Joint TS Beamforming and Hybrid TS-PS Receiving Design for SWIPT Systems

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ABSTRACT Simultaneously wireless information and power transfer technology enables information and energy to be transmitted over the same radio frequency (RF) signal. We investigate a multiple input simple output (MISO) system where the multiple-antenna base station not only transmits information to single-antenna users, but also supplies all power they need. The same beamforming at base station under two modes of energy transfer and information transmission causes the problem of low system energy efficiency. To solve this, we put forward a novel transmission scheme where beamforming is divided by time switching (TS) into two parts, energy beamforming and information beamforming, and users receive by hybrid time switching and power splitting (hybrid TS-PS) correspondingly. Under constraints of information and energy, we aim to achieve the maximal energy efficiency by jointly optimize power splitting, time allocation, beamforming for energy transfer and information transmission phase respectively. In the solving process, we transfer the maximal energy efficiency problem into the minimal energy consumption problem, analyze the feasibility, then prove the existing of optimal solution. Furthermore, we put forward a semidefinite relaxation (SDR) based algorithm to solve the problem optimally and two sub-optimal designs to simplify computing complexity. Simulation results illustrate that our proposed design can achieve the optimal energy efficiency and prove the asymptotic optimality of two sub-optimal solutions.

INDEX TERMS Beamforming, energy efficiency, power splitting, SWIPT, time switching.

I. INTRODUCTION
A. MOTIVATION AND RELATED WORKS

Simultaneously wireless information and power transfer (SWIPT) technology is derived in [1] as a theoretical perspective. In recent years, this technology has attracted a lot of research in the field of wireless communication [2]–[4]. It provides great benefits in terms of power consumption, spectrum efficiency, interference management and transmission delay by simultaneously transmitting energy and information. Users convert the received RF signal into energy through a rectifier circuit to maintain the normal work. Appropriate transmission design can significantly improve the energy efficiency of the system and effectively extend the lifetime caused by insufficient power supply of nodes. At the same time, information interaction provides advanced applications and services for the network. In new era of network, SWIPT technology is of fundamental importance for all types of energy and information transmission [5].

Dense small unit deployment network has been becoming a main structure in the fifth generation mobile networks (5G) [6]. However, the character of no power supply due to remote deployment of small devices causes attention that the energy consumption problem of this network need to be solved. On the other hand, 5G wireless communication network brings trends such as the Internet of Things (IOT) and machine-like communications (MTC), adapting to more flexible transmission for information sharing [7]–[9]. While, green communication and power consumption reduction have become two of the eight requirements of modern communication recognized by the industry and academia [7]. In these cases, aiming at the double demands of energy supply and information transmission, this paper designs a transmission for high energy utilization efficiency.

The process of energy collection is destructive to the information decoding part of the RF signal. At the same time due to the limitation of rectifier circuit function in the actual system,
it is not feasible to collect energy and decode information directly with the same RF signal. Therefore, the received signal must be divided into two parts. Trade-off between them is a very important aspect of SWIPT system. The main schemes for receivers are TS mode and PS mode [10]. With PS, users divide the received signal into two parts according to a power portion through power splitter. One part for energy collection and the other for information decoding. Unlike the two phases working simultaneously, in the TS mode, received signal is divided by time into two parts. One part for energy harvest, the remaining for the other. Studying for the above has been done by large numbers of researchers [11]–[13]. The TS mode is easy to be applied in practical system due to its simple structure, while the PS mode outperforms the TS. On the other hand, the non-linear energy harvesting models have been discussed in [14]–[16], where the practical harvested energy are related to maximum power that a receiver can harvest, and physical hardware in terms of its circuit sensitively, limitations, and leakage currents, besides the input power considered in the linear model. We observe that the differences are determined by each receiver itself. Regardless of the differences of each user in each period, we mainly focus on transmission designs of beamforming, power splitting, time allocation. Thus, in this paper, we assume that users have the same parameters in each period, and adopt linear energy harvesting model, which uses a linear factor to represent the nonlinear functional result.

Transmitting beamforming can improve the transmission efficiency by making the RF signal transmit in the narrow-band beam with more centralized orientation towards users. In traditional wireless communication network, [17]–[22] have analyzed the structure of multi-cell and single-cell MISO network, where [17]–[19] solve the formulated problem based on a distributed method of Lagrangian duality. Adding energy transfer, [23]–[27] design joint beamforming and PS mode transmission schemes in SWIPT system. They achieve the minimal transmitting power of base station under constraints of system signal to noise ratio (SINR) and minimum energy collection. The quadratic problem can be regarded as a semi-positive definite programming problem with a rank one matrix constraint, and [27] presents a stochastic method based on semidefinite relaxation. In order to raise applicability of the method, [28] gives a transmission design based on the maximal ratio transmission strategy, and a suboptimal solution to optimize the SINR is proposed in [24]. On the other hand, under energy constraints, [29] studies the maximum transmission rate of a multi-user system in the interference channel, where authors design a transmission strategy for the transmitter and TS receiver. Also in the interference channel, the joint optimization of beamforming and PS receiver is carried out in [30], and the minimal transmitting power is obtained under conditions of SINR and energy collection. Authors in [31] optimize the users’ transmission rate under energy and security constraints. Transmitting TS mode is derived in [32], which enables two kinds of transmissions for energy and information differently, leading to a more efficient transmission. In this paper, to further improve transmission performance, we combine the advantages to design a joint TS mode transmitting and hybrid TS-PS receiving scheme, under constraints not only of the above, but also of information volume. Furthermore, beamforming based on SWIPT technology in scenarios of orthogonal Multiple Access (OFDM) systems [33], in Non-orthogonal Multiple Access (NOMA) [34], relay system [35], and sensors network [36] are also widely studied.

In the meanwhile, energy efficiency has become a hot research issue in emerging networks. It is defined by the ratio of information transmission rate to energy consumption, representing the amount of data transmitted per unit of energy consumed by the system. The optimization of it satisfies the current need of green communication. [37] discusses in detail the influence of base station hardware structure, users’ signal receiving, signal processing and other aspects on energy efficiency in 5G network structure. [38] studies the optimal energy efficiency in wireless energy supply network (WPCN). Authors designs a time and power allocation strategy under SINR and energy constraints. Conditions of whether there are transmission volume constraints or not are analyzed. With no requirements, authors equalize the original problem into two known traditional network structures and solve them separately. While with the other, it is a non-convex optimization problem of fractional structure, which is transformed into a standard convex optimization problem by using the fractional programming theory. In [39], the authors study the energy efficiency of OFDM systems. By optimizing the frequency and power resources, it achieves the maximal energy efficiency under the constraint of minimum energy collection. [40] optimizes the energy efficiency of a large-scale antenna MIMO system, however, the scheme for single user cannot adapt to the conditions of multi-users due to different time and power allocation. Meanwhile in [41], energy efficiency is optimized under security demanding, achieving a balance between transmission security and energy consumption in the scene of artificial noise and statistical channel state. In [42], authors optimize spectral efficiency and energy efficiency in MIMO system for secure transmission. In [43] and [44], it is optimized in secure cognitive radio networks, while in MIMO-NOMA Systems in [45], [46] studies energy efficiency in a MISO downlink transmission system. Authors optimizes the power allocation of base station and the power splitting schemes factor of users, obtaining the closed form expression. Notably, although the structure in this paper is similar to [46], it adapts matched filter beamforming in the transmitter, and PS splitting for users, achieving the corresponding maximal energy efficiency under constraints of minimum transmitting rate. Besides, we design an energy beamforming for transmitter and a TS scheme for the BS and users. we also consider information volume of transmission, achieving optimal energy efficiency of the system.

B. CONTRIBUTION
In this paper, energy efficiency of downlink SWIPT system is studied. Users are supplied by the collected energy for all the
work. The potential applications are, e.g., WPCN for sensors and/or densely deployed information and energy transmission cellular networks. We analyze deeply relationship between the optimal energy efficiency and time distribution of the transmitter, their corresponding beamforming vectors, and power splitting of users. The optimal transmission scheme is also proposed. Furthermore, two suboptimal schemes are proposed to solve the problem of high computational complexity of the optimal transmission design. In practical systems, users transmit training symbols in the uplink to the BS, which can obtain the CSI by channel reciprocity. The time and energy consumption of this process are both independent to the design of downlink energy and information transmission. Therefore we mainly focus on the downlink process in this paper. Main contributions of this paper are summarized below. 

(1) We put forward a novel transmission design based on the TS transmitter and hybrid TS-PS users, and optimize energy efficiency for downlink SWIPT system. Aiming at different requirements for information transmission and energy transfer, we design to switch beamforming according to time, and jointly optimize two kinds of beamforming to achieve collaborative energy efficient transmission. At the same time, taking advantages of simple structure of TS and outperformance of PS, hybrid TS-PS design makes energy storage and decoding more flexible and efficient. Two types of beamforming vectors, time allocation and power splitting factors at users are optimized jointly to obtain the global optimal transmission strategy.

(2) We prove existence of the maximal energy efficiency and achieve it. Due to requirements of information decoding and energy harvest, we have constraints of minimal energy storage, minimal SINR for receiving and decoding, besides, minimal data transmission volume for normal communication. Firstly, the problem of maximal energy efficiency is equally transformed into minimal energy consumption problem under rated amount of data. Then we prove condition for the optimal solution is mainly related to the channel state. We also divide the original quadratic non-convex problem equally into two sub-problems and solve them optimally. Finally we prove the equality of every transforming and achieve the optimal solution.

(3) We put forward two low complexity sub-optimal transmission schemes and analyze the asymptotic optimality between the two and the optimal. In view of high complexity caused by multiple variables coupled together, zero interference design and SINR-optimal scheme are raised. The former is based on zero-forcing beamforming for information transmitting then jointly design energy beamforming and others. In the latter, we first solve it under information transmission requirements, then amplify the solution to meet other constraints, leading to the design meeting energy requirement with better SNR performance.

The rest of this paper is organized as follows. Section II presents and analyzes the system model then formulates the problem. Section III gives the feasibility of optimal problem. While Section IV solves the problem optimally based on SDR and obtains the optimal energy efficiency transmission scheme. In Section V, two sub-optimal designs are put forward. We simulate, analyze and compare the designs in Section VI. Finally, Section VII concludes the paper. Variables and corresponding meanings are described in TABLE 1.

### II. SYSTEM MODEL AND PROBLEM FORMULATION

This paper considers a downlink multi-user periodic information and energy transmission, which is shown as FIGURE 1, where there is one BS equipped with multiple antennas ($N_t > 1$) and $K$ single antenna users, $U_1, \ldots, U_K$. Assuming the base station adapts linear transmission precoding, each user is assigned a dedicated beam. And transmitting signal can be written as

$$x = \sum_{k=1}^{K} v_k l_k, \quad (1)$$

where $l_k$ denotes transmitted sequence for $U_K$, and $v_k$ means corresponding preconding vector. We also assume $l_k \sim CN(0, 1)$, denoting that $l_k, k = 1, \ldots, K$ are random variables, independent and identically distributed with zero mean and unit variance.

It is supposed that channels between base station and all users are quasi - static flat fading, denoted by $h_k, k =$

| Variable | Meaning |
|----------|---------|
| $N_t$    | Number of antennas |
| $K$      | Number of users |
| $U_k$    | The $k$th user |
| $T$      | Length of one period time |
| $\alpha$ | Time switching factor at BS |
| $\rho_k$ | Power splitting factor for $U_k$ |
| $\nu^i$  | Information beamforming vector at BS |
| $\nu^E$  | Energy beamforming vector at BS |
| $h_k$    | Channel matrix between BS and $U_k$ |
| $\zeta_k$| Energy collection efficiency factor |
| $\delta_k^2$ | Decoding noise variance at $U_k$ |
| $\sigma_k^2$ | Transmission noise variance to $U_k$ |
| $\Phi_k$ | Data volume threshold at $U_k$ |
| $\epsilon_k$ | Harvested power threshold at $U_k$ |
| $\gamma_k$ | SINR threshold at $U_k$ |
| Rank(A)  | Rank of matrix A |
| $A^H$    | Conjugate transpose of matrix A |
| $E[\cdot]$ | Mathematical expectation |
The transmitter, BS transfers energy in

transmitting signal is expressed as

\[ y_k = h_k^H \sum_{i=1}^{K} v_i l_i + n_k, \]

where \( n_k \sim CN(0, \sigma_k^2) \), meaning transmission noise between BS and \( U_k \).

The BS is designed to switch by TS, while users apply hybrid TS-PS scheme, the details are shown in FIGURE 2. One period length of transmission time is denoted as \( T \), and in \( \alpha (0 \leq \alpha \leq 1) \) portion of time BS transfers energy by beamforming vectors \( v_k^E = [v_1^E, \ldots, v_K^E] \). In this case, transmitting signal is expressed as

\[ x = \sum_{k=1}^{K} v_k^E l_k. \]

In the rest of time \((1 - \alpha)T\), BS transmits signal like its traditional way by beamforming vectors \( v_k^I = [v_1^I, \ldots, v_K^I] \), while transmitting signal is written as

\[ x = \sum_{k=1}^{K} v_k^I l_k. \]

Receivers follow the same time switching factor with the transmitter, BS transfers energy in \( \alpha T \), expressed as

\[ y_k = h_k^H \sum_{i=1}^{K} v_i^E l_i + n_k. \]

And the harvested energy by users can be written as

\[ E_k = \zeta_k \alpha T \left( \sum_{i=1}^{K} |h_i v_i^E|^2 + \sigma_i^2 \right). \]

where \( \zeta_k \) is energy collection efficiency factor.

On the other hand, in \((1 - \alpha)\) portion of time, users adopt PS mode to decode information (ID mode) and harvest energy (EH mode). With a power splitting factor \( \rho_k \), \((0 \leq \rho \leq 1)\), \( U_k \) decodes information by \( \rho_k \) portion of received signal, while harvests energy from the rest. Therefore, the received signal in ID mode is expressed as

\[ y_k^{ID} = \sqrt{\rho_k} \left( h_k^H \sum_{i=1}^{K} v_i^I l_i + n_k \right) + z_k, \]

where \( z_k \sim CN(0, \sigma_k^2) \) denotes decoding noise at \( U_k \). And correspondingly, we express SINR of ID mode as

\[ \text{SINR}_k = \frac{\rho_k |h_k^I v_k^I|^2}{\rho_k \sum_{i \neq k} |h_i^H v_i^I|^2 + \rho_k \sigma_k^2 + \delta_k^2}. \]

And with the bandwidth \( B \), we have the transmitting rate in bits/second (bps) as follows

\[ R_k = B \log_2 \left( 1 + \frac{\rho_k |h_k^I v_k^I|^2}{\rho_k \sum_{i \neq k} |h_i^H v_i^I|^2 + \rho_k \sigma_k^2 + \delta_k^2} \right). \]

As for the EH mode, the signal that \( U_k \) collects energy can be written as

\[ y_k^{EH} = \sqrt{1 - \rho_k} \left( h_k^H \sum_{i=1}^{K} v_i^I l_i + n_k \right), \]

and the harvested energy is

\[ E_k = \zeta_k (1 - \rho_k) (1 - \alpha) T \left( \sum_{i=1}^{K} |h_i v_i^I|^2 + \sigma_i^2 \right). \]

According to the definition, energy efficiency of system is presented as

\[ \eta_{EE} = \frac{\alpha \sum_{k=1}^{K} \|v_k^I\| + (1 - \alpha) \sum_{k=1}^{K} \|v_k^E\|}{(1 - \alpha) \sum_{k=1}^{K} \|v_k^I\| + (1 - \alpha) \sum_{k=1}^{K} \|v_k^E\|} \cdot \frac{\sum_{k=1}^{K} \log_2 \left( 1 + \frac{\rho_k |h_k^I v_k^I|^2}{\rho_k \sum_{i \neq k} |h_i^H v_i^I|^2 + \rho_k \sigma_k^2 + \delta_k^2} \right)}{\sum_{k=1}^{K} \log_2 \left( 1 + \frac{\rho_k |h_k^I v_k^I|^2}{\rho_k \sum_{i \neq k} |h_i^H v_i^I|^2 + \rho_k \sigma_k^2 + \delta_k^2} \right)}. \]
The optimization problem is shown as

\[
\begin{align*}
\max & \quad \eta_{EE} \\
\text{s.t.} & \quad \text{SINR}_k \geq \gamma_k \\
& \quad (1 - \alpha) T \log_2(1 + \text{SINR}_k) \geq \Phi_k, \\
& \quad \zeta_k (1 - \rho_k) (1 - \alpha) T \left( \sum_{i=1}^{K} |h_k^i v_i^E|^2 + \sigma_k^2 \right) \\
& \quad + \zeta_k \alpha \left( \sum_{i=1}^{K} |h_k^i v_i^E|^2 + \sigma_k^2 \right) \geq e_k, \\
& \quad 0 \leq \rho_k \leq 1, \quad \forall k, \\
& \quad 0 \leq \alpha \leq 1,
\end{align*}
\]  

(13a)

(13b)

(13c)

(13d)

(13e)

(13f)

where SINR constraints to ensure normal receiving by users are denoted in (13b), (13c) and (13d) are information volume and collected power thresholds respectively, presupposed practically for U_k. Due to monotonicity of the logarithm function, we simplify (13c) into \((1 - \alpha) \text{SINR} \geq \Phi_k\). In practice, both of information and energy thresholds are not zero, \(\Phi_k > 0, e_k > 0\). And power splitting factor \(\rho\) (13e) satisfies 0 < \(\rho\) < 1, \(\rho = 1\) when power supply is sufficient within \(\alpha\) portion of time for only energy transfer. We also observe that in (13b) and (13c), there must be intersection for SINR, [SINR|SINR > max\{\gamma_k, (1 - \alpha)T/\Phi_k\}], therefore we combine then into SINR > \(\bar{\gamma}_k(\alpha)\), which is only linearly due to variable \(\alpha\).

For the sake of description, problem (13) is referred to as the energy efficient hybrid TS-PS optimization problem (EE-HTPO). It is analyzed that the problem is nonconvex and hard to solve directly, where fractional form objective function, quadratic energy expression, and four variables coupled constraints make a difficult solving process. Considering downlink transmission of SWIPT is often applied in sensors networks and other environments, where most information is to control, with a relatively less and fixed transmission volume, we assume a fixed data volume, then the problem of energy efficiency maximization can be transformed into the energy consumption minimization, which is shown as

\[
\begin{align*}
\min & \quad \alpha T \sum_{k=1}^{K} ||v_k^E|| + (1 - \alpha) T \sum_{k=1}^{K} ||v_k^I|| \\
\text{s.t.} & \quad \text{SINR}_k \geq \gamma_k, \\
& \quad (1 - \alpha) T \log_2(1 + \text{SINR}_k) \geq \Phi_k, \\
& \quad \zeta_k (1 - \rho_k) (1 - \alpha) T \left( \sum_{i=1}^{K} |h_k^i v_i^E|^2 + \sigma_k^2 \right) \\
& \quad + \zeta_k \alpha \left( \sum_{i=1}^{K} |h_k^i v_i^E|^2 + \sigma_k^2 \right) \geq e_k, \\
& \quad 0 \leq \rho_k \leq 1, \quad \forall k, \\
& \quad 0 \leq \alpha \leq 1.
\end{align*}
\]  

(14a)

(14b)

(14c)

(14d)

(14e)

(14f)

The equivalence condition of the transformation is that the optimal solution can satisfy the equal information constraints. It is proved in solving optimal solution part of Section-IV.

In (14), the objective function is the product of norm of beamforming vectors and the allocated time. Where \(T\) can be ignored in the solution in the following. On the other hand, even under fixed \(\rho_k\) and \(\alpha\), the energy and information beamforming vector optimization problem is still non-convex. However, in addition ignoring energy constraints, the problem becomes a joint optimization of the transmitter TS mode under the condition of ensuring the transmission volume of each user, which has been studied in [49]. In the following, we discuss feasibility of the optimization problem and present optimal solution and two suboptimal solutions. Notably, in practical system, the BS calculates all the beamforming vectors for information transmission and energy transfer, time switching factor, and power splitting factor and the transmits latter two to users.

III. FEASIBILITY OF THE EE-HTPO PROBLEM

In this section, we investigate the feasibility of optimization problem under given thresholds \(\Phi_k, e_k, (k = 1, \ldots, K)\). Firstly, we focus on restricted conditions.

**Lemma 1:** The sufficient and necessary condition for problem (14) to have a solution is that the following problem has a solution.

\[
\begin{align*}
\text{find } & \quad \{v_k^1, v_k^E, \alpha, \rho_k\} \\
\text{s.t.} & \quad \rho_k (1 - \alpha) T |h_k^I v_k^I|^2 + \rho_k \sigma_k^2 + \delta_k^2 \geq \bar{\gamma}_k(\alpha), \quad \forall k, \\
& \quad 0 \leq \rho_k \leq 1, \quad \forall k.
\end{align*}
\]  

(15)

**Proof:** First of all, we focus on the necessity condition. (15) considers no energy constraints compared with (14), and we know that if (14) has a solution, so does (15). Then with the sufficiency, assuming a solution for (15) \(\{v_k^1, v_k^E, \alpha, \rho_k\}\), we have \(\theta v_k^1, v_k^E, \alpha, \rho_k\), \(\theta \geq 1\), satisfying (14), because a large enough \(\theta\) must meet (14c). Therefore, we prove that (14) is a sufficient and necessary condition of (15).

From **Lemma 1**, it is observed that the feasibility of EE-HTPO problem is deserved by information constraints, not power collection conditions. In the following part, we study further on it.

**Lemma 2:** The sufficient and necessary condition for the solution of (15) is that the following problem has a solution.

\[
\begin{align*}
\text{find } & \quad \{v_k^1, v_k^E, \alpha\} \\
\text{s.t.} & \quad \frac{(1 - \alpha) T |h_k^I v_k^I|^2 + \sigma_k^2 + \delta_k^2}{\sum_{i \neq k} |h_k^i v_i^E|^2 + \sigma_k^2 + \delta_k^2} \geq \bar{\gamma}_k(\alpha), \quad \forall k, \\
& \quad 0 \leq \alpha \leq 1.
\end{align*}
\]  

(16)

**Proof:** As for sufficiency condition, we assume a solution \(\{v_k^1, v_k^E, \alpha\}\) for (16). While the (15) has the solution \(\{v_k^1, v_k^E, \alpha, \rho_k\}\) under a given \(\rho_k\), where
\( \tilde{\mathbf{v}}_k^x = \mathbf{v}_k^x / \sqrt{\rho_k}, x \in \{I, E\}. \) And due to
\[
\begin{align*}
(1 - \alpha) \rho_k T |\mathbf{h}_k^H \mathbf{v}_k^x|^2 \\
\rho_k \sum_{i \neq k} |\mathbf{h}_i^H \mathbf{v}_k^x|^2 + \rho_k \sigma_k^2 + \delta_k^2 \\
\leq (1 - \alpha) T |\mathbf{h}_k^H \mathbf{v}_k^x|^2 \\
\rho_k \sum_{i \neq k} |\mathbf{h}_i^H \mathbf{v}_k^x|^2 + \rho_k \sigma_k^2 + \delta_k^2 \\
\geq (1 - \alpha) T |\mathbf{h}_k^H \mathbf{v}_k^x|^2 \\
\sum_{i \neq k} |\mathbf{h}_i^H \mathbf{v}_k^x|^2 + \sigma_k^2 + \delta_k^2 \geq \tilde{\gamma}_k(\alpha), \quad (17)
\end{align*}
\]
we know that the solution for (16) is a sufficient condition for that of (15). Then with necessity, supposing a solution \( \{\mathbf{v}_k^I, \mathbf{v}_k^E, \alpha, \rho_k\} \) for (15), we have
\[
\begin{align*}
\tilde{\gamma}_k(\alpha) & \leq \frac{\rho_k (1 - \alpha) T |\mathbf{h}_k^H \mathbf{v}_k^x|^2}{\rho_k \sum_{i \neq k} |\mathbf{h}_i^H \mathbf{v}_k^x|^2 + \rho_k \sigma_k^2 + \delta_k^2} \\
& = \frac{(1 - \alpha) T |\mathbf{h}_k^H \mathbf{v}_k^x|^2}{\sum_{i \neq k} |\mathbf{h}_i^H \mathbf{v}_k^x|^2 + \sigma_k^2 + \delta_k^2} \\
& < \frac{(1 - \alpha) T |\mathbf{h}_k^H \mathbf{v}_k^x|^2}{\sum_{i \neq k} |\mathbf{h}_i^H \mathbf{v}_k^x|^2 + \sigma_k^2 + \delta_k^2}. \quad (18)
\end{align*}
\]
It is analyzed that the solution of (15) also satisfies problem (16). So far, we prove the sufficiency and necessity between these two problems.

[47] has stated that, without consideration of time switching factor \( \alpha \), (16) has a solution if and only if SINR requirements of each user meet the following conditions
\[
\sum_{k=1}^K \frac{\tilde{\gamma}_k(\alpha)}{1 + \gamma_k} \leq \text{Rank}(\mathbf{H}), \quad (19)
\]
where \( \mathbf{H} \overset{\Delta}{=} [\mathbf{h}_1, \ldots, \mathbf{h}_K] \). The \( \alpha \) in our system divides the transmission into two parts, [47] considers the sufficiency and necessity condition of the part corresponding to our \( (1 - \alpha) T \). While in \( \alpha T \), it is a process of energy transfer, which can be seen as a kind of energy collection, relating to energy threshold \( \varepsilon_k \).

Hence, the feasible condition that EE-HTPO problem can be solved in the case of given transmission volume and energy requirements is equivalent to whether there is a solution in (19). Without loss of generality, it is argued later in this paper that the EE-HTPO problem is feasible unless specifically emphasized.

### IV. ENERGY EFFICIENCY OPTIMAL SOLUTION

In this section, we solve the EE-HTPO problem optimally based on SDR. Defining \( \mathbf{X}_k^x = \mathbf{v}_k^x (\mathbf{v}_k^x)^H, x \in \{I, E\}, \forall k \), we know that \( \text{Rank}(\mathbf{X}_k) \leq 1 \). Ignoring the constraint of rank-one of all \( \mathbf{X}_k^x \), the SDR of original problem is expressed as
\[
\begin{align*}
\min_{\{\mathbf{v}_k^I, \mathbf{v}_k^E, \alpha, \rho_k\}} & \sum_{k=1}^K \text{Tr} (\mathbf{X}_k^E) + (1 - \alpha) \sum_{k=1}^K \text{Tr} (\mathbf{X}_k^I) \\
\text{s.t.} & (1 - \alpha) \rho_k \mathbf{h}_k^H \mathbf{X}_k^I \mathbf{h}_k + \rho_k \sigma_k^2 + \delta_k^2 \geq \tilde{\gamma}_k(\alpha), \quad (20a) \\
& \xi_k (1 - \rho_k) (1 - \alpha) T \left( \sum_{i=1}^K \mathbf{h}_k^H \mathbf{X}_i^I \mathbf{h}_k + \sigma_k^2 \right) \\
& + \xi_k \alpha T \left( \sum_{i=1}^K \mathbf{h}_i^H \mathbf{X}_k^E \mathbf{h}_k + \sigma_k^2 \right) \geq \varepsilon_k, \quad (20b) \\
& 0 \leq \alpha \leq 1, 0 \leq \rho_k \leq 1, \quad \forall k, \quad (20d) \\
& \mathbf{X}_k \succeq 0, \quad \forall k. \quad (20c)
\end{align*}
\]
(20) is still a non-convex optimization problem, \( \mathbf{X}_k^x, \alpha, \) and \( \rho_k \) are coupled in constraints of information and energy.

We transform (20) into
\[
\begin{align*}
\min_{\{\mathbf{v}_k^I, \mathbf{v}_k^E, \alpha, \rho_k\}} & \sum_{k=1}^K \text{Tr} (\mathbf{X}_k^E) + (1 - \alpha) \sum_{k=1}^K \text{Tr} (\mathbf{X}_k^I) \\
\text{s.t.} & \frac{T}{\tilde{\gamma}_k(\alpha)} (1 - \alpha) \mathbf{h}_k^H \mathbf{X}_k^I \mathbf{h}_k - \sum_{i \neq k} \mathbf{h}_i^H \mathbf{X}_k^I \mathbf{h}_k \succeq \sigma_k^2 + \frac{\delta_k^2}{\rho_k} \quad (21a) \\
& \alpha \left( \sum_{i=1}^K \mathbf{h}_i^H \mathbf{X}_k^E \mathbf{h}_k \right) + (1 - \rho_k) (1 - \alpha) \left( \sum_{i=1}^K \mathbf{h}_i^H \mathbf{X}_i^I \mathbf{h}_k \right) \\
& \geq \frac{\varepsilon_k}{\alpha T \xi_k} - (1 - \rho_k + \alpha \rho_k) \sigma_k^2, \quad (21c) \\
& 0 \leq \alpha \leq 1, 0 < \rho_k \leq 1, \quad \forall k, \quad (21d) \\
& \mathbf{X}_k \succeq 0, \quad x \in \{I, E\}, \quad \forall k. \quad (21e)
\end{align*}
\]
It is observed that, objective function of (21) consists of two parts. The former part is for energy transfer, where \( \alpha \) is only related to information constraints (21b), and beamforming vectors are due to the first part in (21c). The latter part is for information transmission, and as information constraints are only associated to data decoding, the optimal solution of (21b) is the same with optimal vectors for beamforming. Hence, we divide the original problem into two subproblems,
\[
\begin{align*}
\min_{\{\mathbf{v}_k^E, \alpha\}} & \sum_{k=1}^K \text{Tr} (\mathbf{X}_k^E) \\
\text{s.t.} & \sum_{i=1}^K \mathbf{h}_k^H \mathbf{X}_i^E \mathbf{h}_k \geq \frac{\varepsilon_k}{\alpha T \xi_k} - \sigma_k^2, \quad (22b) \\
& 0 \leq \alpha \leq 1, \quad \forall k. \\
\min_{\{\mathbf{v}_k^I, \alpha, \rho_k\}} & (1 - \alpha) \sum_{k=1}^K \text{Tr} (\mathbf{X}_k^I) \\
\text{s.t.} & \sum_{i=1}^K \mathbf{h}_k^H \mathbf{X}_i^I \mathbf{h}_k \geq \frac{\varepsilon_k}{(1 - \alpha) (1 - \rho_k) T \xi_k} - \sigma_k^2 - \frac{\rho_k \sigma_k^2}{(1 - \rho_k)}, \quad (23b) \\
& - \frac{T}{\tilde{\gamma}_k(\alpha)} (1 - \alpha) \mathbf{h}_k^H \mathbf{X}_k^I \mathbf{h}_k - \sum_{i \neq k} \mathbf{h}_i^H \mathbf{X}_k^I \mathbf{h}_k \succeq \sigma_k^2 + \frac{\delta_k^2}{\rho_k}, \quad (23c)
\end{align*}
\]
\[
0 \leq \alpha \leq 1, \quad 0 < \rho_k \leq 1, \quad \forall k.
\]  
(23d)

It can be seen that when (22) and (23) achieve the optimal solution simultaneously, (21) can reach the optimal solution. By analyzing, when \(0 < \rho_k < 1\) the two subproblems are both convex. While \(\rho_k = 1\) the user only receives information in \((1 - \alpha)T\). It is the optimization of transmitter TS mode which is studied in [49]. If the optimal solution \(X_k^{x*}, \forall k\), satisfies \(\text{Rank}(X_k^{x*}) = 1\), the corresponding beamforming vectors can be obtained by eigenvalue decomposition of it, and we have the other optimal variables by optimal conditions. Otherwise, under any \(k\), existing of \(\text{Rank}(X_k^{x*}) > 1\) raises that the optimal solution of (21) cannot be considered as the optimal solution of EE-HTPO problem in (14). In the following, we prove that it is true that \(\text{Rank}(X_k^{x*}) = 1\).

**Lemma 3:** In problem (21), under given \(\gamma_k(\alpha) > 0\) and \(e_k > 0\), we have optimal solution \(X_k^{x*}, X_k^{E*}, \rho_k^*, \alpha^*\) satisfies the equality conditions in (21b), and (21c). In addition, \(\text{Rank}(X_k^{x*}) = 1, \forall x \in \{I, E\}\).

Proof: We have transformed the optimization into two subproblems in the previous, and it is seen that the lemma includes two parts, equality conditions and rank-one. So in the following we demonstrate the two parts of lemma 3 for two subproblems respectively.

With (23), the objective function only presents information transmission, and constraints consist of information and energy aspects. The problem is a joint optimization problem of the transmit beamforming and the receiving PS mode with the target of minimum energy consumption. Under a given \(\alpha\), [50] has proved it satisfies slater condition, the zero duality gap, and the equality of information and energy constraints by complementary condition with \(\text{Rank}(X_k^{x*}) = 1\). On the other hand, by the definition of time switching factor, \(\alpha^*\) can be seen as a value part of beamforming vectors, which not affects the argument. Thus, (23) conforms to lemma 3.

While in the following we demonstrate problem (22). As for equation condition, (22) is convex, satisfying slater conditions with a zero duality gap. Let \(\lambda_k^*\) be Lagrangian multiplier, and the Lagrangian duality function is shown as

\[
L(X_k^{E}, \rho_k, \alpha, \lambda_k^*) = \alpha \sum_{k=1}^{K} \text{Tr}(X_k^{E}) - \sum_{k=1}^{K} \lambda_k^* \left( \sum_{i=1}^{K} h_i^H X_k^{E} h_i - \frac{e_k}{\alpha T \xi_k} + \sigma_k^2 \right).
\]

We present the duality problem as

\[
\min L \left( X_k^{E}, \rho_k, \alpha, \lambda_k^* \right) = \min \sum_{k=1}^{K} \text{Tr} \left( A_k X_k^{E} \right) - \sum_{k=1}^{K} \lambda_k^* e_k - \sum_{k=1}^{K} \frac{\lambda_k^* e_k}{\alpha T \xi_k},
\]

where

\[
A_k = I_{N_t} - \sum_{i=1}^{K} \lambda_i^* h_i h_i^H.
\]

Assuming \(\lambda_k^*\) as optimal multiplier, we have

\[
A_k^* = I_{N_t} - \sum_{i=1}^{K} \lambda_i^* h_i h_i^H.
\]

By (25), it is identified that the condition for optimal solution satisfies

\[
\min \text{Tr}(A_k^* X_k^{E*})
\]

In addition, we need \(A_k^{E*} \succeq 0\) in order to confirm the feasibility of (25). Therefore the minimum of problem (28) is 0, that is \(\text{Tr}(A_k^* X_k^{E*}) = 0\). With the condition \(X_k^{E} \succeq 0\), it is analyzed that

\[
A_k^* X_k^{E*} = 0
\]

By (25), it is learned that the optimal time switching factor \(\alpha^*\) satisfies

\[
\min \sum_{k=1}^{K} \frac{\lambda_k^* e_k}{\alpha T \xi_k}, \quad \text{s.t. } 0 < \alpha < 1.
\]

If \(\lambda_k^* = 0\), optimal solution demands \(\alpha \to 0\). However, \(\alpha\) has to meet solutions for all \(e_k\), hence we ignore this situation and \(\lambda_k^* > 0\). According to complementary relaxation condition [48], it is proved the equation condition.

With regard to Rank-one condition, due to (27) \(\text{Rank}(A_k^*) + \text{Rank}(\sum_{i=1}^{K} \lambda_i^* h_i h_i^H) \leq \text{Rank}(I_{N_t})\), that is \(\text{Rank}(A_k^*) \geq N_t - 1\).

If \(A_k^*\) is full rank, we have a zero matrix \(X_k^{E*}\) by (29), which means the BS transmits information all the time like traditional PS receiving mode. We has stated that this mode cannot achieve the optimal energy efficiency. Therefore \(\text{Rank}(A_k^*) = N_t - 1\), \(\forall k\). At the same time by (29), \(\text{Rank}(A_k^* X_k^{E*}) \geq \text{Rank}(A_k^*) + \text{Rank}(X_k^{E*}) - n\). So far, we demonstrate that \(\text{Rank}(X_k^{E*}) = 1\).

Finally, we prove the two sub-problems can achieve the optimal solution simultaneously. (22) and (23) have a same variable \(\alpha\), which has been seen as a given factor. By analyzing above, we have the relationship between optimal variables \(X_k^{E*}, X_k^{E*}, \rho_k^*\) and \(\alpha^*\) respectively. And we can search \(\alpha\) for the optimal solution between 0 and 1. Above all, lemma 3 has been proved. Besides, the divided two sub-problems both satisfy slater condition and zero duality gap, which leads to tight constraints and the two achieve equal conditions by optimal solution. Therefore, it is proved that the maximal energy efficiency problem can be equivalent to the minimal energy consumption problem under the constraints of given information transmission volume.

**Lemma 3** illustrates that the optimal solution of relaxed problem (21) satisfies original problem (13). Hence optimal solution of (13) can be obtained mainly by the results of solving (22) and (23) by inner-point method, which is shown in Algorithm 1. It is observed that the computational complexity of Algorithm 1 is derived by inner-point method, that is \(O(\sqrt{KN_t(K^3 N_t^2 + K^2 N_t^2)})\).
Algorithm 1 Optimal Algorithm for EE-HTPO

1: Check the feasibility condition. If \( \gamma_k \) satisfies the (19), go to step 2; otherwise, exit the algorithm;
2: Solve (22) and (23) and obtain the optimal solutions \( \{ \mathbf{X}_k^r (\alpha) \}, \{ \mathbf{X}_k^w (\alpha), \sigma_k^w (\alpha) \} \) respectively;
3: Find \( \alpha^* \), \( 0 \leq \alpha^* \leq 1 \), to make min \( \{ \alpha^* \sum_{k=1}^{K} \text{Tr} (\mathbf{X}_k^r) \} \) + \( (1 - \alpha^*) \sum_{k=1}^{K} \text{Tr} (\mathbf{X}_k^w) \);
4: Check the feasibility condition again. If \( \gamma_k \) satisfies the (19), go to step 5; otherwise, exit the algorithm;
5: Obtain \( \mathbf{v}_k \) and \( \mathbf{v}_k^* \) by EVD of \( \mathbf{X}_k^r \) and \( \mathbf{X}_k^w \).

\[ \begin{align*}
\text{V. ENERGY EFFICIENCY SUB-OPTIMAL SOLUTIONS} \\
\text{In this section, we put forward two sub-optimal algorithms to simplify computational complexity. Considering better information transmission, we design two schemes based on no interference beamforming and SINR optimal principles.}
\end{align*} \]

A. NO INTERFERENCE TRANSMISSION DESIGN

When \( N_k \geq K \), zero-forcing beamforming based transmitting can avoid interference between signal for different users, that is \( \mathbf{h}_k^t \mathbf{v}_k = 0, \forall i \neq k \). While due to interference is treated as power to be received for storage, hence only information beamforming adapts zero-forcing beamforming. In this case, the original problem is expressed as

\[ \begin{align*}
\min_{\{ \mathbf{v}, \mathbf{v}^*, \alpha, \rho \}} & \sum_{k=1}^{K} \text{Tr} (\mathbf{X}_k^*) + (1 - \alpha) \sum_{k=1}^{K} \text{Tr} (\mathbf{X}_k^1) \\
\text{s.t.} & \frac{T}{\gamma_k (\alpha)} (1 - \alpha) \mathbf{h}_k^t \mathbf{x}_k^1 \mathbf{h}_k - \sum_{i \neq k} \mathbf{h}_i^t \mathbf{x}_i^1 \mathbf{h}_i \geq \sigma_k^2 + \frac{T \delta_k^2}{\rho_k} \\
& \alpha \left( \sum_{i=1}^{K} \mathbf{h}_i^t \mathbf{x}_i^1 \mathbf{h}_i \right) + (1 - \rho_k) (1 - \alpha) \left( \sum_{i=1}^{K} \mathbf{h}_i^t \mathbf{x}_i^1 \mathbf{h}_i \right) \geq \frac{e_k}{T \xi_k} - (1 - \rho_k + \alpha \rho_k) \delta_k^2, \\
& 0 \leq \alpha \leq 1, 0 < \rho_k \leq 1, \forall k, \\
& \mathbf{X}_k^1 \succeq 0, \forall x \in [1, E], \forall k, \\
& \mathbf{h}_k^t \mathbf{v}_k = 0, \forall i \neq k.
\end{align*} \]

It is learned that as \( \mathbf{h}_k \) is independent with each other, the feasibility of (31) is same as the original problem (13) when \( N_k \geq K \). Then we solve (31). Due to the fixed information beamforming vectors, we obtain a sub-optimal energy efficiency by solving (31).

As the method of obtaining optimal solution, (31) is also divided into two sub-problems, shown as follows

\[ \begin{align*}
\min_{\{ \mathbf{v}^*, \alpha \}} & \sum_{k=1}^{K} \text{Tr} (\mathbf{X}_k^*) \\
\text{s.t.} & \frac{K}{\alpha T \xi_k} \mathbf{h}_k^t \mathbf{x}_k^1 \mathbf{h}_k \geq \frac{e_k}{\alpha T \xi_k} - \sigma_k^2, \\
& 0 \leq \alpha \leq 1, \forall k.
\end{align*} \]

It is observed that comparing to optimal algorithm, we simplify the solving process of information transmission part, while the energy part is similar to the optimal algorithm. In the following we focus on problem (33).

By analyzing (32), we learn that the objective function is the sum of precoding 2-norm by all users. While constraints are relations between information and energy thresholds and beamforming vectors for \( U_k \). So the minimal optimization can be considered as the sum of optimization for \( U_k \), each of which is presented as

\[ \begin{align*}
\min_{\{ \mathbf{v}^*, \alpha, \rho \}} & (1 - \alpha) \| \mathbf{v}_k^* \|_2^2 \\
\text{s.t.} & \frac{T}{\gamma_k (\alpha)} (1 - \alpha) \mathbf{h}_k^t \mathbf{x}_k^1 \mathbf{h}_k - \sum_{i \neq k} \mathbf{h}_i^t \mathbf{x}_i^1 \mathbf{h}_i \geq \sigma_k^2 \\
& \alpha \left( \sum_{i=1}^{K} \mathbf{h}_i^t \mathbf{x}_i^1 \mathbf{h}_i \right) + (1 - \rho_k) (1 - \alpha) \left( \sum_{i=1}^{K} \mathbf{h}_i^t \mathbf{x}_i^1 \mathbf{h}_i \right) \geq \frac{e_k}{T \xi_k} - (1 - \rho_k + \alpha \rho_k) \delta_k^2, \\
& 0 \leq \alpha \leq 1, 0 \leq \rho_k \leq 1, \forall k.
\end{align*} \]

It is still seen \( \alpha \) as a given factor. Next, this paper will adopt proof by contradiction to prove that the optimal solution of problem (34) \( \{ \mathbf{v}_k^*, \rho_k^* \} \) satisfies the constraints with equation. Firstly, it is assumed that optimal solution \( \{ \mathbf{v}_k^*, \rho_k^* \} \) makes neither of the two constraints be equal. So it exists a solution \( \{ \theta_k \mathbf{v}_k^*, \rho_k^* \} \), \( 0 < \theta_k < 1 \) to make at least one kind of the information constraint and energy constraint be equal. Which raises the more energy consumption than it of \( \{ \mathbf{v}_k^*, \rho_k^* \} \). And it contradicts the hypothesis because the solution is not optimal. Then suppose the information condition is tight and the energy constraint cannot be equal. We increase \( \rho_k^* \) by sufficient little. So we can see that the information constraint is no longer tight, and the energy constraint is not equal. Similar to the first case, that is impossible. On the other hand,
when the energy constraint is tight and the SINR constraint is not tight, it exists no optimal solution. To sum up, we get a demonstration that the optimal solution \( \{ \tilde{v}_k^*, \tilde{\rho}_k^* \} \) satisfies two constraints by equation. Then (34) can be transformed into

\[
\begin{aligned}
\min_{\{v_k^*, \rho_k\}} & \quad (1 - \alpha) \| v_k^* \|^2 \\
\text{s.t.} & \quad (1 - \alpha) T \rho_k h_k^H x_k^* h_k = \tilde{\gamma}_k(\alpha) \\
& \quad h_k^H x_k^* = \frac{e_k}{(1 - \alpha) (1 - \rho_k) T \zeta_k} - \rho_k \sigma_k^2 \\
& \quad h_k^H v_k^* = 0, \quad \forall i \neq k, \\
& \quad 0 \leq \alpha \leq 1, \quad 0 \leq \rho_k \leq 1, \quad \forall k.
\end{aligned}
\]

(35a)

(35b)

(35c)

(35d)

(35e)

By (35b) and (35c), we have

\[
\frac{e_k}{(1 - \alpha) (1 - \rho_k) T \zeta_k} - \rho_k \sigma_k^2 = \gamma_k(\alpha)(\rho_k \sigma_k^2 + \delta_k^2) \\
\frac{1}{(1 - \alpha) T \zeta_k} - \rho_k \sigma_k^2 = \gamma_k(\alpha)(\rho_k \sigma_k^2 + \delta_k^2)
\]

(36)

And it is rewritten as

\[
\rho_k^2 (\sigma_k^2 - \gamma_k^2 \alpha^2) + \rho_k \gamma_k \sigma_k^2 \frac{1}{T (1 - \alpha)} - \frac{1}{(1 - \alpha) T \zeta_k} \gamma_k \sigma_k^2 = 0
\]

(37)

Thus the optimal power splitting factor is shown as (38), shown at the bottom of the page.

Set \( v_k^* = \sqrt{\alpha_k} \tilde{v}_k^* \), where \( \| \tilde{v}_k^* \| = 1 \). Problem (35) is expressed as

\[
\min_{\{v_k, \rho_k\}} \quad (1 - \alpha) A_k \\
\text{s.t.} \quad (1 - \alpha) T A_k \| h_k^H v_k^* \|^2 = \gamma_k(\sigma_k^2 + \frac{\delta_k^2}{\rho_k^2})
\]

(39a)

(39b)

(39c)

As the left side of (39b) is in product form, if \( A_k \) achieves its minimum, the problem satisfies

\[
\max_{\{v_k^*, \rho_k\}} \quad \| h_k^H v_k^* \|^2 \\
\text{s.t.} \quad h_k^H v_k^* = 0, \quad \forall i \neq k, \\
\quad \| v_k^* \| = 1
\]

(40)

Define \( \mathbf{H}_k = [\mathbf{h}_1, \ldots, \mathbf{h}_{k-1}, \mathbf{h}_{k+1}, \ldots, \mathbf{h}_K] \) and \( U_k \) denotes an orthonormal basis for \( \mathbf{H}_k \). Then we have \( \tilde{v}_k^* = \frac{U_k U_k^H h_k}{\| U_k U_k^H h_k \|^2} \)

and \( v_k^* = \sqrt{\tilde{\gamma}_k(\alpha)(\rho_k \sigma_k^2 + \delta_k^2)} \frac{U_k U_k^H h_k}{\| U_k U_k^H h_k \|^2} \).

Finally, we can obtain the optimal time switching \( \alpha \) by jointly optimization of it and energy transfer in (21). The details of solving process is shown in Algorithm 2. By analyzing, the advantage of computing complexity is obvious comparing with Algorithm 1. It is mainly derived from M-times SVD decomposition, and each of which has an \( O((K - 1)^3 + N^2(K - 1)) \) complexity. Therefore, the Algorithm 2 has an \( O(K^4 + N^2 K^2) \) complexity.

**B. SINR OPTIMAL TRANSMISSION DESIGN**

The above design is available only when \( N_t \geq K \), for this case we put forward another scheme for any number of antennas and users. Considering no power splitting, or energy constraints, but information constraints, we have the problem

\[
\min_{\{v_k^*, \alpha\}} \quad (1 - \alpha) \sum_{k=1}^K \| v_k^* \|^2 \\
\text{s.t.} \quad \frac{T}{\gamma_k(\alpha)} (1 - \alpha) \mathbf{h}_k^H \mathbf{x}_k^* \mathbf{h}_k - \frac{1}{\gamma_k(\alpha)} \sum_{i \neq k} \mathbf{h}_k^H \mathbf{x}_i^* \mathbf{h}_k \geq \sigma_k^2 + \frac{\delta_k^2}{\rho_k^2}, \\
\quad 0 \leq \alpha \leq 1, \quad \forall k.
\]

(41)

We still see the time switching factor \( \alpha \) as a given variable, and the problem is a traditional beamforming optimization under SINR constraints which has been investigated in [51]. Assuming \( \{ \tilde{v}_k^* \} \) as the optimal solution of (41), and we amplify it with \( \sqrt{\lambda}(\lambda > 1) \). In that case constraints of
information and energy are both satisfied. Then we have transformed the problem.

\[ \min_{\{v_k^i, \alpha, \rho_k\}} (1 - \alpha) \lambda \sum_{k=1}^{K} \left\| v_k^i \right\|^2 \]  

(42a)

subject to \[ \frac{T}{y_k(\alpha)} (1 - \alpha) \lambda \left\| h_k^H v_k^i \right\|^2 \]

\[ - \lambda \sum_{i \neq k} \left\| h_k^H v_k^i \right\|^2 \geq \sigma_k^2 + \frac{\delta_k^2}{\rho_k}, \]

(42b)

\[ \lambda \sum_{i=1}^{K} \left\| h_k^H v_k^i \right\|^2 \geq \frac{e_k}{(1 - \alpha) (1 - \rho_k) T \zeta_k} - \frac{\rho_k \sigma_k^2}{(1 - \rho_k)}, \]

(42c)

\[ 0 < \rho_k < 1, \]

(42d)

\[ \lambda > 1. \]

(42e)

In the following, we solve the problem (42) by jointly optimizing \( \lambda \) and \( \rho_k \), and finally combine the result with it of problem (22) to obtain the scheme.

Firstly we study feasibility of the problem. Set \( (\rho_k, \lambda) \triangleq \frac{(1 - \alpha) \lambda \| h_k^H v_k^i \|_2^2 + \rho_k \sigma_k^2}{\lambda \rho_k \sum_{i \neq k} \left\| h_k^H v_k^i \right\|^2} \) and \( E(\rho_k, \lambda) = (1 - \rho_k) \lambda \sum_{i=1}^{K} \left\| h_k^H v_k^i \right\|^2 + (1 - \alpha) \rho_k \sigma_k^2. \) As \( \{v_k^i\} \) is the optimal solution of (42), satisfying \( I(1, 1) = \gamma_k \). It is seen that \( (\rho_k, \lambda) \) is increasing monotonically when \( \lambda > 0 \), so \( I(1, \lambda) > \gamma_k, \lambda > 1 \). While, \( I(\rho_k, \lambda) \) is a continuous function of \( \rho_k \), we have \( I(\rho_k, \lambda) > \gamma_k \) when \( \rho_k < 1 \). On the other hand, \( E(\rho_k, \lambda) \) rises when \( \lambda > 0 \). To be concluded, \( I(\rho_k, \lambda) \geq \gamma_k, E(\rho_k, \lambda) \geq e_k \). We prove the necessity, that is if there exists a solution in (13), (42) is feasible. At the same time, it is seen that the solution of (42) satisfies original problem (13). Above all, (13) and (42) share the same feasible conditions.

Define \( a_k = \frac{T}{y_k(\alpha)} (1 - \alpha) \| h_k^H v_k^i \|_2^2 - \sum_{i \neq k} \left\| h_k^H v_k^i \right\|^2 \) and \( b_k = \sum_{i=1}^{K} \left\| h_k^H v_k^i \right\|^2 \). Then the problem is rewritten as

\[ \min_{[\lambda, \alpha, \rho_k]} \lambda \]

s.t. \( \lambda a_k \geq \sigma_k^2 + \frac{\delta_k^2}{\rho_k}, \]

(43b)

\[ \lambda b_k \geq \frac{e_k}{(1 - \alpha) (1 - \rho_k) T \zeta_k} - \frac{\rho_k \sigma_k^2}{(1 - \rho_k)}, \]

(43c)

\[ 0 < \rho_k < 1, \quad \forall k, \]

(43d)

\[ \lambda > 1. \]

(43e)

And it can be transformed equally into

\[ \min_{[\lambda \geq 1]} \lambda, \quad \text{s.t.} \ c_k(\lambda) \leq 1 \]

(44)

where \( c_k \triangleq \frac{\delta_k^2}{\lambda \sigma_k^2} + \frac{e_k}{(1 - \alpha) \lambda \sigma_k^2}. \) It is learned that \( c_k(\lambda) = 1 \) is a quadratic form equation, and we define \( \lambda' \) and \( \lambda'' \) as two solutions, where \( \lambda' \geq \lambda'' \). Due to \( I(1, 1) = 1, c_k(1) > 1 \). Thus, the solutions of \( c_k(\lambda) \leq 1 \) are \( \lambda \geq \lambda' \) or \( \lambda \leq \lambda'' \). As \( c_k(\lambda) \) decreases when \( \lambda > 1 \) and \( c_k(1) > 1 \), we find \( \lambda'' < 1 < \lambda' \). In this case problem (42) is equal to

\[ \min \lambda, \quad \text{s.t.} \lambda \geq \lambda', \quad \forall k. \]

(45)

The optimal solution is \( \lambda^* = \max_{1 \leq k \leq K} \lambda' \) and the corresponding power splitting factor is \( \rho_k^* = \frac{\delta_k^2}{\lambda' \sigma_k^2}. \) The details of solving process are shown in Algorithm 3. We learn that the learning computational complexity is coming from solving problem (41) and (22), that is \( O(K^3 + KN_k^2) \), comparing to \( O(\sqrt{KN}(K^2 N_k^2 + K^2 N_k^2)) \) of the optimal, and \( O(K^4 + K^2 N_k^2) \) of the no interference transmission design. We learn that when user number is large the advantage of computational complexity of SINR-opt is obvious. As we transform the energy efficiency problem into energy consumption problem equally, the computational complexity of calculating the latter is similar to the former.

To sum up, in the optimal algorithm, we divide the original problem into two suboptimal problems, one mainly for information transmission and the other for energy transfer. In sub-optimal algorithms, we simplify the information part by zero-forcing beamforming in no interference transmission design and we linearly amplify traditional information beamforming vectors in SINR optimal transmission design. It is analyzed that the complexity of two sub-optimal designs is obviously simple compared with the optimal scheme. However, they pay prices that constraints cannot reach equality, which refers to a lower energy efficiency.

At last, we investigate the relation between optimal and two sub-optimal solutions. Intuitively, a sufficient large SINR
leads to a sufficient large transmitting power. In this case, the zero-forcing beamforming based design and SINR optimal scheme both achieve asymptotically the maximal energy efficiency result, which is proved in the following.

Define $\mathbf{v}_k^l = \sqrt{p_k} \mathbf{v}_k^l$, $\forall k$, where $\mathbf{v}_k^l$ is information beamforming and $p_k$ is the corresponding power. So the information constraints can be rewritten as

$$\frac{\rho_k p_k |\mathbf{h}_k^l \mathbf{v}_k^l|^2}{\rho_k p_k \sum_{i \neq k} |\mathbf{h}_k^l \mathbf{v}_k^l|^2 + \rho_k \sigma_k^2 + \delta_k^2} \geq \tilde{\gamma}_k(\alpha). \quad (46)$$

As $\rho_k p_k \sum_{i \neq k} |\mathbf{h}_k^l \mathbf{v}_k^l|^2 \geq 0$, $\forall k$, we transform (46) into

$$\frac{\rho_k p_k |\mathbf{h}_k^l \mathbf{v}_k^l|^2}{\rho_k \sigma_k^2 + \delta_k^2 \geq 0} \geq \frac{\rho_k p_k |\mathbf{h}_k^l \mathbf{v}_k^l|^2}{\rho_k p_k \sum_{i \neq k} |\mathbf{h}_k^l \mathbf{v}_k^l|^2 + \rho_k \sigma_k^2 + \delta_k^2} \geq \tilde{\gamma}_k(\alpha), \quad (47)$$

where the top and bottom of the first term can be viewed as linear functions of $p_k$. Thus we know that when $\tilde{\gamma}_k(\alpha)$ goes to infinity, $p_k$ must rise to infinity. On the other hand, information constraints also satisfies

$$\frac{\rho_k p_k |\mathbf{h}_k^l \mathbf{v}_k^l|^2}{\rho_k p_k \sum_{i \neq k} |\mathbf{h}_k^l \mathbf{v}_k^l|^2} \geq \frac{\rho_k p_k |\mathbf{h}_k^l \mathbf{v}_k^l|^2}{\rho_k p_k \sum_{i \neq k} |\mathbf{h}_k^l \mathbf{v}_k^l|^2 + \rho_k \sigma_k^2 + \delta_k^2} \geq \tilde{\gamma}_k. \quad (48)$$

If $\sum_{i \neq k} |\mathbf{h}_k^l \mathbf{v}_k^l|^2$ does not go to zero, there is no solution for the inequality when $\tilde{\gamma}_k$ rises to infinity. Above all, in the case that information threshold approaches infinity, the feasible beamforming vectors $\mathbf{v}_k$ satisfies that $p_k \rightarrow \infty$ and $|\mathbf{h}_k^l \mathbf{v}_k^l|^2 \rightarrow 0$, $\forall i \neq k$.

VI. IMPLEMENTATION AND PERFORMANCE ANALYSIS

In this section, we numerically simulate and analyze the proposed optimal solution and two sub-optimal solutions, which mainly concludes two parts. We also compare the performance of proposed optimal design with jointly transmitting and receiving PS (Re-PS) scheme in [46], transmitting TS scheme (Tr-TS) in [32], and transmitting PS (Re-PS) scheme in [48], transmitting TS scheme (Tr-TS) in [33], transmitting TS scheme (Tr-TS) in [32].

A. ENVIRONMENT DESCRIPTION

It is assumed that number of users is $K = 4$, and default parameters for all users are same, which means that $\zeta_k = \zeta$, $\delta_k = \delta$, $e_k = e$, and $\Phi_k = \Phi$ for all $k$. We also suppose that $\zeta = 0.5$, $\sigma_k^2 = -70$dBm, $\delta_k^2 = -50$dBm. Furthermore, the attenuation from transmitter to all users is 40dB. On the other hand, the bandwidth is 20MHz, and length of period time is 1s. In the propagation process, line-of-sight fading (LOS) is the main mode, for which we adopt Rician fading model. Thus, we express the channel as

$$\mathbf{h}_k = \sqrt{\frac{\alpha_k}{1 + \alpha_k}} \mathbf{h}_k^\text{LOS} + \sqrt{\frac{\lambda_k}{1 + \lambda_k}} \mathbf{h}_k^\text{NLOS}, \quad (49)$$

where $\mathbf{h}_k^\text{LOS}$ denotes LOS component and $\mathbf{h}_k^\text{NLOS}$ means Rayleigh fading component. They both obey the circular symmetric Gaussian distribution whose mean is zero and covariance is -40Dbm. Rician factor $\tilde{\alpha}_k = 5$dB.

We adopt far field uniform antenna array model and $\mathbf{h}_k = 0.04 \begin{pmatrix} e^{j2\pi d \sin(\phi_k)/\lambda} & \cdots & e^{j(N-1)d \sin(\phi_k)/\lambda} \end{pmatrix}$, where $\theta_k = -2\pi d \sin(\phi_k)/\lambda$, and $d$ is the distance between adjacent antennas. $\lambda = 2d$ denotes the carrier wavelength and $\phi_k$ direction between BS to $U_k$, where $\{\phi_1, \phi_2, \phi_3, \phi_4\} = \{-30^\circ, -60^\circ, 60^\circ, 30^\circ\}$. It is also assumed that the battery capacity of users is limited, that is in the practical system the harvested power has a maximal constraint. Next, performance of the proposed algorithm in this paper is simulated and analyzed.

B. SIMULATION RESULTS

In this part, we compare the performance of proposed optimal design with jointly transmitting and receiving PS (Re-PS) scheme in [46], transmitting TS scheme (Tr-TS) in [32]. As we discuss in the related works, the two outperforms in their research field. As well, the optimal algorithm proposed in this paper is compared with two sub-optimization algorithms in many aspects. Relationship between transmission data and energy efficiency is studied under different energy threshold. We also investigate energy threshold with energy efficiency under different information volume constraints. As we transform the energy optimization into an equal energy consumption problem in the former, we focus on energy consumption first, then on energy efficiency.

Firstly, we evaluate the performance of our proposed hybrid TS-PS transmission design in MISO SWIPT system. It is assumed that $N = 4$, and FIGURE 3 focus on the information threshold and total power consumption by the hybrid TS-PS, Re-PS scheme and Tr-PS scheme. When $e$ rises from -20dBm to 0dBm, the total transmission energy consumption also increases. Yet, under a fixed $e$, power consumption goes up with an increasing information threshold $\tilde{\gamma}_k$. Actually, as energy constraint rises, the BS has to supply more power
to satisfy information constraint for users. Correspondingly, when information threshold rises, the transmitter should satisfy the fixed energy constraint by lifting transmitting power. The results conform to the transmission theory in section II.

Next, FIGURE 4 simulates the relationship between information threshold and energy efficiency under energy thresholds of 0dBm and −20dBm respectively. It also compares our proposed optimal transmission design, and other two schemes. It is observed that when energy threshold increases form −20dBm to 0dBm, energy efficiency decreases. With a given $e$, energy efficiency first goes up until the peak then decreases. It is known that whether information or energy threshold increases it need more transmitting power, and it is obtained a high energy efficiency by an appropriate $\tilde{\gamma}_k$. However, for the high information demanding, it consumes too much energy which leads to a low energy efficiency. We further learn that no matter $e = 0$dBm or $e = -20$dBm three schemes have a similar energy efficiency when $\tilde{\gamma}_k$ is small. It is because that in Tr-TS scheme almost all the period time is allocated to energy transfer, resulting in the objective of maximal energy transfer. In Re-PS design, users harvest energy by large portion of signal power, and beamforming design is mainly for energy harvest. While in our design, users harvest energy within $\alpha$ portion of time, in the other portion of time receivers adapt power splitting factor to store energy. It satisfies the differences between three designs. We further known that Tr-PS design and our scheme outperform Re-PS design in energy efficiency. And our proposed achieves a obviously higher energy efficiency than Tr-TS design when $\tilde{\gamma}_k$ is small. They obtain a similar energy efficiency during a high section of $\tilde{\gamma}_k$. Spectral efficiency is also an important factor, we can get it by the ratio of achievable rate to bandwidth, where the denominator is constant, and the numerator can be obtained by the product result of energy efficiency multiplied by energy consumption, which are discussed in FIGURE3 and FIGURE4. In his paper, they have the same spectral efficiency, due to the assumption that they transmit the same amount of data.

Then we focus on the relationship between energy threshold and transmitting power. Considering our proposed design, Re-PS scheme and Tr-TS scheme, FIGURE 5 reveals the effects of harvested energy to transmitting power under information threshold $\tilde{\gamma}_k = 30$dB and 10dB. It is observed that when $\tilde{\gamma}_k$ increases form 10dB to 30dB, power consumption has a significant rising. And no matter $\tilde{\gamma}_k = 30$dB or 10dB, the transmitting power consumption of our proposed design is lower than Re-PS scheme and Tr-TS scheme under any energy threshold. This result is consistent with their energy efficiency performances. Notably, we learn that when $\tilde{\gamma}_k = 10$dB, our design outperforms obviously, while it is similar when $\tilde{\gamma}_k = 30$dB. It further illustrates that under high information thresholds our proposed design has a similar performance with Tr-TS scheme, and it has an obvious advantage during low $\tilde{\gamma}_k$. However our design has the lowest energy consumption comparing with other two, and with the increasing of energy threshold, the effect is more obvious.

Next, we study the optimal design (EE-opt ) and two sub-optimal schemes, no interference transmission design (No-interf) and SINR optimal transmission design (SINR-opt). Considering three transmission methods,
FIGURE 6 illustrates the relationship between information threshold and energy efficiency under energy threshold $e = 0$dBm and $e = -20$dBm. We can see that when energy threshold increases form -20dBm to 0dBm, the energy efficiency decreases. This is because with the rising of harvested energy, transmitting power has a visibly increasing. At the same time, no matter $e = 0$dBm or $e = -20$dBm, the optimal design outperforms in energy efficiency comparing to the two sub-optimal schemes under any information constraints. We also learn that under low information thresholds no interference transmission design has an advantage comparing with SINR optimal transmission design. The results verify the disadvantages of the two sub-optimal algorithms. Notably, different to the waste of energy caused by zero forcing beamforming under the low information threshold, our proposed hybrid TS-PS transmission scheme can allocate more portion of time for energy transfer to avoid unnecessary waste. On the other hand, with the rising up of $\tilde{\gamma}_k$, the difference of energy efficiency between two sub-optimal designs becomes smaller and smaller. When this parameter is large enough, performance of the three algorithms tends to be close, which is consistent with the previous analysis.

VII. CONCLUSION
In this paper, the simultaneous wireless information and power transfer in the downlink is studied. We put forward a novel transmission design based on transmitter TS and receiver hybrid PS-TS scheme. Under information and energy constraints, we achieve the maximal energy efficiency by jointly optimizing transmitting and receiving transmission methods. In the process of solving optimization problem, we first transform it equally into minimal energy consumption optimization problem, and obtain its feasibility. Then we prove existing of the problem and solve it optimally based on SDR, where optimal solutions of the two divided sub-problems are achieved simultaneously. Furthermore, two sub-optimal transmission designs are put forward to reduce computational complexity. Finally we analyze that our proposed design can achieve maximal energy efficiency, and the two sub-optimal designs get closed to the optimal in high SINR environment.

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REFERENCES
[1] L. R. Varshney, “Transporting information and energy simultaneously,” in Proc. IEEE Int. Symp. Inf. Theory, Jul. 2008, pp. 1612–1616.
[2] W. Wu, F. Zhou, R. Q. Hu, and B. Wang, “Energy-efficient resource allocation for secure NOMA-enabled mobile edge computing networks,” IEEE Trans. Commun., vol. 68, no. 1, pp. 493–505, Jan. 2020.
[3] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, “Wireless networks with RF energy harvesting: A contemporary survey,” IEEE Commun. Surveys Tuts., vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.
[4] O. Messadi, A. Sali, V. Khodamoradi, A. A. Salah, G. Pan, S. J. Hashim, and N. K. Noorlind, “Optimal relay selection scheme with multiantenna power beacon for wireless-powered cooperation communication networks,” Sensors, vol. 21, no. 1, p. 147, Dec. 2020.
[5] T. D. Ponnimbaduge Perera, D. N. K. Jayakody, S. K. Sharma, S. Chatzinotas, and J. Li, “Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges,” IEEE Commun. Surveys Tuts., vol. 20, no. 1, pp. 264–302, 1st Quart., 2018.
[6] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, “What will 5G be?” IEEE J. Sel. Areas Commun., vol. 32, no. 6, pp. 1065–1082, Jun. 2014.
[7] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. Schober, “An overview of sustainable green 5G networks,” IEEE Wireless Commun., vol. 24, no. 4, pp. 72–80, Aug. 2017.
[8] X. Liu, X. B. Zhai, W. Lu, and C. Wu, “QoS-guarantee resource allocation for multiebeam satellite industrial Internet of Things with NOMA,” IEEE Trans. Ind. Informat., vol. 17, no. 3, pp. 2052–2061, Mar. 2021.
[9] X. Liu and X. Zhang, “Rate and energy efficiency improvements for 5G-based IoT with simultaneous transmit,” IEEE Internet Things J., vol. 6, no. 4, pp. 5971–5980, Aug. 2019.
[10] Z. Ding, C. Zhong, D. Wing Kwan Ng, M. Peng, H. A. Suraweera, R. Schober, and H. V. Poor, “Application of smart antenna technologies in simultaneous wireless information and power transfer,” IEEE Commun. Mag., vol. 53, no. 4, pp. 86–93, Apr. 2015.
[11] Z. Ding, S. M. Perlaza, I. Esnaola, and H. V. Poor, “Power allocation strategies in energy harvesting wireless cooperative networks,” IEEE Trans. Wireless Commun., vol. 13, no. 2, pp. 846–860, Feb. 2014.
[12] Z. Ding, I. Krikidis, B. Sharif, and H. V. Poor, “Wireless information and power transfer in cooperative networks with spatially random relays,” IEEE Trans. Wireless Commun., vol. 13, no. 8, pp. 4440–4453, Aug. 2014.
[13] Y. Liu, Z. Ding, M. Elkashlan, and H. V. Poor, “Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer,” IEEE J. Sel. Areas Commun., vol. 34, no. 4, pp. 938–953, Apr. 2016.
[14] H. Sun, F. Zhou, R. Q. Hu, and L. Hanzo, “Robust beamforming design in a NOMA cognitive radio network relying on SWIPT,” IEEE J. Sel. Areas Commun., vol. 37, no. 1, pp. 142–155, Jan. 2019.
[15] F. Zhou and R. Q. Hu, “Computation efficiency maximization in wireless-powered mobile edge computing networks,” IEEE Trans. Wireless Commun., vol. 19, no. 5, pp. 3170–3184, May 2020.
[16] F. Zhou, Z. Chu, H. Sun, R. Q. Hu, and L. Hanzo, “Artificial noise aided secure cognitive beamforming for cooperative MISO-NOMA using SWIPT,” IEEE J. Sel. Areas Commun., vol. 36, no. 4, pp. 918–931, Apr. 2018.
[17] H. Dahrouj and W. Yu, “Coordinated beamforming for the multicell multi-antenna wireless system,” IEEE Trans. Wireless Commun., vol. 9, no. 5, pp. 1748–1759, May 2010.
[18] S. He, Y. Huang, L. Yang, A. Nallanathan, and P. Liu, “A multi-cell beamforming design by uplink-downlink max-min SINR duality,” IEEE Trans. Wireless Commun., vol. 11, no. 8, pp. 2858–2867, Aug. 2012.
[19] H. Pemanenn, A. Tolli, and M. Lahtivaara, “Multi-cell beamforming with decentralized coordination in cognitive and cellular networks,” IEEE Trans. Signal Process., vol. 62, no. 2, pp. 295–308, Jan. 2014.
[20] E. Che and H. D. Tuan, “Sum-rate based coordinated beamforming in multicell multi-antenna wireless networks,” IEEE Commun. Lett., vol. 18, no. 6, pp. 1019–1022, Jun. 2014.
[21] E. Che, H. D. Tuan, H. H. M. Tam, and H. H. Nguyen, “Maximization of sum rate in cognitive multi-cell wireless networks with QoS constraints,” in Proc. 5th Int. Conf. Signal Process. Commun. Syst. (ICSPCS), Dec. 2014, pp. 1–4.
[22] Y. Huang and D. P. Palomar, “Rank-constrained separable semidefinite programming with applications to optimal beamforming,” IEEE Trans. Signal Process., vol. 58, no. 2, pp. 664–678, Feb. 2010.
[23] Z. Zhu, Z. Wang, X. Gui, and X. Gao, “Robust downlink beamforming and power splitting design in multiuser MISO SWIPT system,” in Proc. IEEE/CIC Int. Conf. Commun. China (ICCC), Oct. 2014, pp. 271–275.
[24] Q. Shi, L. Liu, W. Xu, and R. Zhang, “Joint transmit beamforming and receive power splitting for MISO SWIPT systems,” IEEE Trans. Wireless Commun., vol. 13, no. 6, pp. 3269–3280, Jun. 2014.
[25] M. R. A. Khandaker and K.-K. Wong, “SWIPT in MISO multicasting systems,” IEEE Wireless Commun. Lett., vol. 3, no. 3, pp. 277–280, Jun. 2014.
[26] Q. Shi, W. Xu, T.-H. Chang, Y. Wang, and E. Song, “Joint beamforming and power splitting for MISO interference channel with SWIPT: An SOCOP relaxation and decentralized algorithm,” IEEE Trans. Signal Process., vol. 62, no. 23, pp. 6194–6208, Dec. 2014.
[27] S. Timotheou, I. Krikidis, G. Zheng, and B. Ottersten, “Beamforming for MISO interference channels with QoS and RF energy transfer,” IEEE Trans. Wireless Commun., vol. 13, no. 5, pp. 2646–2658, May 2014.
[28] H. Zhang, K. Song, Y. Huang, and L. Yang, “Energy harvesting balancing technique for robust beamforming in multiuser MISO SWIPT system,” in Proc. Int. Conf. Wireless Commun. Signal Process., Oct. 2013, pp. 1–5.

[29] C. Shen, W.-C. Li, and T.-H. Chang, “Simultaneous information and energy transfer: A two-user MISO interference channel case,” in Proc. IEEE Global Comm. Conf. (GLOBECOM), Dec. 2012, pp. 3862–3867.

[30] S. Timotheou, I. Krikidis, and B. Ottersten, “MISO interference channel with QoS and RF energy harvesting constraints,” in Proc. IEEE Int. Conf. Commun. (ICC), Jun. 2013, pp. 4191–4196.

[31] K. Xu, Z. Shen, M. Zhang, Y. Wang, X. Xia, W. Xie, and D. Zhang, “Beam-domain SWIPT for mMIMO system with nonlinear energy harvesting legitimate terminals and a non-cooperative terminal,” IEEE Trans. Green Commun. Netw., vol. 3, no. 3, pp. 703–720, Sep. 2019.

[32] A. A. Nasir, H. D. Tuan, D. T. Ngo, T. Q. Duong, and H. V. Poor, “Beamforming design for wireless information and power transfer systems: Receive power-splitting versus transmit time-switching,” IEEE Trans. Commun., vol. 65, no. 2, pp. 876–889, Feb. 2017.

[33] X. Zhou, R. Zhang, and C. K. Ho, “Wireless information and power transfer in multiuser OFDM systems,” IEEE Trans. Wireless Commun., vol. 13, no. 4, pp. 2282–2294, Apr. 2014.

[34] S. M. R. Islam, N. Avazov, O. A. Dobre, and K.-S. Kwak, “Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges,” IEEE Commun. Surveys Tuts., vol. 19, no. 2, pp. 721–742, 2nd Quart., 2017.

[35] W. Huang, H. Chen, Y. Li, and B. Vucetic, “On the performance of multi-antenna wireless-powered communications with energy beamforming,” IEEE Trans. Veh. Technol., vol. 65, no. 3, pp. 1801–1808, Mar. 2016.

[36] I. F. Akyildiz, T. Melodia, and K. R. Chowdhury, “A survey on wireless multimedia sensor networks,” Comput. Netw., vol. 51, no. 4, pp. 921–960, Mar. 2007.

[37] R. L. G. Cavalcante, S. Stanczak, M. Schubert, A. Eisenblaetter, and U. Tuerke, “Toward energy-efficient 5G wireless communications technologies: Tools for decoupling the scaling of networks from the growth of operating power,” IEEE Signal Process. Mag., vol. 31, no. 6, pp. 24–34, Nov. 2014.

[38] Q. Wu, M. Tao, D. W. Kwan Ng, W. Chen, and R. Schober, “Energy-efficient resource allocation for wireless powered communication networks,” IEEE Trans. Wireless Commun., vol. 15, no. 3, pp. 2312–2327, Mar. 2016.

[39] D. W. K. Ng, E. S. Lo, and R. Schober, “Wireless information and power transfer: Energy efficiency optimization in OFDMA systems,” IEEE Trans. Wireless Commun., vol. 12, no. 12, pp. 6352–6370, Dec. 2013.

[40] X. Chen, X. Wang, and X. Chen, “Energy-efficient optimization for wireless information and power transfer in large-scale MIMO systems employing energy beamforming,” IEEE Wireless Commun. Lett., vol. 2, no. 6, pp. 667–670, Dec. 2013.

[41] A. Zappone, P.-H. Lin, and E. A. Jorswieck, “Energy efficiency of confidential multi-antenna systems with artificial noise and statistical CSI,” IEEE J. Sel. Topics Signal Process., vol. 10, no. 8, pp. 1462–1477, Dec. 2016.

[42] K. Xu, Z. Shen, Y. Wang, X. Xia, and D. Zhang, “Hybrid time-switching and power splitting SWIPT for full-duplex massive MIMO systems: A beam-domain approach,” IEEE Trans. Veh. Technol., vol. 67, no. 8, pp. 7257–7274, Aug. 2018.

[43] L. Ni, X. Da, H. Hu, M. Zhang, and K. Cumanan, “Outage constrained robust secrecy energy efficiency maximization for EH cognitive radio networks,” IEEE Wireless Commun. Lett., vol. 9, no. 3, pp. 363–366, Mar. 2020.

[44] M. Zhang, K. Cumanan, J. Thiyyagalingam, W. Wang, A. G. Burr, Z. Ding, and O. A. Dobre, “Energy efficiency optimization for secure transmission in MISO cognitive radio network with energy harvesting,” IEEE Access, vol. 7, pp. 126234–126252, 2019.

[45] M. Zhang, K. Cumanan, W. Wang, A. G. Burr, Z. Ding, S. Lamotheharan, and O. A. Dobre, “Energy efficiency optimization for secure transmission in a MIMO-NOMA system,” in Proc. IEEE Wireless Commun. Netw. Conf. (WCN), Seoul, South Korea, May 2020, pp. 1–6.

[46] L. Zhao and X. Wang, “Massive MIMO downlink for wireless information and energy transfer with energy harvesting receivers,” IEEE Trans. Commun., vol. 67, no. 5, pp. 3309–3322, May 2019.

[47] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, “Relaying protocols for wireless energy harvesting and information processing,” IEEE Trans. Wireless Commun., vol. 12, no. 7, pp. 3622–3636, Jul. 2013.

[48] A. M. Fouladgar and O. Simeone, “On the transfer of information and energy in multi-user systems,” IEEE Commun. Lett., vol. 16, no. 11, pp. 1733–1736, Nov. 2012.

[49] I. Krikidis, S. Timotheou, and S. Sasaki, “RF energy transfer for cooperative networks: Data relaying or energy harvesting?” IEEE Commun. Lett., vol. 16, no. 11, pp. 1772–1775, Nov. 2012.

[50] J. Park and B. Clerckx, “Joint wireless information and energy transfer in a two-user MIMO interference channel,” IEEE Trans. Wireless Commun., vol. 12, no. 8, pp. 4210–4221, Aug. 2013.

[51] M. Schubert and H. Boche, “Solution of the multiuser downlink beamforming problem with individual SINR constraints,” IEEE Trans. Veh. Technol., vol. 53, no. 1, pp. 18–28, Jan. 2004.

[52] E. Karipidis, N. D. Sidiropolous, and Z.-Q. Luo, “Far-field multicast beamforming for uniform linear antenna arrays,” IEEE Trans. Signal Process., vol. 55, no. 10, pp. 4916–4927, Oct. 2007.

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