped with multiple antennas to efficiently transfer energy and information, while the SNs are restricted to a single antenna due to size limitations. Additionally, all the SNs operate in half-duplex mode, meaning they cannot transmit and receive simultaneously.

The SNs exhibit the ability to switch flexibly between energy harvesting and information decoding during downlink (DL) transmissions. To prevent interference among the SNs, a Time Division Multiple Access (TDMA) protocol is adopted. The operation cycle of the BS, denoted as T_T, is divided into two phases: the control phase (T_C) and the transmission phase (T_{EI}) as depicted in Fig. 1. During the T_C phase, the BS estimates the channel gain and synchronizes the SNs. The T_{EI} phase is dedicated to energy harvesting and information transmission and is further divided into N time slots $(T_1, T_2, ..., T_N)$. Representing the time assignment vector as $\mathbf{t} = [T_1, T_2, ..., T_N]^T$, it is evident that $\mathbf{t^T 1} = T_{EI}$. Each time slot T_i, within the operating cycle of the ith SN, consists of three durations: $\mathbf{T^E} = \{T_i^E | i = 1, 2, ..., N\}$ for energy harvesting during DL, $\mathbf{T^D} = \{T_i^D | i = 1, 2, ..., N\}$ for information receiving during DL, and $\mathbf{T^U} = \{T_i^U | i = 1, 2, ..., N\}$ for uplink (UL) transmission. During the energy harvesting and DL information receiving times of the jth SN, the ith SN (where $i \neq j$) also detects RF signals due to the broadcast nature of the BS. Consequently, the ith SN is capable of harvesting energy during $T_j^{DL} = T_j^E + T_j^D$ and also during its dedicated T_i^E time slot. It is important to note that SNs cannot perform energy harvesting during the UL time slot.

The UL and DL channels are considered as quasi-static independent block fading channels i.e., channel power gain remains constant during each frame time and may change independently from frame to frame. The DL channel from $BS - to - SN_i, g_i \sim \mathcal{CN}(0, \sigma^2_{BS_i})$ and UL channel $SN_i - to - BS, h_i \sim \mathcal{CN}(0, \sigma^2_{S_i B}), (i = 1, 2, ..., N)$ are Rayleigh faded channels and normalized channel power gains are symbolized as $|g_i|^2$ and $|h_i|^2$ respectively. The instantaneous channel gains of g_i and h_i are exponentially distributed with mean λ_x and λ_y respectively. It is also assumed that perfect channel state information is available. The UL and DL channel noise is symbolized as n_b and n_s, and respective noise powers σ_U^2 and σ_D^2 are assumed to be identical. For simplicity, let $\sigma_U^2 = \sigma_D^2 = \sigma^2$.

3 Problem Formulation

$y_D(k)$, the DL received signals at the ith SN and $y_D(k)$, the UL transmitted signal from ith SN at kth time instant are given by (1) and (2), respectively.

$$y_D(k) = \sqrt{P_i^B d_i^{-m}} g_i S_b(k) + n_s \quad (1)$$

$$y_U(k) = \sqrt{P_i d_i^{-m}} h_i S_s(k) + n_b \quad (2)$$

where, P_i^B and P_i are the transmitted power from the BS and SN respectively, d_i represent the distance between the BS and the ith SN, m denote the path loss exponent, and $S_b(k)$ and $S_s(k)$ represent the normalized information signal from the BS. and SN.i.e $E\{|S_b(k)|^2\} = 1$ and $E\{|S_s(k)|^2\} = 1$. When the jth SN uses $y_D(k)$ signal for energy harvesting during T_j^E and information receiving during T_j^D, ith SN $(i \neq j)$ uses for energy harvesting during T_j^{DL}. It is noticeable that

ith SN is also in energy harvesting mode during T_i^E. Hence, T_i^{EH}, the total time for energy harvesting by ith SN can be denoted as

$$T_i^{EH} = \sum_{j=1, j\neq i}^{N} T_j^{DL} + T_i^E = \sum_{i=1}^{N} T_i^{DL} - T_i^D \tag{3}$$

Using (1), Eh_i, the energy harvested by ith node can be expressed as

$$Eh_i = \frac{\eta T_i^{EH} P_i^B |g_i|^2 + \sigma^2}{d_i^m} \tag{4}$$

The symbol η denotes the efficiency of the rectifier circuit which converts the received radio signal to direct current. For the sack of simplicity, η is considered same for all SNs.

3.1 Equal Time Distribution

In this section, we will analyze outage when the data rate on any of UL and DL falls below R_{th}, a threshold data rate. It is assumed that an equal time frame is assigned to all the SNs, i.e., $T_1 = T_2 = ... = T_N = T$. We also assumed $T^E = \alpha_i T, T^D = T^U = (1-\alpha_i)T/2$. The ith SN utilizes harvested energy, expressed in (4), to DL transmission during $(1-\alpha_i)T/2$. Hence, transmit power of ith SN is expressed as

$$P_i = \frac{2Eh_i}{\Big(1-\alpha_i)T} = \frac{2\Big(\eta T_i^{EH} P_i^B |g_i|^2 + \sigma^2\Big)}{d_i^m (1-\alpha_i)T} \tag{5}$$

It is noticeable that only a fraction of the time of the received signal is exploited by SN for DL and the harvested energy during $\mathbf{T^{EH}}$ is fully exploited for UL transmission. R_i^D and R_i^U are the achievable DL and UL throughput of SN_i expressed in (6) and (7), respectively.

$$R_i^D = \frac{(1-\alpha_i)T}{2} \log_2\left(1 + \frac{P_i^B |g_i|^2}{\sigma^2}\right) \tag{6}$$

$$R_i^U = \frac{(1-\alpha_i)T}{2} \log_2\left(1 + \frac{P_i |h_i|^2}{\sigma^2}\right) \tag{7}$$

It is noticeable that the operation of SN is uncorrelated to each other. Hence, sum of the maximum achievable throughput of each SN is the maximum achievable throughput of the system. Therefore,

$$\text{Objective:} \quad \text{maximize} \quad R_i^U = \sum_{i=1}^{N} \frac{(1-\alpha_i)T}{2} \log_2\left(1 + \frac{P_i |h_i|^2}{\sigma^2}\right) \tag{8a}$$

$$\text{Constraints:} \quad R_i^D = \frac{(1-\alpha_i)T}{2} \log_2\left(1 + \frac{P_i^B |g_i|^2}{\sigma^2}\right) \geq R_{th}, \ \forall i \tag{8b}$$

$$0 < \alpha_i < 1 \tag{8c}$$

The constraint (8b) ensures minimum QoS requirement for downlink data rate. The optimization problem (8a) is a convex problem, which is proved in Appendix I.

Theorem 1. *The fraction of energy harvesting time* α_i, $\forall i \in \mathcal{N}$ *for the optimal solution of throughput maximization problem (8a) with constraints (8b) and (8c), can be expressed as*

$$\alpha_i = 1 - \frac{2R_{th}}{T \log_2\left(1 + \frac{P_i^B |g_i|^2}{\sigma^2}\right)}, \qquad \forall i \in \mathcal{N}, \tag{9}$$

Proof. The proof is reproduced from standard literature in Appendix II.

It should be noted that for $\alpha_i > 0$, it is necessary to have $\frac{2R_{th}}{T \log_2\left(1+\frac{P_i^B |g_i|^2}{\sigma^2}\right)} < 1$, which determines the minimum transmit power of the BS for a particular R_{th} as $P_i^B > \frac{\sigma^2}{|g_i|^2}\left(2^{\frac{2R_{th}}{T}} - 1\right)$. The BS needs to transmit signals with varying power levels for each subscriber node (SN), and this can be expressed as:

$$P_i^B = \frac{\sigma^2}{|g_i|^2}\left(2^{\frac{2R_{th}}{T}} - 1\right) + P_b \tag{10}$$

where P_b represents the additional power beyond the minimum transmit power.

3.2 Unequal Time Distribution

In the previous subsection, we assumed an equal operating time frame for each of all SNs i.e., $T_1 = T_2 = ... = T_N = T$. Here we propose an operating time distribution scheme that decides T_i, $\forall i \in N$, the single operating time frame of each SN based on their UL and DL channel gain quality as

$$T_i = T^{EI} \frac{g_i h_i}{\sum_{i=1}^{N} g_i h_i}. \tag{11}$$

Now the fraction of energy harvesting time α_i, $\forall i \in \mathcal{N}$ can be expressed as

$$\alpha_i = 1 - \frac{2R_{th}}{T_i \log_2\left(1 + \frac{P_i^B |g_i|^2}{\sigma^2}\right)}, \qquad \forall i \in \mathcal{N}. \tag{12}$$

It is acknowledged that the problem of maximizing throughput, as expressed in Eq. (8a), can be formulated to determine the optimal T_i. However, this specific task is left for future research and exploration.

4 Simulation Results

In this section, we have examined the optimal uplink (UL) sum throughput and outage probability of the proposed WEH system model through simulation. The

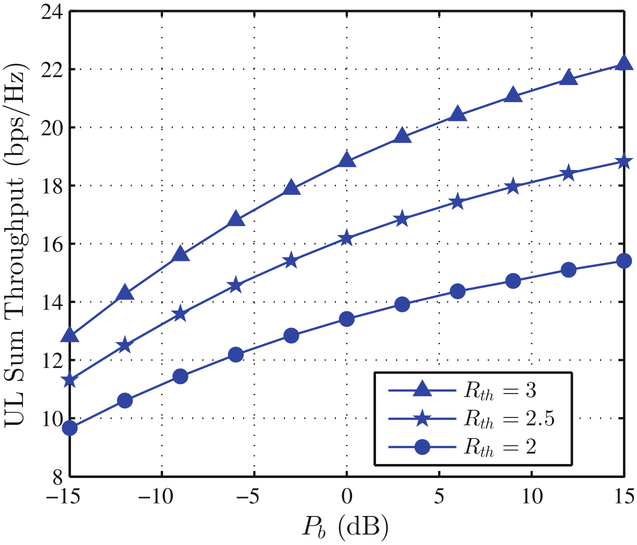

Fig. 2. Achievable UL sum throughput as a function of P_b, the additional transmit power

simulation process was conducted using Matlab software, taking into account the following crucial parameters for the analysis; $N = 10$, $m = 2.7$, $\eta = 0.9$, $d = \{4, 6, 9, 5, 10, 7, 8, 10, 5, 9\}$ meter. The simulation results were obtained by averaging over 10^5 independent Monte Carlo trials. It is important to highlight that the minimum data rate for the DL transmission is guaranteed. Therefore, the simulation results focus on the performance analysis of the UL communication.

The achievable UL sum throughput as a function of P_b, the additional transmit power for varying DL throughput is shown in Fig. 2. As expected, the UL sum throughput improves with an increase in P_b. It is worth noting that the UL sum throughput also strongly depends on the DL threshold of the system. Interestingly, the UL sum throughput improves as the DL threshold increases. This can be explained by the fact that an increase in R_{th} leads to an extended UL transmission time T^U, resulting in enhanced system performance.

Figure 3 illustrates the relationship between the outage probability and P_b the additional transmit power of the BS for the nearest and farthest SN. As expected, the outage probability decreases with an increase in transmit power, and the nearest user exhibits better outage performance compared to the farthest user. When the operating time frame for each SN is increased (from $T = 1$ s to 1.5 s and 2 s), the SNs have more time to harvest energy, resulting in an improved outage performance. As the minimum UL rate requirement, Ru_{th}, increases, the outage performance degrades. However, it is worth noting that the outage performance improves when the minimum DL rate, R_{th}, increases. This is because as R_{th} increases, α_i decreases, which leads to an increase in both

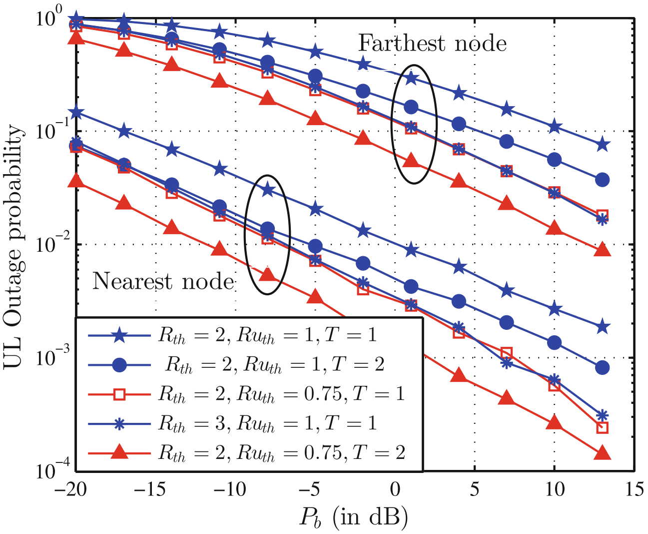

Fig. 3. UL outage performance of the nearest and farthest user as a function of additional transmit power of BS for the following parameters, DL threshold $R_{th} = \{2, 3\}$ bps/Hz, UL threshold $Ru_{th} = \{0.75, 1\}$ bps/Hz, equal operating time frame $T = \{1, 2\}$ s.

DL and UL transmission time (i.e., T^U and T^D). As a result, the UL transmission rate also improves.

The superiority of the proposed channel gain-based unequal SN operating time over equal SN operating time in terms of UL sum throughput is

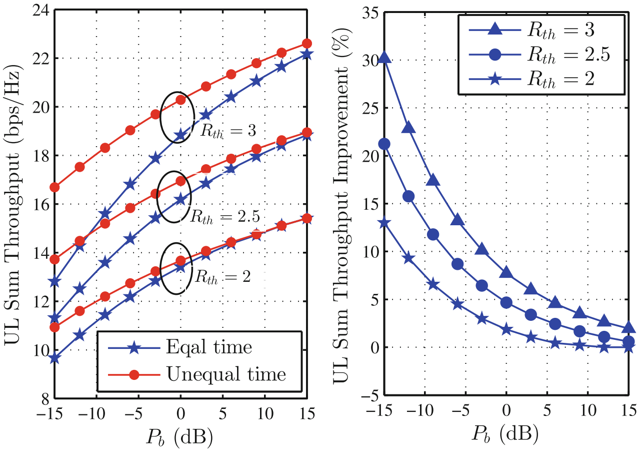

Fig. 4. (a) UL sum throughput comparison between equal operating time frame and proposed unequal operating time frame for $R_{th} = \{2, 2.5, 3\}$ bps/Hz, (b) UL sum throughput improvement achieved by proposed unequal operating time frame over the equal operating time frame for $R_{th} = \{2, 2.5, 3\}$ bps/Hz.

demonstrated in Fig. 4. The results clearly indicate that the proposed method achieves enhanced sum throughput, especially in the lower transmit power region. Notably, Fig. 4(b) illustrates that as the DL threshold increases, the performance of the proposed method surpasses that of the lower DL threshold. This outcome validates the effectiveness of incorporating the channel gain-based unequal SN operating time in WEH-based sensor networks, as it significantly improves system throughput.

5 Conclusion

In conclusion, this research paper presents significant findings in the field of WEH in sensor networks. The proposed TS-based WEH protocol, along with the formulated optimization problem, offers a promising solution to maximize the UL sum throughput while maintaining a minimum DL throughput. The results indicate that increasing the DL threshold data rate enhances UL performance in terms of sum throughput and outage. Additionally, the channel gain-based unequal sensor node operating time is shown to be superior to the equal operating time, further improving system performance. These findings highlight the potential of WEH protocols and unequal operating time allocation to enhance the performance of sensor networks, contributing to the advancement of wireless communication systems. In the future, we will extend this work to the cognitive radio systems and analyze the system's performance. Furthermore, there is a scope to introduce non-orthogonal multiple access (NOMA)-based [15] transmission and cell-free massive MIMO [16] in the WEH systems.

Appendix-I

To prove that the function

$$f(\boldsymbol{\alpha}) = \sum_{i=1}^{N} \frac{(1-\alpha_i)T}{2} \log_2\left(1 + \frac{P_i|h_i|^2}{\sigma^2}\right) \tag{13}$$

is convex, we need to show that the Hessian matrix of the function is positive semidefinite for all valid values of $\boldsymbol{\alpha}$. The Hessian matrix of a function is a matrix of second-order partial derivatives. For our function $f(\boldsymbol{\alpha})$, the Hessian matrix is defined as:

$$H = \begin{bmatrix} \frac{\partial^2 f}{\partial \alpha_1^2} & \frac{\partial^2 f}{\partial \alpha_1 \partial \alpha_2} & \cdots & \frac{\partial^2 f}{\partial \alpha_1 \partial \alpha_N} \\ \frac{\partial^2 f}{\partial \alpha_2 \partial \alpha_1} & \frac{\partial^2 f}{\partial \alpha_2^2} & \cdots & \frac{\partial^2 f}{\partial \alpha_2 \partial \alpha_N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial \alpha_N \partial \alpha_1} & \frac{\partial^2 f}{\partial \alpha_N \partial \alpha_2} & \cdots & \frac{\partial^2 f}{\partial \alpha_N^2} \end{bmatrix} \tag{14}$$

Let's compute the second-order partial derivatives:

$$\frac{\partial^2 f}{\partial \alpha_i \partial \alpha_j} = -\frac{T}{2} \log_2\left(1 + \frac{P_i|h_i|^2}{\sigma^2}\right) \delta_{ij}, \tag{15}$$

where δ_{ij} is the Kronecker delta function. Notice that the second-order partial derivatives are constant with respect to $\boldsymbol{\alpha}$, which means the Hessian matrix is a constant matrix. Specifically, all diagonal elements are the same, and all off-diagonal elements are zero. The Hessian matrix of our function is then:

$$H = -\frac{T}{2}\log_2\left(1+\frac{P|h|^2}{\sigma^2}\right)I, \tag{16}$$

where I is the identity matrix. Since the Hessian matrix is a constant matrix with negative values on the diagonal (due to the negative logarithm term), it is negative definite, which implies it is also positive semidefinite. Therefore, the function $f(\boldsymbol{\alpha})$ is convex, as the Hessian matrix is positive semidefinite for all valid values of $\boldsymbol{\alpha}$.

Appendix-II

To solve the optimization problem using the Lagrangian and KKT method, we first define the Lagrangian function as follows:

$$\begin{aligned} L(\boldsymbol{\alpha},\boldsymbol{\lambda},\boldsymbol{\mu}) = &\sum_{i=1}^{N}\frac{(1-\alpha_i)T}{2}\log_2\left(1+\frac{P_i|h_i|^2}{\sigma^2}\right)+\sum_{i=1}^{N}\lambda_i\left(\frac{(1-\alpha_i)T}{2}\log_2\left(1+\frac{P_i^B|g_i|^2}{\sigma^2}\right)-R_{th}\right)\\ &+\sum_{i=1}^{N}\mu_i(\alpha_i)(1-\alpha_i) \end{aligned} \tag{17}$$

where $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \ldots, \alpha_N]$ is the vector of variables, $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \ldots, \lambda_N]$ and $\boldsymbol{\mu} = [\mu_1, \mu_2, \ldots, \mu_N]$ are the Lagrange multipliers for the inequality constraints and bound constraints, respectively. Next, to find the stationary points we need partial derivatives of the Lagrangian with respect to α_i, λ_i, and μ_i and setting them to zero:

$$\frac{\partial L}{\partial \alpha_i} = \frac{T}{2}\log_2\left(1+\frac{P_i|h_i|^2}{\sigma^2}\right)-\lambda_i\frac{T}{2}\log_2\left(1+\frac{P_i^B|g_i|^2}{\sigma^2}\right)-2\mu_i\alpha_i = 0 \tag{18}$$

$$\frac{\partial L}{\partial \lambda_i} = \frac{(1-\alpha_i)T}{2}\log_2\left(1+\frac{P_i^B|g_i|^2}{\sigma^2}\right)-R_{th} = 0 \tag{19}$$

$$\frac{\partial L}{\partial \mu_i} = \alpha_i(1-\alpha_i) = 0 \tag{20}$$

Note that to find the α_i from $\frac{\partial L}{\partial \alpha_i}$, we need to find the values of the Lagrange multipliers λ_i and μ_i. This can be done iteratively using numerical methods, such as gradient descent or Newton's method. However, we can solve for α_i from the derivative of the Lagrangian with respect to λ_i. Finally, solving for α_i:

$$\alpha_i = 1-\frac{2R_{th}}{T\log_2\left(1+\frac{P_i^B|g_i|^2}{\sigma^2}\right)} \tag{21}$$

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