SIMULTANEOUS INFORMATION-AND-POWER TRANSFER FOR BROADBAND DOWNLINK SYTEMS

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***Abstract*—Far-field wireless recharging based on *microwave power transfer* (MPT) will free mobile devices from interruption due to finite battery lives. Integrating MPT with wireless communications to support *simultaneous information-and-power transfer* (SIPT) allows the same spectrum to be used for dual purposes without compromising the quality of service. In this paper, we propose the novel approach of realizing SIPT in a broadband downlink system where users are assigned orthogonal frequency sub-channels and a base station transfers information and energy to users over spatially separated channels called the data and MPT channels. Optimizing the power control for such a system results in a new class of multiuser power-control problems featuring the *circuit-power constraints*, namely that the wirelessly transferred power must be sufficiently large for operating receiver circuits. Solving these problems gives a set of power-control algorithms that exploit channel diversity in frequency for simultaneously enhancing the throughput and MPT efficiency. For the single-user SIPT system, the optimal power allocation is shown to perform water filling in frequency with water levels for different users depending on the corresponding MPT sub-channel gains. Next, an efficient power-control algorithm is proposed for the multiuser SIPT system based on sequential scheduling of mobiles by comparing their data rates and circuit-power constraints. This algorithm is proved to be optimal for the practical scenario of highly correlated data and MPT channels.**

***Index Terms*—Power transmission, cellular networks, power control, energy harvesting, mobile communication.**

I. INTRODUCTION

Microwave power transfer (MPT) for far-field wireless recharging will eliminate the cables tethering mobiles to the electric grid [1]. The integration between MPT and wireless communication, called *simultaneous information-and-power transfer* (SIPT), allows a same spectrum to be used for dual purposes, which is the theme of this paper [2].

MPT research in past decades have focused on developing microwave devices for large-scale and long-distance power transfer either terrestrially [1], from solar satellites to the earth [3], or for powering small airplanes [4]. These devices such as rectifying antennas are essential for implementing SIPT transceivers. However, a complete SIPT solution is much more complex and requires sophisticated algorithms for resource allocation, adaptive transmission and signal processing targeting SIPT, which is an area largely open. This motivates the current work that proposes novel power-control algorithms for enabling SIPT in broadband systems e.g., 3GPP LTE or WiFi.

Researchers have studied SIPT from the information-theoretic perspective [5]–[7]. In [5], the capacity of a single-user channel is derived under the constraint that the received power must exceed a threshold representing fixed circuit-power consumption, referred to as the *circuit-power constraint*. For SIPT over an inductive-coupling circuit, maximizing the information capacity under the mentioned constraint yields a tradeoff between the information-and-energy transfer-rates [6]. Similar tradeoffs have been formulated and optimized for various types of SIPT systems including two-user MIMO broadcast channels [7], [8], two-way communication links [9], multiple-access channels and point-to-point links assisted by passive relays [10]. SIPT has been also investigated from the network perspective using stochastic geometry and the optimal density tradeoffs have been derived between base stations for data access and those for MPT [11]. In addition, an efficient receiver design for implementing SIPT was reported in [12].

In contrast with most prior work assuming narrow-band channels, we consider SIPT for broadband downlink systems based on the *orthogonal frequency-division multiple-access* (OFDMA) and optimize power allocation over frequency sub-channels. To this end, a novel class of power-control problems are formulated by introducing multiuser-circuit-power constraints. Each receiver is assumed to comprise an information processor (for demodulating and decoding data) and an energy harvester, which are attached to separate single antennas. Given a multi-antenna base station and transmit beamforming, this receiver architecture creates two effective single-input-single-output (SISO) broadband channels of different functions for each link, referred to as the *data channel* and the *MPT channel*. Note that transmit beamforming is particularly suitable for cellular systems where feedback methods have been implemented for acquiring transmit CSI [13]. For a single-user system, the optimal power-control over frequency is proved to follow watering filling with the water level for each user being a monotone increasing function of the corresponding MPT sub-channel gain. Next, for multiuser downlink, an efficient sub-optimal algorithm is proposed for multiuser power control. This algorithm combines the classic water filling and sequential scheduling of users by comparing the gains of their data and MPT sub-channels, achieving close-to-optimal performance. Furthermore, the proposed algorithm is proved to be optimal for the practical scenario that the data and MPT channels are highly correlated.

II. SYSTEM MODEL

Consider the multiuser system as illustrated in Fig. 1 where a multi-antenna base-station serves K mobiles. The spectrum is partitioned into K sub-channels and each is assigned to one

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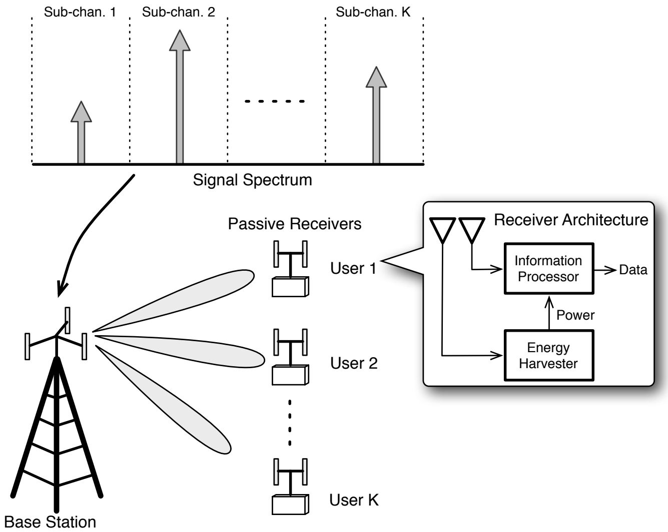

Fig. 1. Simultaneous information-and-power transfer in a broadband multiuser system where K users share the channel by OFDMA.

user. Note that the problem formulation for the case of one user assigned multiple sub-channels differs from the current one in having more complex circuit-power constraints but the solution methods are similar. Ideally, the sub-channel assignments should be jointly optimized with power control over the states of both the data and MPT channels under the multiuser-circuit-power constraints but the optimal design seems intractable. For tractability, we assume given sub-channel assignments and focus on power control.

The passive receiver used by each user comprises an information processor and an energy harvester as illustrated in Fig. 1. The energy harvester converts input signals into DC power for supplying the receiver's fixed circuit power consumption denoted as p_c. Let the vectors $\mathbf{h}_n$ and $\mathbf{h}'_n$ represent particular realizations of the n-th multiple-input-single-output (MISO) data and MPT sub-channels, respectively. Moreover, the transmit-beamforming vector for user n is denoted as $\mathbf{f}_n$. This implies that the same beamforming vector is used for both information and data transfers and this assumption is viable since the typical environment for efficient MPT has lines-of-sight. A beamforming vector for this case steers a beam towards the intended user and can be computed by estimating the user's direction of arrival. However, in the presence of rich scattering, the beamforming vectors for the two purposes should be different, giving rise to the issue of power splitting for data and information transfers as addressed in [7]. The beamforming vectors $\{\mathbf{f}_n\}$ are assumed given and their designs are outside the scope of this paper. Then the effective SISO-channel gains resulting from beamforming can be written as $h_n = |\mathbf{f}_n^\dagger \mathbf{h}_n|^2$ for the data channel and $h'_n = |\mathbf{f}_n^\dagger \mathbf{h}'_n|^2$ for the MPT channel. It follows that the sum throughput is

$$C = \sum_{n=1}^{K} \log_2(1 + P_n h_n) \tag{1}$$

where unit noise variance is assumed to simplify notation and the transmission powers $\{P_n\}$ satisfy both the transmission-power constraint $\sum_n P_n \le p_t$ with p_t being the total available power, and the circuit-power constraint, namely $P_n h'_n \ge p_c$ for all n.

The single-user system is also considered where the user is assigned all K sub-channels. The corresponding throughput is given by C in (1) under the same transmission-power constraint but a different single circuit-power constraint $\sum_n P_n h'_n \ge p_c$ since the harvested power is $\sum_n P_n h'_n$.

III. SIPT for Single-User Systems

Using (1), the problem of the optimal power control for a single-user system can be formulated as:

$$(\mathbf{P1}) \qquad \begin{aligned} \text{maximize:} \quad & \sum_{n=1}^{K} \log(1 + P_n h_n) \\ \text{subject to:} \quad & P_n \ge 0 \ \forall\ n, \\ & \sum_{n=1}^{K} P_n \le p_t, \\ & \sum_{n=1}^{K} P_n h'_n \ge p_c \end{aligned}$$

where the last inequality is the circuit-power constraint. P1 is observed to be a convex optimization problem. Note that P1 with $\{h'_n\}$ replaced by $\{h_n\}$ is equivalent to the problem formulated in [6] where information and power propagate through the same channel.

For the remaining part of this section, we investigate the structure of the optimal power-control policy by solving P1. First, it is necessary to test the feasibility of powering the receiver given transmission power p_t. This requires computing the limit of the harvested power $p_{\max}$ by solving the following optimization problem:

$$(\mathbf{P1.1}) \qquad \begin{aligned} \text{maximize:} \quad & \sum_{n=1}^{K} P_n h'_n \\ \text{subject to:} \quad & P_n \ge 0 \ \forall\ n \\ & \sum_{n=1}^{K} P_n \le p_t. \end{aligned}$$

By inspecting P1.1, it is obtained that $p_{\max} = p_t \max_n h'_n$. It follows that SIPT is feasible if and only if

$$p_t \ge \frac{p_c}{\max_n h'_n}. \tag{2}$$

Next, given the condition in (2), we check if the circuit-power constraint in P1 is active. Assuming it is inactive, P1 reduces to the following problem for the classic multi-channel power-control:

$$(\mathbf{P1.2}) \qquad \begin{aligned} \text{maximize:} \quad & \sum_{n=1}^{K} \log(1 + P_n h_n) \\ \text{subject to:} \quad & P_n \ge 0 \ \forall\ n \\ & \sum_{n=1}^{K} P_n = p_t. \end{aligned}$$

Note that the inequality in the transmission-power constraint in P1 is replaced with equality without loss of generality since the objective function is a strictly monotone increasing function of $\{P_n\}$. The solution for P1.2, denoted as $\{\tilde{P}\}$, follows the water-filling power control [14]:

$$\tilde{P}_n = \begin{cases} \frac{1}{\zeta^*} - \frac{1}{h_n}, & n \in \mathcal{A} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where $\mathcal{A}$ denotes the set grouping the indices of users assigned nonzero powers, namely $\mathcal{A} = \{1 \leq n \leq K \mid \tilde{P}_n > 0\}$, and ζ^* is the matching Lagrange multiplier given as

$$\zeta^* = \frac{|\mathcal{A}|}{p_t + \sum_{m \in \mathcal{A}} \frac{1}{h_m}}. \tag{4}$$

It follows that the circuit-power constraint in P1 is inactive if and only if

$$\sum_{n=1}^{K} \tilde{P}_n h'_n > p_c. \tag{5}$$

The results from the above analysis are summarized as the following lemma.

Lemma 1. Assume that the feasibility condition in (2) is satisfied. The optimal solution for P1, denoted as $\{P_n^*\}$, satisfies the following conditions.

1) If the inequality in (5) holds, $P_n^* = \tilde{P}_n$ for $1 \leq n \leq K$.
2) Otherwise, $\{P^\star\}$ solves the following optimization problem:

$$(\mathbf{P1.3}) \quad \begin{aligned} \text{maximize:} \quad & \sum_{n=1}^{K} \log(1 + P_n h_n) \\ \text{subject to:} \quad & P_n \geq 0 \ \forall\ n, \\ & \sum_{n=1}^{K} P_n = p_t, \\ & \sum_{n=1}^{K} P_n h'_n = p_c. \end{aligned}$$

Last, the constrained optimization problem P1.3 can be solved using the method of duality [15]. As a result, the optimal transmission powers are obtained as

$$P_n^\star = \begin{cases} \frac{1}{\lambda^* - \mu^* h'_n} - \frac{1}{h_n}, & n \in \mathcal{O} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where the set $\mathcal{O}$ is chosen to ensure $\{P_n\}$ being nonnegative and the positive scalars λ^* and μ^* are the Lagrange multipliers solving the dual problem, namely unconstrained minimization of the following convex function [15]:

$$\sum\nolimits_{n \in \mathcal{O}} \log \frac{1}{\lambda - \mu h'_n} + (\lambda + \mu) \sum\nolimits_{n \in \mathcal{O}} \frac{1}{h_n} + \lambda p_t + \mu p_c.$$

The optimal power allocation in (6) can be interpreted as water filling in frequency with a water level decreasing with the increasing MPT sub-channel gain or vice versa. This agrees with the intuition that less transmission power is required for turning on a receiver if the MPT loss is smaller. In contrast, the classic water filling in (3) has a constant water level.

IV. SIPT for Multi-User Systems

A. Power Control

The power-control problem for the multiuser SIPT system is formulated as follows:

$$(\mathbf{P2}) \quad \begin{aligned} \text{maximize:} \quad & \sum_{n=1}^{K} \log(1 + P_n h_n) \\ \text{subject to:} \quad & \sum_{n=1}^{K} P_n \leq p_t \\ & P_n \in \{0\} \cup \left[\frac{p_c}{h'_n}, \infty\right) \quad \forall\ n \end{aligned}$$

where the last line is the multiuser circuit-power constraints.

To solve P2, it is useful to consider the traditional power-control problem P1.2 that is equivalent to P2 with the circuit-power constraints relaxed. Given the solution for P1.2 in (3), define a subset $\mathcal{S}$ of $\mathcal{A}$ as $\mathcal{S} = \{n \in \mathcal{A} \mid \tilde{P}_n < p_c/h'_n\}$. Then the users whose indices belong to $\mathcal{S}$ fail to satisfy their circuit-power constraints. It may be unnecessary to deactivate all users in $\mathcal{S}$ since turning off any of them allows the originally assigned power to be redistributed for potentially helping others in $\mathcal{S}$ to meet their circuit-power constraints. Determining the optimal subset of users from $\mathcal{S}$ for deactivation requires jointly considering the originally allocated powers and additional amounts for meeting their circuit-power constraints. This is analytically intractable and requires testing all subsets of $\mathcal{S}$ by reallocating power for each subset, whose complexity grows exponentially with the size of $\mathcal{S}$.

To address this issue, a sub-optimal but efficient algorithm is proposed for sequentially deactivating users in $\mathcal{S}$ that have relatively small gains for both their data and MPT sub-channels. Note that the Lagrange multiplier ζ^* in (4) can be interpreted as the price for allocating one unit of power as measured against the data rate. Therefore, a suitable metric H_n can be defined as

$$H_n = \log\left(1 + \frac{p_c h_n}{h'_n}\right) - \frac{\zeta^* p_c}{h'_n}, \qquad n \in \mathcal{S} \tag{7}$$

for comparing the gains for satisfying the circuit-power constraints for the users in $\mathcal{S}$. The proposed algorithm uses $\{H_n\}$ to search for the set of active users under the circuit-power constraints and the detailed procedure is described as follows.

Algorithm 1.

1) Obtain $\mathcal{A}$ and $\mathcal{S}$ by solving P1.2. Compute ζ^* and $\{H_n\}$ using (4) and (7), respectively.
2) Deactivate the user in $\mathcal{S}$ that has the smallest H_n. In other words, modify the active user set as $\mathcal{A} = \mathcal{A} \backslash \{m\}$ with $m = \arg\min_{n \in \mathcal{S}} H_n$.
3) Given $\mathcal{A}$, re-compute $\{\tilde{P}_n\}$ and ζ^* using (3) and (4), respectively. Furthermore, applying the circuit-power

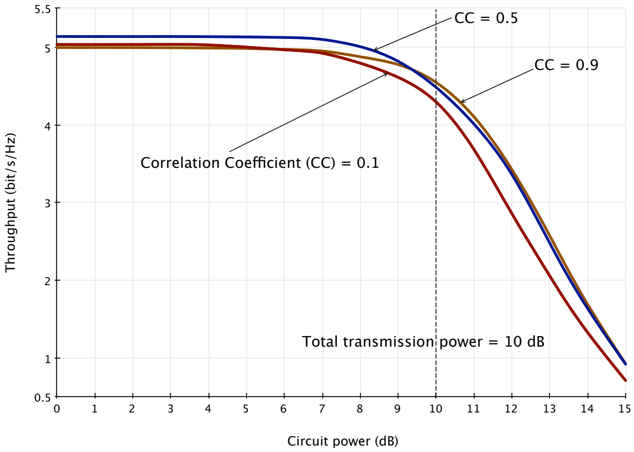

Fig. 2. Throughput versus circuit power for the single-user SIPT system.

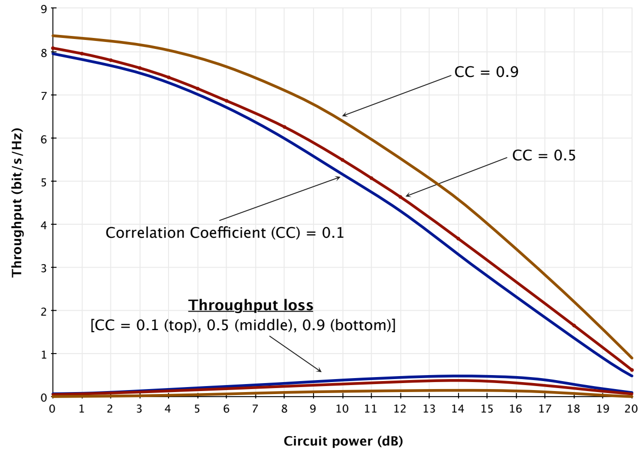

Fig. 3. Sum throughput versus circuit power for the multiuser SIPT system.

constraints on $\{\tilde{P}_n\}$ to obtain $\mathcal{S}$. If $\mathcal{S} = \emptyset$, all active users in $\mathcal{A}$ satisfy their circuit-power constraints and the algorithm terminates. Otherwise, compute $\{H_n\}$ in (7) using the updated $\mathcal{S}$ and ζ^* and go to Step 2.

Two remarks are offered as follows.

a) By the iteration of Algorithm 1, since the number of active users decreases, the values of $\{\tilde{P}_n\}$ increase; the set $\mathcal{S}$ reduces and eventually becomes empty.
b) The feasibility condition in (2) also applies to the multiuser system. If this condition holds, Algorithm 1 will select at least one active user.

B. Power Control for Correlated Data-and-MPT Channels

The data and MPT sub-channels for the same link are highly correlated since they are created by two collocated receive antennas. Thus, their gains are expected to follow the same order, namely that $h_m \geq h_m$ if and only if $h'_m \geq h'_n$ for all (m, n). Without loss of generality, it is assumed in this section that $h_1 \geq h_2 \cdots \geq h_k$ and $h'_1 \geq h'_2 \cdots \geq h'_k$. Note that the minimum transmission powers under the circuit-power constraints, namely $\{p_c/h'_n\}$, follow the reverse order: $p_c/h'_1 \leq p_c/h'_2 \cdots \leq p_c/h'_k$. Therefore, it is optimal to activate those users having the largest data/WPT channel gains since they achieve high information rates but have relatively loose circuit-power constraints. Let ℓ denote the largest positive integer in the range $1 \leq \ell \leq K$ such that given $\{\tilde{P}_n\}$ computed using (3) with $\mathcal{A} = \{1, 2, \cdots, \ell\}$, $\{\tilde{P}_n \mid 1 \leq n \leq \ell\}$ all satisfy their corresponding circuit-power constraints. The following proposition is a direct result of the above discussion.

Proposition 1. Consider the case where $h_1 \geq h_2 \cdots \geq h_k$ and $h'_1 \geq h'_2 \cdots \geq h'_k$. The solution for P2 is given by $\{\tilde{P}_n\}$ computed using (3) with $\mathcal{A} = \{1, 2, \cdots, \ell\}$.

Last, Algorithm 1 in the preceding sub-section is shown to be optimal for the current scenario.

Proposition 2. Consider the case where $h_1 \geq h_2 \cdots \geq h_k$ and $h'_1 \geq h'_2 \cdots \geq h'_k$. Algorithm 1 yields the solution for P2 as given in Proposition 1.

The proof of Proposition 2 is omitted due to the space limitation. The key step of the proof is to show that the metrics $\{H_n\}$ defined in (7) and used in Algorithm 1 follow the same order as $\{h_n\}$ [or equivalently $\{h'_n\}$] for the current case by exploiting the monotonicity of the Lagrangian (from solving P2) with respect to allocated powers larger than $\{\tilde{P}_n\}$.

V. Simulation Results

The data and MPT sub-channel gains for each link are modeled as the absolute values of a pair of complex $\mathcal{CN}(0, 1)$ random variables with the correlation coefficient ρ. The gains for different links are independent and identically distributed. The number of sub-channels is $K = 5$ and the total transmission power is $p_t = 10$ dB and 15 dB for the single-user and multiuser systems, respectively.

Consider a single-user SIPT system with the optimal power control. The curves of throughput versus circuit power p_c are plotted in Fig. 2 for $\rho = \{0.1, 0.5, 0.9\}$. The throughput is observed to be almost constant for $p_c \leq p_t$ but decrease rapidly as p_c exceeds p_t. The changes on ρ are found to cause only small variations of the throughput. Low correlation ($\rho = 0.1$) results in throughput loss of about 0.4 bit/s/Hz in the range of $p_c \geq p_t$ due to that the circuit-power constraint is active more frequently for less correlated data/MPT channels. However, moderate correlation ($\rho = 0.5$) balances the diversity and correlation for these two channels so as to yield the small throughput gain in the range of $p_c \leq p_t$.

Next, for a multiuser SIPT system with power control using Algorithm 1, Fig. 3 displays the curves of throughput versus p_c for $\rho = \{0.1, 0.5, 0.9\}$. In addition, the bottom of Fig. 3 shows the throughput loss with respect to the maximum values computed by an exhaustive search. The threshold effect at $p_c = p_t$ in Fig. 2 is not observed in Fig. 3 due to the *multiuser-diversity gain*, namely that the presence of multiple receivers and independent sub-channels increases the probability that at least one receiver is active even if p_c is large. Moreover, the sum throughput is observed to increase and the throughput loss reduce as ρ grows.

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