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5G-based green broadband communication system design with simultaneous wireless information and power transfer

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ABSTRACT

In 5G communications, the increasing demand for high data rate and ubiquitous services has led to a large energy consumption in both transmitter and receiver. Wireless power transfer (WPT) has been proposed as an effective energy saving method. However, WPT and wireless information transfer (WIT) are often separated in a communication system. In this paper, a 5G-based green broadband communication system with simultaneous wireless information and power transfer (SWIPT) is proposed to combine WIT and WPT. In the system, the subband sets available for WIT and WPT are defined by two complementary spectrum marker vectors, and two independent frequency domain signals using different subband sets are achieved by calculating the inner product of spectrum marker vector, pseudo-random (PR) phase and power scaling vector. Time domain fundamental modulation waveform (FMW) is generated by doing inverse fast Fourier transform (IFFT) of the frequency domain signal. The data stream is modulated on the FMW for WIT, while the FMW for WPT is transmitted directly. The BER performance of the system is analyzed. A joint optimization unit has been deployed to maximize the system throughput by jointly optimizing subband sets and subband powers subject to the constraints of energy requirement and interference. The simulation results have shown the outstanding performance of the designed system.

1. Introduction

Compared to the current 4G network, the future 5G network must satisfy the increasing demand for thousand-times communication capacity. To improve the system performance, some technologies increasing capacity, such as orthogonal frequency division multiplexing (OFDM), massive multiple-input multiple-output (MIMO), cooperative communications and millimeter wave communications etc., have been investigated [1–4]. However, the increasing demand for high data rate and ubiquitous services has led to large energy consumption in both transmitter and receiver. Thus, green communications, which can save the communication energy, plays a vital role to achieve continuous 5G communications. Especially in high-density cellular communication system, the green communications face a great challenge in achieving long-term and self-sustainable operations [5–7]. Traditional green communications focus on achieving higher transmission performance with less power consumption through optimizing some system parameters. However, the energy is still shortage if there is not enough energy supply. Hence, using renewable energy in 5G communications has attracted the attentions of many scholars [8–10].

Recently, wireless power transfer (WPT) has emerged as a promising technology to prolong system lifetime. Energy harvesting is the key of the WPT, which can reuse the radio frequency (RF) energy of the surrounding signal resources through a rectifying circuit that changes alternating current (AD) power into direct current (DC) power. The DC power is stored in a rechargeable battery of the communication systems instead of a fixed power supply [11–14]. However, the traditional WPT carries out independently from wireless information transfer (WIT), and sometimes WPT and WIT are contradictory. Because WIT is to maximize the transmission throughput while WPT is to maximize the energy efficiency [15–18]. Since the transmission signal carries both data information and RF energy, WIT and WPT can be combined in one system to improve both throughput and energy efficiency [19–22]. Hence, simultaneous wireless information and power transfer (SWIPT) has been proposed to receive information while harvesting energy. Two traditional SWIPT models time switching and power splitting

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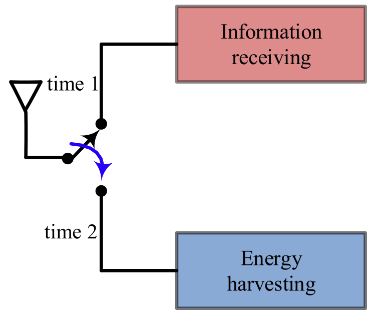
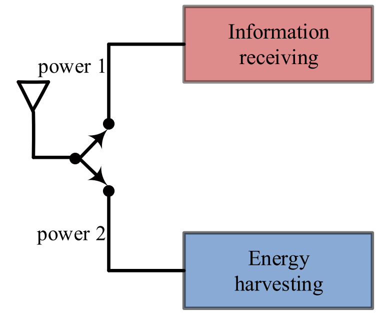


(a) Time switching.



(b) Power splitting.

Fig. 1. Traditional SWIPT models.

have been proposed to implement WIT and WPT in different time slots and power streams, respectively, as shown in Fig. 1 [23–25]. However, time switching can cause communication time delay while power splitting may lead to low signal to noise ratio (SNR).

In multiband-based 5G communications, WIT and WPT can be carried out simultaneously in different subbands, which can solve the time delay and low SNR brought by the traditional models. The contributions of the paper are listed as follows:

- A subband allocation-based SWIPT model for 5G communications has been proposed, in which some of the subbands are used for WIT while the others are used for WPT simultaneously. The proposed model implements SWIPT in two separated subband sets, thus avoiding time delay and SNR decreasing.
- A novel 5G-based broadband communication system with SWIPT including transmitter and receiver has been firstly designed. The subband sets available for WIT and WPT are defined by two complementary spectrum marker vectors. Two independent frequency domain signals using different subband sets are achieved by calculating the inner product of spectrum marker vector, pseudo-random (PR) phase and power scaling vector. Time domain carrier namely fundamental modulation waveform (FMW) is generated by doing inverse fast Fourier transform (IFFT) of the frequency domain signal. The data stream is modulated on the FMW for WIT, while the FMW for WPT is transmitted directly. The receiver can demodulate the data using the same FMW as the transmitter. The BER performance of the system using binary modulation and cyclic code shift keying (CCSK) modulation is analyzed, respectively. The proposed system can achieve SWIPT from the hardware architecture.
- A joint optimization unit has been proposed to improve the system performance by jointly optimizing subband sets and subband powers. A joint optimization problem has been formulated to express the system optimization process, which seeks to maximize the system throughput subject to the constraints of energy requirement and interference. Alternatively, the optimization problem can maximize the harvested energy while the minimal throughput is ordered. A joint optimization algorithm based on the Lagrange dual optimization has been proposed to get the joint optimal solutions.

2. System model

The broad frequency band is divided into N subbands. In the SWIPT, some of the subbands are selected for WIT while the other subbands are chosen for WPT. A joint optimization unit of subbands and subband powers is deployed to guarantee the performance of data transmission and energy harvesting.

2.1. SWIPT transmitter

The SWIPT transmitter is shown in Fig. 2. The N subbands are divided into two subband sets, one set for WIT and the other one for WPT. Supposing the band frequency is ω, we use spectrum marker vectors $\boldsymbol{A}(\boldsymbol{\omega}) = \{A_1, A_2, \ldots, A_N\}$ and $\bar{\boldsymbol{A}}(\boldsymbol{\omega}) = \{\bar{A}_1, \bar{A}_2, \ldots, \bar{A}_N\}$ to define the subband availability in the two sets, respectively. That is, if subband n for $n = 1, 2, \ldots, N$ is used for data transmission, the corresponding element $A_n = 1$ in $\boldsymbol{A}(\boldsymbol{\omega})$, otherwise $A_n = 0$. Similarly, if subband n is used for WPT, $\bar{A}_n = 1$ in $\bar{\boldsymbol{A}}(\boldsymbol{\omega})$, otherwise $\bar{A}_n = 0$. Hence, $A_n, \bar{A}_n = \{0, 1\}$ for $n = 1, 2, \ldots, N$. The use of PR phase in the transmitter ensures that the time-domain FMW has noise-like property, which can improve the anti-jamming performance of the system [26,27]. The PR phase vector is defined as follows

$$\boldsymbol{e}^{\boldsymbol{j\theta}(\boldsymbol{\omega})} = \left\{ e^{j\frac{2\pi m_1}{D}}, e^{j\frac{2\pi m_2}{D}}, \ldots, e^{j\frac{2\pi m_N}{D}} \right\} \tag{1}$$

where $D = 2^r$ denotes the length of the m sequence and m_n is a random number within 0 to $D-1$. The power scaling vector is used to allocated the transmission power for each subband, which is described as $\mathbf{C}(\boldsymbol{\omega}) = \{\sqrt{p_1}, \sqrt{p_2}, \ldots, \sqrt{p_N}\}$. We have $\sum_{n=1}^{N} p_n \leq p_{max}$, where p_{max} is the maximal power of the transmitter. Hence, the frequency domain signals of the carriers for data transmission and power transfer are respectively given by

$$\begin{aligned} \boldsymbol{B}(\boldsymbol{\omega}) &= \boldsymbol{A}(\boldsymbol{\omega}) \bullet \mathbf{C}(\boldsymbol{\omega}) \bullet \boldsymbol{e}^{\boldsymbol{j\theta}(\boldsymbol{\omega})} \\ \bar{\boldsymbol{B}}(\boldsymbol{\omega}) &= \bar{\boldsymbol{A}}(\boldsymbol{\omega}) \bullet \mathbf{C}(\boldsymbol{\omega}) \bullet \boldsymbol{e}^{\boldsymbol{j\theta}(\boldsymbol{\omega})} \end{aligned} \tag{2}$$

where $\bullet$ denotes the vector inner product. Then the time domain FMW for data transmission is obtained by doing the IFFT of $\boldsymbol{B}(\boldsymbol{\omega})$, which is given by

$$b(t) = \frac{1}{N} \sum_{n=1}^{N} A_n \sqrt{p_n} e^{j\frac{2\pi m_n}{D}} e^{j\frac{2\pi nt}{N}}, t = 1, 2, \ldots, N \tag{3}$$

Similarly, we can obtain the FMW for WPT, $\bar{b}(t)$, by doing IFFT of $\bar{\boldsymbol{B}}(\boldsymbol{\omega})$. The bit stream S is modulated on the FMW $b(t)$. There are two kinds of modulation modes as follows

- **binary modulation**: S is one-bit stream 0/1, and the modulated signal is given by

$$r_1(t) = \begin{cases} b(t), & S = 1 \\ -b(t), & S = 0 \end{cases} \tag{4}$$

- **CCSK modulation**: S is M-ary stream, and the high-order modulated signal is given by

$$r_1(t) = b\left(t - \frac{SN}{M}\right), S = 0, 1, 2, \ldots, M-1 \tag{5}$$