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Joint Uplink and Downlink Resource Allocation in Data and Energy Integrated Communication Networks

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Abstract

In this paper, we propose a joint power control strategy for both the uplink and downlink transmission by considering the energy requirements of the user equipments' uplink data transmissions in data and energy integrated communication networks (DEINs). In DEINs, the base station (BS) adopts the power splitting (PS) aided simultaneous wireless information and power transfer (SWIPT) technique in the downlink (DL) transmissions, while the user equipments (UEs) carry out their own uplink (UL) transmissions by exploiting the energy harvested during the BS's DL transmissions. In our DEIN model, there are M UEs served by the BS in order to fulfil both of their DL and UL transmissions. The orthogonal frequency division multiple access (OFDMA) technique is adopted for supporting the simultaneous transmissions of multiple UEs. Furthermore, a transmission frame is divided into N time slots in the medium access control (MAC) layer. The mathematical model is established for maximizing the sum-throughput of the UEs' DL transmissions and for ensuring their fairness during a single transmission frame T, respectively. In order to achieve these goals, in each transmission frame T, we optimally allocate the BS's power for each subcarrier and the PS factor for each UE during a specific time slot. The original optimisation problems are transformed into convex forms, which can be perfectly solved by convex optimisation theories. Our numerical results compare the optimal results by conceiving the objective of maximising the sum-throughput and those by conceiving the objective of maximising the fair-throughput. Furthermore, our numerical results also reveal the inherent tradeoff between the DL and the UL transmissions.

Keywords: Power allocation, integrated data and energy transfer, sum-throughput, fair-throughput, convex optimization.

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1. Introduction

Recently, Data and Energy Integrated communication Networks (DEINs) become appealing by essentially providing perpetual energy sources for wireless communication networks [1]. Radio-Frequency (RF) signals are capable of satisfying both the communication demands and charging demands of electronic devices by transferring energy and information simultaneously. Therefore, DEINs has drawn an upsurge of research interest in [1]-[4]. The authors of [2] summarise the recent trend in the research of DEINs. The authors of [5]-[7] consider the different situations of the capacity of the battery. Furthermore, an efficient resource allocation algorithm is proposed in [8] for the wireless networks embedded with the function of RF energy harvesting, which is referred to as RF energy harvesting networks (RR-EHNs). In the existing literature, there mainly exist two techniques for splitting RF signals and for realising the integrated data and energy transfer, which are known as the time switching (TS) technique and the power splitting (PS) technique [9]. Having TS technique adopted at the receiver, the received signal is either processed by an energy receiver for energy harvesting (EH) or processed by an information receiver for information decoding (ID). Having PS technique applied at the receiver, the received signal is split into two signal streams according to a fixed splitting ratio of a power splitter in the power domain. One stream flows to the energy receiver for EH, while the other flows to the information receiver for ID. It is demonstrated in [10] that a tradeoff exists between the amount of harvested energy and the achievable transmission rate. Most of the research focuses on striking against this tradeoff in order to balance the attainable amount of harvested energy and the achievable transmission rate in [2], [8], [11], which optimises the performance of the integrated data and energy transfer. Additionally, the PS and TS techniques are compared in terms of the integrated data and energy transfer in some existing literature and it is demonstrated in [12] that the PS technique usually achieves better performance, since UEs can always harvest the energy during the communication period. Moreover, other energy harvesting schemes in DEINs have been studied for achieving a balance between the rate and energy performance in [13]-[15]. In [13], the authors propose a dynamic power splitting (DPS) strategy and a dynamic time switching (DTS) strategy for the sake of optimally coordinating the EH and ID functions. In [16], [17], the authors maximise the data rate and the harvested energy for an individual user by dynamically designing the transmitting beamformer in a multi-user MIMO system. In [18], the authors exploit the information theoretic tools for analysing the energy transfer constraints required by the additional coordination among distributed nodes in wireless networks. The authors of [19] design an optimal cooperative mechanism for the wireless energy harvesting and the spectrum sharing in cognitive 5G networks, where secondary users harvest energy from both ambient RF signals and primary users' RF signals simultaneously. They focus on maximising both the throughputs of primary users and those of secondary users subject to the data rate and energy requirements.

Orthogonal frequency division multiple access (OFDMA) is a popular technique for realising high-rate wireless communications, which has been exploited in various communication standards [11], such as 3GPP-Long Term Evolution (LTE) and 802.11a/g/n/ac. Sometimes, the communication performance may be largely constrained by the energy available in communication devices in some practical application scenarios. The authors of [12] study the optimal design for simultaneous wireless information and power transfer in downlink multiuser OFDM system, in which the performance of the TS technique and that of the PS technique have been numerically compared with each other. A fair data-and-energy resource allocation algorithm is proposed in [3] for the integrated data and energy transfer by jointly considering the downlink energy beamforming and the power-and-time allocation. Furthermore, the existing research of DEINs mainly focuses on the low-power sensor networks [20] [21]. It is shown in [20] that the tradeoff exists between the achievable data rate and the transferred energy by allocating the transmit power in different frequency bands. For sufficiently small amount of energy transferred, the optimal power allocation scheme obeys the classic water-filling (WF) approach in order to maximise the information transmission rate. By increasing the energy transferred, more power has to be allocated to the channels having higher channel gains. By further increasing the energy transferred, the strategy finally converges to the case that all the power is allocated to the channel having the highest channel gain. However, since the energy harvesting circuit is not capable of decoding the information from the RF signals, the results in [13] only provides an upper bound for the rate-energy tradeoff in a single-user OFDMA system.

As a natural extension of pervious works for DEINs, in our paper, we study a multiuser DEINs relying on the OFDM. Different from the conventional works about DEINs that mostly discuss the minimum energy demands and the information transmission rate, we mainly focus on the inherent relationship between the uplink and downlink transmissions in DEINs. We assume that each UE is equipped with an independent energy receiver for harvesting energy from the RF-signals transmitted by the base station (BS). For the information transmission, the OFDMA technique is adopted for supporting the simultaneous transmissions of multiple users, while the PS technique is exploited by all the UEs for splitting the received RF signals for EH and ID functions. Note that the energy consumed for the uplink transmissions are harvested from the BS’s downlink transmission. We also take the time-varying channel state into account, and establish channel model based on the research result in [22]. As a result, we focus on satisfying the UEs’ uplink transmission requirements by optimally allocating the downlink transmit power of the BS for different UEs and by optimally selecting the signal splitting ratio of the PS technique for each UE. An efficient algorithm is proposed by iteratively optimizing the transmit power for the BS’s downlink transmission and the signal splitting ratios of the PS technique for each UE until the convergence is reached.

Specifically, our novel contributions can be summarised in the following aspects:

(1) A multi-user DEIN system is investigated, which is constituted of a single BS and multiple UEs. In this DEIN system, UEs may simultaneously receive information and harvest energy from the BS’s downlink (DL) transmissions. Then the harvested energy may be depleted by UEs for supporting their uplink (UL) transmissions.

(2) We formulate the sum-throughput maximisation problem for the BS’s downlink transmission by considering the UEs’ UL transmission requirements. The optimal solution for the BS’s power allocation and the PS ratio selection is obtained by exploiting the classic KKT conditions.

(3) We also formulate the fair throughput maximisation problem for the BS’s downlink transmission by further ensuring the fairness among the UEs. The original optimisation problem is equivalently transformed, based on which a high-efficient iterative algorithm is proposed for obtaining the optimal solution.

(4) Our numerical results reveal the inherent tradeoff between the UEs’ downlink transmission throughput and their uplink counterparts.

The rest of this paper is organized as follows. The system model and problem formulation are presented in Section 2. The optimal solution of the problem is obtained in Section 3. Then, numerical results are provided in Section 4 in order to characterise the performance of our optimal power allocation and PS ratio selection. Finally, the paper is concluded in Section 5.

2. System Model and Problem Formulation

A single cell DEIN system is illustrated in **Fig. 1**, which consists of a single BS and M UEs. The OFDMA technique is adopted by the BS for supporting the simultaneous transmissions of multiple UEs. We assume that the BS and any of the UEs are equipped with a single antenna. During the DL transmission, the BS sends the dedicated signals to the corresponding UEs in their assigned orthogonal sub-carriers. These UEs are denoted by $(U_1, U_2, U_3, ..., U_M)$. The UEs transmit their data to the BS during their UL transmissions in their assigned orthogonal sub-carriers. Our DEIN operates in a discrete-time manner. A transmission frame T is equally divided into N time slots, which are denoted by $(\tau_1, ..., \tau_N)$. We further assume that these time slots are statistical independent of one another. We assume block fading for the channel attenuation, which is unchanged during a single time slot but varies among different time slots. For a specific time slot τ_i, the BS allocates its transmit power, which is denoted by $\mathbf{p}_\mathbf{i}^\mathbf{d} = (p_{i,1}^d, ..., p_{i,M}^d)$, to M DL orthogonal sub-carriers in order to simultaneously send signals to M UEs by relying on the OFDMA technique. We have a maximum allowable total power $p_{\max}$ for every time slot. We also have an average power constraint p_{avg} for a single transmission frame T. Hence, these two power constrains can be formulated as

$$\sum_{j=1}^{M} p_{i,j}^d \le p_{\max}, \; i = 1, ..., N, \tag{1}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{M} p_{i,j}^d \le N p_{avg}. \tag{2}$$

respectively.

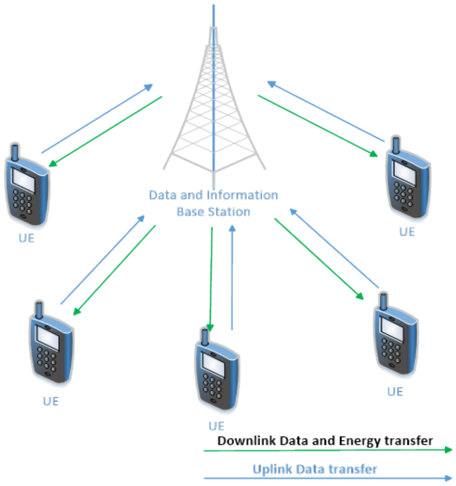

Fig. 1. A multiuser DEIN system

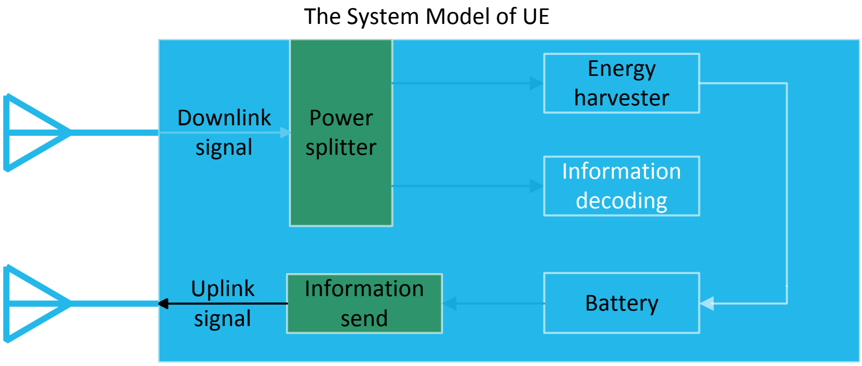

Fig. 2. The functional module of a UE in the DEIN system

As shown in **Fig. 2,** for a specific UE U_j during the time slot τ_i, the PS technique is exploited for splitting the received RF signal into two portions in the power domain. The PS ratio of the UE U_j during the time slot τ_i is denoted as $\mu_{i,j} \in [0,1]$. One portion of the received RF signal flows to the energy harvesting circuit, while the rest of the received RF signals flows to the information decoder module. Therefore, for a specific UE U_j during the time slot τ_i, we denote the power of the portion of the signal dedicated for EH and that dedicated for ID by $p_{i,j}^{EH}(\mu_{i,j},\mathbf{p_i^d})$ and $p_{i,j}^{ID}(\mu_{i,j},\mathbf{p_i^d})$, which can be formulated as:

$$p_{i,j}^{EH}(\mu_{i,j},\mathbf{p_i^d}) = \beta h_{i,j}^d (1-\mu_{i,j}) p_{i,j}^d, \tag{3}$$

$$p_{i,j}^{ID}(\mu_{i,j},\mathbf{p_i^d}) = \mu_{i,j} h_{i,j}^d p_{i,j}^d, \tag{4}$$

respectively. In Eqs. (3) and (4), β represents the conversion rate from the RF signals to the direct current (DC), which is set to be a percentage of unity for simplicity, while $h_{i,j}^d$ represents the power gain of the orthogonal sub-carrier assigned to U_j for its DL transmission during time slot τ_i .The channel power gain $h_{i,j}^d$ obeys the exponential distribution, if the channel is assumed to be Rayleigh block fading channel. We further assume that the UEs can use all the energy harvested from the BS's DL transmission for supporting their UL transmissions and no other types of the energy consumption exist at the UEs. As a result, the DL and UL throughputs of U_j during τ_i, which are denoted by $R_{i,j}^d(\mu_{i,j},\mathbf{p_i^d})$ and $R_{i,j}^u(\mu_{i,j},\mathbf{p_i^d})$ in (bit/s/Hz), can be expressed as:

$$R_{i,j}^d(\mu_{i,j},\mathbf{p_i^d}) = \log_2(1+\frac{p_{i,j}^{ID}(\mu_{i,j},\mathbf{p_i^d})}{\sigma_N^2}), \tag{5}$$

$$R_{i,j}^u(\mu_{i,j},\mathbf{p_i^d}) = \log_2(1+\frac{p_{i,j}^{EH}(\mu_{i,j},\mathbf{p_i^d}) h_{i,j}^u}{\sigma_N^2}), \tag{6}$$

respectively, where $h_{i,j}^{u}$ represents the channel power gain of U_j s' UL channel during τ_i by obeying the exponential distribution. In Eqs. (5) and (6), σ_N^2 represents the sum of noise power of the corresponding sub-carrier and the noise power of the information decoder. When the noise power of the sub-carrier is far lower than that of the information decoder, σ_N^2 is approximately equal to the noise power of the information decoder. Our formulations for the DL and UL throughput is a little diverted from the classic Shannon-Hartely theory. We omit the term of bandwidth in (5) and (6). As a result, they represent the throughput for a bandwidth of unity, which also represent the spectrum efficiency.

In our DEIN model, the BS has to allocate its transmit power to every orthogonal sub-carrier during every time slot, while the UEs have to decide their PS ratios for efficiently splitting the received RF signals for different purposes. Our objective is to maximise the total DL throughput during a transmission frame T subject to the conditions that all the UEs' UL throughputs during the transmission frame T satisfy their minimum requirements, which are denoted by $\mathbf{D}=[D_1,...,D_j]$. By further considering the maximum and average power constraints, the maximisation of the sum-throughput during the BS's DL transmission can be formulated as:

$$\begin{aligned} &(\mathbf{P1}) \max_{\mathbf{p_i^d},\mu_{i,j}} \quad \frac{T}{N}\sum_{i=1}^{N}\sum_{j=1}^{M} R_{i,j}^{d}(\mu_{i,j},\mathbf{p_i^d}) \qquad (7a) \\ &s.t \begin{cases} \dfrac{T}{N}\sum_{i=1}^{N} R_{i,j}^{u}(\mu_{i,j},\mathbf{p_i^d}) \geq D_j, & (7b) \\ 0\leq \mu_{i,j} \leq 1, & (7c) \\ \text{Eqs. } (1),(2), \\ 1\leq j\leq M, 1\leq i\leq N, \end{cases} \end{aligned} \tag{7}$$

Since wireless communication always suffers from the stubborn 'near–far' phenomenon, the maximisation of the sum-throughput may always lead to the unfair treatment of UEs during the BS's DL transmission. For example, in order to achieve the maximum sum-throughput, more resources are inclined to be allocated to the UEs having better channel conditions towards the BSs, which results in that only a few UEs near the BS may gain a major portion of the BS's transmit power, while most of UEs far from the BS gain little BS's transmit power and hence they suffer from near-zero DL throughputs. As a result, we have to study the fairness among the UEs, when allocating the BS's transmit power during the DL transmission.. The minimum throughput during the BS's DL transmission among the UEs is denoted as R_{fair}. Hence, the fairness among the UEs can be achieved by maximising R_{fair}. We formulate the fair-throughput maximization problem as:

$$(\textbf{P2})\max_{\mathbf{p_i^d},\mu_{i,j}} \; R_{fair} \qquad (8a)$$

$$s.t\begin{cases} \frac{T}{N}\sum_{i=1}^{N} R_{i,j}^{u}(\mu_{i,j},\mathbf{p_i^d}) \ge D_j, & (8b)\\ \frac{T}{N}\sum_{j=1}^{M} R_{i,j}^{d}(\mu_{i,j},\mathbf{p_i^d}) \ge R_{fair}, & (8c)\\ 0 \le \mu_{i,j} \le 1, & (8d)\\ (1), & \\ (2), & \\ 1 \le j \le M, 1 \le i \le N & \end{cases} \qquad (8)$$

Note that whatever the PS ratios are, neither (P1) nor (P2) are convex optimization problems due to the existence of the term $p_{i,j}^{d}\mu_{i,j}$, which makes the corresponding Hessian matrix non-positive definite for the expressions of $R_{i,j}^{u}(\mu_{i,j},\mathbf{p_i^d})$ and $R_{i,j}^{d}(\mu_{i,j},\mathbf{p_i^d})$. As a result, a new variable $g_{i,j} = p_{i,j}^{d}\mu_{i,j}$ is introduced for equivalently transforming the original $R_{i,j}^{u}(\mu_{i,j},\mathbf{p_i^d})$ and $R_{i,j}^{d}(\mu_{i,j},\mathbf{p_i^d})$ into the functions with respect to $g_{i,j}$ and $\mathbf{p_i^d}$, which are formulated as:

$$R_{i,j}^{d}(g_{i,j},\mathbf{p_i^d}) = \log_2(1+\frac{g_{i,j}h_{i,j}^{d}}{\sigma_N^2}), \qquad (9)$$

$$R_{i,j}^{u}(g_{i,j},\mathbf{p_i^d}) = \log_2(1+\frac{p_{i,j}^{EH}(g_{i,j},\mathbf{p_i^d})h_{i,j}^{u}}{\sigma_N^2}), \qquad (10)$$

As a result, (P1) and (P2) may be reformulated as the following maximisation problems (P3) and (P4):

$$(\text{P3})\max_{\mathbf{p_i^d},g_{i,j}} \; \frac{T}{N}\sum_{i=1}^{N}\sum_{j=1}^{M} R_{i,j}^{d}(g_{i,j},\mathbf{p_i^d}) \qquad (11a)$$

$$s.t\begin{cases} \frac{T}{N}\sum_{i=1}^{N} R_{i,j}^{u}(g_{i,j},\mathbf{p_i^d}) \ge D_j, & (11b)\\ 0 \le g_{i,j} \le p_{i,j}^{d}, & (11c)\\ (1),(2), & \\ 1 \le j \le M, 1 \le i \le N, & \end{cases} \qquad (11)$$

$$
\begin{aligned}
&(\mathrm{P4}) \max_{\mathbf{p}_\mathbf{i}^\mathbf{d}, g_{i,j}} \; R_{fair} && \text{(12a)}\\
&s.t \begin{cases}
\dfrac{T}{N}\displaystyle\sum_{i=1}^{N} R_{i,j}^{u}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}) \ge D_j, & \text{(12b)}\\
\dfrac{T}{N}\displaystyle\sum_{j=1}^{M} R_{i,j}^{d}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}) \ge R_{fair}, & \text{(12c)}\\
0 \le g_{i,j} \le p_{i,j}^{d}, & \text{(12d)}\\
(1),\\
(2),\\
1 \le j \le M, 1 \le i \le N
\end{cases}
\end{aligned}
\tag{12}
$$

respectively. Note that since $p_{i,j}^{EH}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d})$ is an affine function, $R_{i,j}^{u}(\mu_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d})$ and $R_{i,j}^{d}(\mu_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d})$ are hence concave, which guarantees that (P3) and (P4) are both convex optimization problems.

3. Power Allocation in the Multiuser System

In this section, we present the optimal solution for solving the problems in Section 2. Since the transformed optimisation problems are convex problems in basic forms, they can be effectively solved by the convex tool box CVX. Furthermore, analytical solutions by exploiting the Lagrange dual approach are provided in this section.

3.1 Sum-throughput maximization

First, we consider that UEs may harvest energy during the BS's DL transmission in its assigned sub-carrier. The Lagrange function of (P3) can be formulated as:

$$
\begin{aligned}
\underset{g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}\in\mathbb{D}}{\mathcal{L}}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d},\boldsymbol{\lambda},\boldsymbol{\nu},\omega) = {}& \frac{T}{N}\sum_{i=1}^{N}\sum_{j=1}^{M} R_{i,j}^{d}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}) + \sum_{j=1}^{M}\lambda_j\Big[\frac{T}{N}\sum_{i=1}^{N} R_{i,j}^{u}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}) - D_j\Big]\\
&+\sum_{i=1}^{N}\nu_i\Big(p_{\max} - \sum_{j=1}^{M} p_{i,j}^{d}\Big) + \omega\Big(p_{avg}N - \sum_{i=1}^{N}\sum_{j=1}^{M} p_{i,j}^{d}\Big),
\end{aligned}
\tag{13}
$$

while its dual function may be expressed as:

$$
\underset{g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}\in\mathbb{D}}{\mathcal{G}}(\boldsymbol{\lambda},\boldsymbol{\nu},\omega) = \sup_{g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}\in\mathbb{D}} \mathcal{L}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d},\boldsymbol{\lambda},\boldsymbol{\nu},\omega),
\tag{14}
$$

where $\boldsymbol{\lambda} = (\lambda_1,\ldots,\lambda_M)$, $\boldsymbol{\nu}=(\nu_1,\ldots,\nu_\mathrm{N})$ and ω are the Lagrange multipliers. According to the KKT conditions, the optimal results $g_{i,j}{}^{*},\mathbf{p}_\mathbf{i}^{\mathbf{d}*},\boldsymbol{\lambda}^{*},\boldsymbol{\nu}^{*},\omega^{*}$ have to satisfy the following set of equations:

$$\begin{aligned}
&\frac{h_{i,j}^{d}/{\sigma_N}^2}{1+h_{i,j}^{d}g_{i,j}/{\sigma_N}^2}-\lambda_j\frac{h_{i,j}^{d}h_{i,j}^{u}/{\sigma_N}^2}{1+h_{i,j}^{d}h_{i,j}^{u}(p_{i,j}^{d}-g_{i,j})/{\sigma_N}^2}=0, && \text{(15a)}\\
&\lambda_j\frac{h_{i,j}^{d}h_{i,j}^{u}/{\sigma_N}^2}{1+h_{i,j}^{d}h_{i,j}^{u}(p_{i,j}^{d}-g_{i,j})/{\sigma_N}^2}-v_i-\omega=0, && \text{(15b)}\\
&\lambda_j[\frac{T}{N}\sum_{i=1}^{N}R_{i,j}^{u}(g_{i,j},\mathbf{p_i^d})-D_j]=0, && \text{(15c)}\\
&v_i(p_{\max}-\sum_{j=1}^{M}p_{i,j}^{d})=0, && \text{(15d)}\\
&\omega(p_{avg}N-\sum_{i=1}^{N}\sum_{j=1}^{M}p_{i,j}^{d})=0, && \text{(15e)}
\end{aligned}\qquad (15)$$

where $i=1,...N$ and $j=1,...M$. Hence, the optimal ${g_{i,j}}^*,\mathbf{p_i^{d*}}$ can be calculated by the following equations:

$$\begin{aligned}
g_{i,j}^{*}&=(\frac{1}{v_i^*+\omega^*}-\frac{{\sigma_N}^2}{h_{i,j}^{d}})^{+}\\
p_{i,j}^{d*}&=(\frac{\lambda_j^*}{v_i^*+\omega^*}-\frac{{\sigma_N}^2}{h_{i,j}^{d}h_{i,j}^{u}})^{+}+g_{i,j}^{*}
\end{aligned}\qquad (16)$$

where λ^*,v^*,ω^* can be obtained by iteratively invoking the sub-gradient decreasing method according to the equation set (15).

3.2 Fair-throughput maximization

We then consider the fair-throughput maximization problem (P4). After the equivalent transformation on (P4), we may iteratively solve the following convex optimisation problem:

$$\begin{aligned}
&(\text{P5})\min_{\mathbf{p_i^d},g_{i,j}}\ \sum_{i=1}^{N}\sum_{j=1}^{M}p_{i,j}^{d} && \text{(17a)}\\
&s.t\left\{\begin{array}{ll}
\frac{T}{N}\sum_{i=1}^{N}R_{i,j}^{u}(g_{i,j},\mathbf{p_i^d})\ge D_j, & \text{(17b)}\\
\frac{T}{N}\sum_{j=1}^{M}R_{i,j}^{d}(g_{i,j},\mathbf{p_i^d})\ge R_{fair}, & \text{(17c)}\\
0\le g_{i,j}\le p_{i,j}^{d}, & \text{(17d)}.\\
(1), & \\
1\le j\le M,1\le i\le N &
\end{array}\right.
\end{aligned}\qquad (17)$$

We can readily prove that R_{fair} increases when the total energy consumption Np_{avg} during the transmission frame T increases. Hence, we may solve (P5) by determining whether the system can achieve data transmission requirements and the power constraints as expressed in (17b), (17c) and (17d), for a given R_{fair}. If not, R_{fair} has to be reduced. Otherwise, we will further increase R_{fair} for the next round of the problem solving.

The Lagrange function of (P5) can be formulated as:

$$\begin{aligned}\underset{g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}\in\mathbb{D}}{\mathcal{L}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d},\boldsymbol{\lambda},\boldsymbol{\nu},\boldsymbol{\omega})} &= \sum_{i=1}^{N}\sum_{j=1}^{M} p_{i,j}^{d} - \sum_{j=1}^{M}\lambda_j[\frac{T}{N}\sum_{i=1}^{N} R_{i,j}^{u}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}) - D_j] \\ &\quad -\sum_{i=1}^{N}\nu_i(p_{\max}-\sum_{j=1}^{M}p_{i,j}^{d}) - \sum_{j=1}^{M}\omega_j(\frac{T}{N}\sum_{i=1}^{N}R_{i,j}^{d}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}) - R_{fair}),\end{aligned}\tag{18}$$

while its dual function can be expressed as:

$$\underset{g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}\in\mathbb{D}}{\mathcal{G}(\boldsymbol{\lambda},\boldsymbol{\nu},\boldsymbol{\omega})} = \inf_{g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d}\in\mathbb{D}} \mathcal{L}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d},\boldsymbol{\lambda},\boldsymbol{\nu},\omega),\tag{19}$$

According to the KKT conditions, the optimal results $g_{i,j}{}^{*},\mathbf{p}_\mathbf{i}^{\mathbf{d}*},\boldsymbol{\lambda}^{*},\boldsymbol{\nu}^{*},\boldsymbol{\omega}^{*}$ have to obey the following equations:

$$\begin{aligned}\frac{h_{i,j}^{d}/\sigma_N{}^2}{1+h_{i,j}^{d}g_{i,j}/\sigma_N{}^2}-\lambda_j\frac{h_{i,j}^{d}h_{i,j}^{u}/\sigma_N{}^2}{1+h_{i,j}^{d}h_{i,j}^{u}(p_{i,j}^{d}-g_{i,j})/\sigma_N{}^2}&=0, && \text{(20a)}\\ \lambda_j\frac{h_{i,j}^{d}h_{i,j}^{u}/\sigma_N{}^2}{1+h_{i,j}^{d}h_{i,j}^{u}(p_{i,j}^{d}-g_{i,j})/\sigma_N{}^2}-\nu_i-\omega&=0, && \text{(20b)}\\ \lambda_j[\frac{T}{N}\sum_{i=1}^{N}R_{i,j}^{u}(g_{i,j},\mathbf{p}_\mathbf{i}^\mathbf{d})-D_j]&=0, && \text{(20c)}\\ \nu_i(p_{\max}-\sum_{j=1}^{M}p_{i,j}^{d})&=0, && \text{(20d)}\\ \omega(p_{avg}N-\sum_{i=1}^{N}\sum_{j=1}^{M}p_{i,j}^{d})&=0, && \text{(20e)}\end{aligned}\tag{20}$$

The optimal results may be obtained by iteratively invoking the following method:

- We fix an arbitrary Lagrange multiplier and calculate its sub-gradient by the equation set (20);
- We then update the multiplier until we find the optimal result.

Having the optimal solution of problem (P5) for a given R_{fair}. We can iteratively update R_{fair} by binary search, which is detailed in Algorithm 1.

Algorithm 1: Iterative Algorithm for fair-throughput maximization

```
Input: $C_\delta$; $D_j$; $h^u_{i,j}$; $h^d_{i,j}$; ${\sigma_N}^2$;
        $D_j$ -- the UL traffic demand.
        $C_\delta$ -- the error tolerance.
        $h^u_{i,j}$ --the power gain of the UL channel.
        $h^d_{i,j}$ --the power gain of the DL channel.
        ${\sigma_N}^2$ -- the power of nosie.
Output: ${\mu_{i,j}}^*$; ${p^d_{i,j}}^*$; ${R_{fair}}^*$
    $R_{fair,\max} = R$ (random value but large enough), $R_{fair,\min} = 0$.
    while $R_{fair,\max} - R_{fair,\min} \geq C_\delta$ do
        $R_{fair} = (R_{fair,\max} + R_{fair,\min}) / 2$,
        Solve (P5) and obtain the corresponding optimal factors ${\mu_{i,j}}^*$, ${p^d_{i,j}}^*$,
        if the optimal result of (P5) greater than $Np_{avg}$ do
            $R_{fair,\max} = R_{fair}$.
        else do
            $R_{fair,\min} = R_{fair}$
    end while
```

4. Simulation and Performance Analysis

In this section, we provide a range of numerical results by solving the sum-throughput and fair-throughput optimisation problem. Given the numerical results, we will deeply investigate the inherent relationships between the throughput performance and various system factors, such as the UL transmission requirements, the power constraints and the PS ratios and etc.

4.1Parameter settings

In this section, the Monte-Carlo simulations are carried out for demonstrating the performance of the proposed model and for characterising the relationship between the integrated data and energy DL transmissions and the classic data UL transmissions in our DEIN system. The general parameter settings are summarised in **Table 1**, while some of the specific settings are stated in the context.

Table 1. Simulation parameters

Parameters	Value
UE number, M	2
Propagation distance d_1	2m
Propagation distance d_2	7m
ID noise power, σ^2	10^{-5}W
P_{max}	1w

P_{max}/P_{avg}	1.4
Time slot, N	5
Period T	1s
Path loss exponent, α	2

4.2 Numerical Result and Analysis

First, a DEIN system consisting of two UEs is considered. We fix the power gains of the multi-path fading channel in both the UL and DL channels. The UL channel gains of UE1 are set to be **(**1.2873, 0.3861, 0.4230, 1.8164, 2.1287) during the five consecutive time slots of its UL transmissions, while its DL channel gains are set to be (0.7138, 0.8084, 0.4365, 0.3434, 0.2815) for the five consecutive time slots of its DL transmissions. Furthermore, the channel power gains of the five consecutive time slots of UE2's UL transmissions are set to be (0.1942, 0.3641, 1.1485, 0.0511, 3.3684), while the channel power gains of its DL transmissions are set to be (0.8238, 0.9635, 0.2672, 0.2292, 1.6773) during another five consecutive time slots.We will provide an exemplary result of the BS's power allocation for the UEs' downlink transmissions.

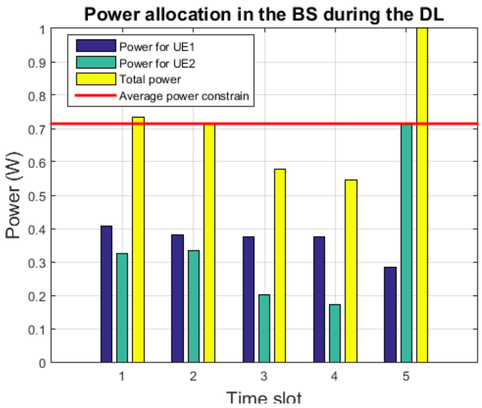

Fig. 3. Power allocation in the BS in sum-throughput maximization

The power allocated during each time slot for the pair of the UEs is illustrated in **Fig. 3**. We can observe from **Fig. 3** that more power is distributed to the time slots having higher channel power gains. Since the channel power gains of UE1 are higher than UE2 during the first four time slots, more power is allocated to UE 1 so as to maximise the sum-throughput of this pair of UEs. Furthermore, since the throughput requirements of the UEs' UL transmission has to be satisfied, the time slots having higher channel power gains of the UL channels and higher channel power gains of the DL channels may receive more transmit power of the BS in order to avoid any power wastage. As portrayed in **Fig. 3** the BS may transmit RF signals with higher power during the fifth time slot.

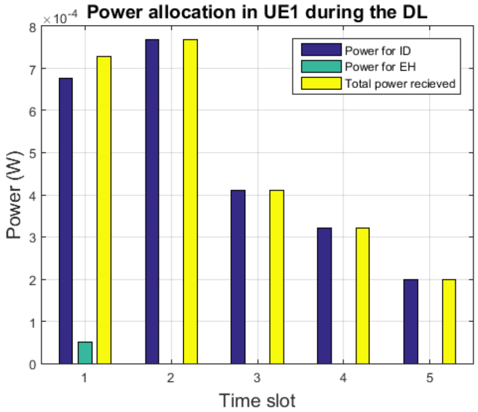

Fig. 4. Power splitting at UE1 by maximising the sum-throughput

Fig. 4 characterises how UE1 splits the received RF signals into two portions for ID and EH by exploiting the PS technique. According to the analytical result of (16), the optimal portion of the received RF power for EH can be calculated by the classic water-filling method, which further indicates that if the channel power gain of the UL channel is very low during a specific time slot, the UL transmission is not performed due to the energy shortage. Hence, as shown in **Fig. 4**, only during the first time slot, UE1 splits the received RF signal for its own EH in order to support its UL transmission.

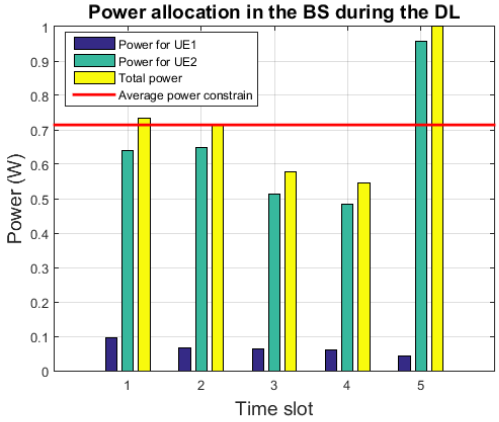

Fig. 5. Power allocation in the BS in fair-throughput maximization

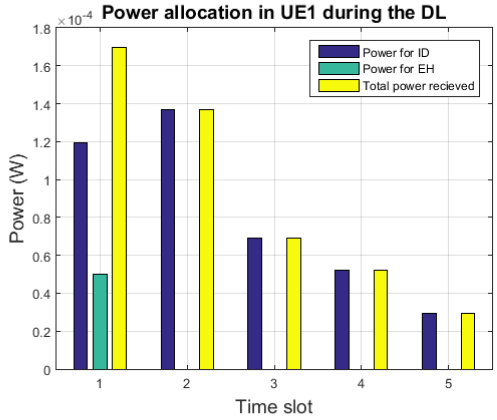

Fig. 6. Power splitting at UE1 in fair-throughput maximization

Due to the nature of the sum-throughput maximization, the BS may allocate more power to UE1, since it has higher channel power gains than its counterpart. As a result, UE1 may enjoy higher DL transmission throughput and receive more data. However, it is unfair for UE2, since its DL channel has a lower channel power gain. As a result, we have to further investigate the so-called fair-throughput maximisation in order to guarantee the fairness among the UEs in the BS's DL transmission.

Fig. 5 and **Fig. 6** characterise the power allocation of the BS's DL transmissions when considering the maximisation of the fair-throughput between UE1 and UE2. The same channel power gains with the investigation of **Fig. 3** and **Fig. 4** are set for their UL and DL channels during five consecutive time slots. Comparing the numerical results of **Fig. 5** with those of **Fig. 3**, we can observe that when our objective is to maximise the fair-throughput, more power is allocated by the BS to the UE2's DL transmissions in order to guarantee the fairness between this pair of UEs in terms of the DL transmission throughput. Although the allocation of the BS's transmit power to this pair of UEs is very different when we conceive different optimisation objectives, the total power allocated to a single time slot remains the same. We further observe from **Fig. 6** and **Fig. 4** that when different maximisation objectives are conceived, different signal splitting strategy is adopted by UE1 for harvesting energy from the received RF signals and for supporting its uplink transmission.

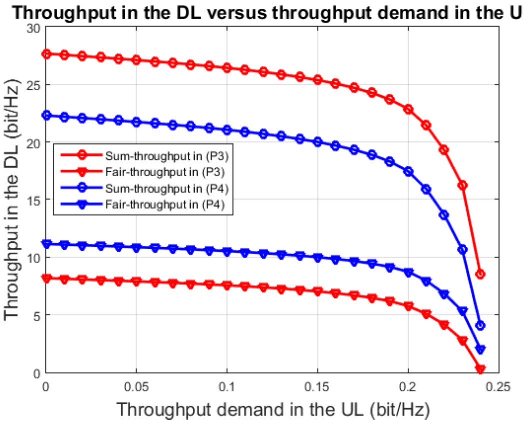

Fig. 7. Throughput in the DL versus throughput demand in the UL

Finally, we plot the sum-throughput of the BS's DL transmissions against the throughput requirements of the UEs' UL transmissionsin **Fig. 7**. We assume that all the UEs' UL transmissions have an identical throughput requirement, which is shown in the x-axis of **Fig. 7**. The numerical results are obtained by averaging 1000 times of the simulation. The channel power gains are modelled by the exponential distributions. Observe from **Fig. 7** that the sum-throughput maximisation produces higher total throughput of the BS's DL transmissions than the fair-throughput maximisation. As portrayed in **Fig. 7**, the sum-throughput of the BS's DL transmissions reduces very slowly by increasing the throughput requirements of the UEs' UL transmissions, when the UL throughput requirement is within the region lower than 0.15 bit/Hz. By contrast, when the UL throughput requirement is within the region higher than 0.2 bit/Hz, the sum-throughput of the BS's DL transmissions falls rapidly. This observation is incurred by the characteristics of the concave log-function, which is exploited for the formulation of the DL and the UL throughputs. If we have an increasing throughput requirement of the UEs' UL transmissions, more energy needs to be harvested from the received RF signals. As a payoff, few portion of the received RF signals can be exploited for the ID during the BS's DL transmissions. As a result, the sum- throughput of the DL transmissions is substantially reduced. Therefore, we should set the UEs' UL transmissions in low rates so as to guarantee the sufficient throughput of the BS's DL transmissions.

5. Conclusion

This paper has proposed a joint power control strategy for both the UL and DL transmissions in a multi-user DEIN, while the PS ratios of the users during their DL transmissions are also optimally decided. During the BS's downlink transmission, the received RF signal is split into two portions by adopting the PS technique. One portion of the RF signal is exploited by the UE for the EH function, while the other portion of the RF signal is exploited by the UE for the ID function. Then, the energy harvested during the BS's downlink transmission is utilised for supporting the UE's UL transmission. We find the optimal power allocation and the PS ratio selection schemes for maximising the sum-throughput of the DL transmissions and for maximising the fair-throughput of the DL transmissions, respectively. A low-complexity iterative algorithm is developed for finding the optimal solutions. Our numerical results thoroughly compare two optimal schemes having different objectives and reveal the inherent relationships between the achievable throughput of the DL transmissions and the throughput requirement of the UL transmissions.

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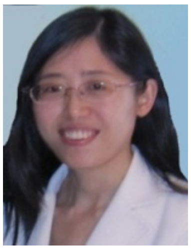

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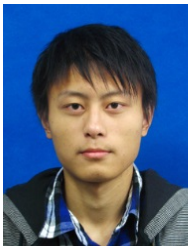

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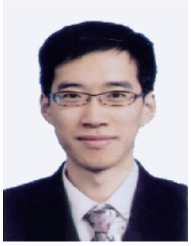

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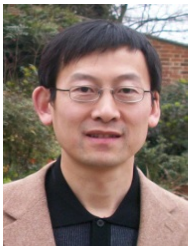

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