Wireless Power Charging Control in Multiuser Broadband Networks

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Abstract—Recent advances in wireless power transfer (WPT) technology provide a cost-effective solution to charge wireless devices remotely without disruption to the use. In this paper, we propose an efficient wireless charging control method for exploiting the frequency diversity in multiuser broadband wireless networks, to reduce energy outage and keep the system operating in an efficient and sustainable state. In particular, we first analyze the impact of charging control method to the operating lifetime of a WPT-enabled broadband system. Based on the analysis, we then propose a multi-criteria charging control policy that optimizes the transmit power allocation over frequency by jointly considering the channel state information (CSI) and the battery state information (BSI) of wireless devices. For practical implementation, the proposed scheme is realized by a novel limited CSI estimation mechanism embedded with partial BSI, which significantly reduces the energy cost of CSI and BSI feedback. Simulation results show that the proposed method could significantly increase the network lifetime under stringent transmit power constraint. Reciprocally, it also consumes lower transmit power to achieve near-perpetual network operation than other single-criterion based charging control methods.

I. INTRODUCTION

The performance of wireless systems is fundamentally constrained by limited device battery life. As frequent battery replacement/recharging by manual operation is often costly and inconvenient, numerous energy-conservation methods have been proposed to prolong the operating lifetime of wireless communication networks, via transmit power control, energy-aware medium access control (MAC) and routing selection, etc [1]–[3]. Alternatively, radio frequency enabled (RF-enabled) wireless power transfer (WPT) technologies provide an attractive solution to power wireless devices (WDs) over the air [4]. By leveraging the far-field radiative properties of microwave, WDs could harvest energy remotely from the RF signals radiated by the dedicated energy transmitter [5]. Currently, RF power in milliwatt (mW) level could be effectively transferred to WDs from a distance of more than 10 meters [6]. The received RF energy is sufficient to power the activities of many low-power devices, such as sensors and RF identification (RFID) tags, where some commercial RF-enabled WPT products have already been developed by Powercast Corp. Besides, the recent development of MIMO technology significantly boosts the energy transfer efficiency [6], [7], which also opens up more potential applications for RF-enabled WPT in the future.

The practical advantages of WPT have recently attracted increasing efforts to develop wireless powered communication systems [4]–[10]. Among them, WPT for broadband networks is of particular interest, where both wireless information and power transfer could benefit from the broadband channel diversity [9], [10]. However, unlike information transfer, WPT does not introduce detrimental interference to unintended co-channel receivers. This fundamental difference motivates this study to redesign the MAC mechanism in WPT-enabled broadband systems for efficient charging coordination among the distributed WDs, which are of general power usage besides communication purpose.

Efficient WPT control in broadband systems requires the energy transmitter to have accurate knowledge of both the channel state information (CSI) and battery state information (BSI) of WDs. While accurate CSI could effectively enhance the energy transfer efficiency, well-informed BSI helps reduce energy outage rate by transmitting on the sub-channels in favor of those close-to-outage WDs. Although being assumed by many previous studies for the simplicity of analysis (e.g., [9], [10]), in practice, however, achieving perfect knowledge of CSI/BSI consumes significant amount of energy for the WDs to perform CSI estimation and CSI/BSI feedback. The energy cost to the WDs may even offset the power gain obtained from more refined transmit power allocation.

In this paper, we propose a new cost-effective charging control method in WPT-based broadband networks. The proposed method has the following main features and advantages:

1) A multi-criteria charging policy is proposed based on the analysis of expected network lifetime of WPT-based systems. Specifically, different metrics are used to evaluate the energy-harvesting performance of the WDs depending on their residual battery levels or BSI.

2) The charging control policy is implemented by a novel limited CSI estimation mechanism embedded with partial BSI, which incurs very low complexity and energy cost on CSI/BSI feedback. In particular, simulations show that good system performance is achievable even with very limited CSI feedback, e.g., by estimating at most 4 out of 50 sub-channels for a WD to feed back.

3) The network lifetime performance of the proposed multi-criteria method is robust against different network deployment, and could be further optimized by tuning the control parameters according to specific applications.

The performance advantage of the proposed multi-criteria charging control method is evaluated through extensive simulations and comparisons with other heuristically designed single-criterion based benchmark schemes.

1See Powercast Corp. website at http://www.powercastco.com.
II. SYSTEM MODEL

We consider a WPT-enabled broadband wireless network, where an energy node (EN) is connected to a stable power source and broadcasts RF energy to power \( K \) distributed WDs. Each WD has an RF energy harvesting circuit and rechargeable battery of capacity \( C \) to store the harvested energy and power the activities of the WD, e.g., event sensing or data transmission. The bandwidth of the system is \( W \) Hz, which is equally divided into \( N \) sub-channels each with bandwidth \( W/N \). The wireless channels are assumed to be reciprocal in the uplink and downlink, and independent among the WDs. For the simplicity of exposition, we assume that the channel experiences block fading, where the sub-channel gains remain constant in a transmission block of length \( T \) and vary independently over different blocks. Notice that the block fading assumption does not affect the validity of our analysis or the operation of the proposed protocols.

In the \( j \)-th transmission block, \( j \in \{0, 1, \cdots \} \), we use \( h_{k_i}^j \) to denote the transmission power gain of the \( i \)-th sub-channel between the EN and the \( k \)-th WD, \( P_i^j \) to denote the transmit power of the EN on the \( j \)-th sub-channel. The total transmit power is bounded by \( \sum_{i=1}^{N} P_i^j \leq P_0, j = 0, 1, \cdots \). Then, the harvested energy by the \( k \)-th WD within the block is [5]

\[
Q_k^j = \eta T \sum_{i=1}^{N} P_i^j h_{k_i}^j, \quad k = 1, \cdots, K,
\]

where \( \eta \in (0, 1] \) is a fixed parameter denoting the energy harvesting efficiency which is assumed to be known by the EN. Let \( X_k^j \) denote the residual energy of the \( k \)-th WD at the end of \( j \)-th transmission block, and \( E_k^j \) denote the amount of energy consumed within the transmission block. Within each block, we assume that the energy consumption rate is constant so that the energy level increases or decreases monotonically. Then, the residual energy at the end of the \( (j+1) \)-th block is

\[
X_k^{j+1} = \min \left\{ \max \left( X_k^j - E_k^j + Q_k^{j+1}, 0 \right), C \right\}.
\]

In this paper, \( E_k^j \) is assumed to follow a general distribution with an average consumption rate \( \mathbb{E}[E_k^j] = \mu_k T, \forall j \).

The output voltage of a battery decreases with the residual energy level. We say an energy outage occurs if the remaining energy of a WD \( k \) is no larger than a certain threshold \( \nu^o \), such that normal device operation could not be maintained. Without loss of generality, we set \( \nu^o = 0 \) throughout this paper. Given the initial battery level \( X_k^0 = [X_1^0, \cdots, X_K^0] \), we define network lifetime as the duration until a WD is in energy outage. Whenever an energy outage occurs, the device in energy outage will enter a hibernation mode, which harvests RF energy and returns to normal operation only after the battery level reaches a prescribed threshold \( \nu^u (\nu^u > \nu^o) \). This is a common practice to avoid frequent energy outage for continuous device operation. Notice that the results obtained from homogeneous battery assumption here could also be extended to heterogeneous case (i.e., WDs have different capacities and threshold parameters) by scaling the respective channel gains and energy consumption rates accordingly.

Due to channel diversities among the WDs over both time and frequency, the network lifetime is determined by the transmit power allocation strategy \( P^j = [P_1^j, \cdots, P_K^j] \) over time \( j = 1, 2, \cdots \). Besides, the knowledge of CSI and BSI, although costly to obtain, is critical to the performance of transmit power allocation. In the following, we first analyze the impact of charging control method to the network lifetime. Based on the analysis, we then propose an efficient charging control method with limited CSI/BSI feedback mechanism.

III. CHARGING CONTROL POLICY ANALYSIS

A point to notice is that the network lifetime is affected by many factors besides transmit power allocation, such as EN placement, total transmit power and channel distributions. In this section, we assume that all the other parameters are fixed to focus on the design of transmit power allocation policy. We denote \( L_{\psi} \) as the expected network lifetime achieved by a charging policy \( \psi \). Specifically, a charging control policy \( \psi \) specifies the transmit power allocation in each transmission block, and thus the harvested energy \( Q_k^j \), for \( k = 1, \cdots, K \) and \( j = 1, 2, \cdots \). To void trivial results, we assume that the expected network lifetime is finite regardless of the charging policy used, i.e.,

\[
\max_{\psi \in \pi} L_{\psi} < \infty, \quad (3)
\]

where \( \pi \) is the set of all feasible policies that satisfy the transmit sum-power constraint, \( P_0 \). In other words, \( P_0 \) is assumed to be sufficiently small, so that the total energy harvesting rate is always lower than the consumption rate, to be consistent with the condition in [3]. In fact, as verified later by simulations, a charging policy \( \psi \) that achieves a longer \( L_{\psi} \) under a given transmit power budget also requires lower transmit power to achieve near-perpetual network operation (i.e., \( L_{\psi} \) is a very large number). Therefore, finding the optimal charging policy under finite network lifetime assumption also has important implication in practical system designs with the guarantee of sufficiently large \( L_{\psi} \).

A. Wireless Charging: A Game-theoretic View

The actual battery dynamic in [2] complicates the analysis because of the max/min operators, yet unable to provide extra insight into charging policy design. To make the problem tractable, we adjust the battery model as follows:

1) The energy level could surpass the battery capacity at the end of a transmission block, but such an overcharged battery cannot harvest any energy in the following transmission block(s) until the energy level drops below the capacity due to power usage;

2) When an energy outage occurs, the residual energy could be negative at the end of the current transmission block.

The first modification helps remove the min operator in [2], while ensuring that the energy level is approximately upper bounded by the capacity \( C \). Specifically, it overestimates the harvested energy when battery is fully-charged in a transmission block, but underestimates the harvested energy in the following transmission block(s). The second modification
removes the max operator in (3). Both modifications have limited effect to the modeling accuracy, because a practical transmission block length is sufficiently small, such that the energy harvested/consumed within a block is marginal compared to the battery capacity. With the two minor modifications, we could express the battery dynamics as a random process \( X_{k+1} = X_k + \sum_{j=1}^{k} \left[ E_{j+1} + Q_{j+1} \right], \ j = 0, 1, \cdots, \) where
\[
Q_{j+1} = \begin{cases} 0, & X_k \geq C, \\ Q_{j+1}, & \text{otherwise} \end{cases}
\]
denotes the harvested energy in the \((j+1)\)-th transmission block of the modified battery model, with \(Q_k\) given in (1). The average energy harvesting rate is determined by the control policy \(\psi\), and denoted by \(\lambda_k^\psi \triangleq \mathbb{E}[Q_k^\psi]/T\). Accordingly, an energy outage occurs if \(X_k^l \leq 0\).

Equivalently, the charging problem could be modeled by a gambling game with the \(K\) WDs as gamblers. \(X_k^l\) is the balance of gambler \(k\), who continuously plays a betting game with \(Q_k^l\) as the income and \(E_{j+1}^l\) as the loss in the \((j+1)\)-th bet, \(j = 0, 1, \cdots\). The game starts with each gambler holding \(X_0^l\) initial balance, and stops once a gambler’s balance becomes zero or negative. Then, the stopping time of the game is also the network lifetime. Evidently, the game is unfair because the average income and loss of each bet are not equal in general, i.e., \(\lambda_k^\psi \neq \mu_k\). In particular, a gambler \(k\) receives zero income in the \((j+1)\)-th bet when \(X_k^l \geq C\). In the following, we derive the expected stopping time of the above gambling game by constructing an auxiliary fair game, such that Martingale stopping time theorem \[11\] could be applied.

### 3.2 Expected Network Lifetime

We first introduce an auxiliary random process \(Z_j = [Z_1^l, Z_2^l, \cdots, Z_K^l], \ j = 0, 1, \cdots, \) where \(Z_k^l \triangleq X_k^l + Y_k^l\) and
\[
Y_k^l = \begin{cases} Y_{k-1}^l + \left( \mu_k - \lambda_k^\psi \right) T, & j > 0 \text{ and } X_{k-1}^l < C, \\ Y_{k-1}^l + \mu_k T, & j > 0 \text{ and } X_{k-1}^l \geq C. \end{cases}
\]
\(Y_k^l\) could be considered as the cumulative compensation given to gambler \(k\) up to the \(j\)-th bet, where the gambler is compensated for \(\left( \mu_k - \lambda_k^\psi \right) T\) in the \(j\)-th bet if its balance before the bet, i.e., \(X_{j-1}^l\), is less than \(C\). Otherwise, it receives \(\mu_k T\) if \(X_{j-1}^l \geq C\). The following lemma shows that the random process \(Z_j\) is a Martingale.

**Lemma 1:** The random process \(\{Z_j, j \geq 0\}\) is a Martingale, or equivalently the bet is a fair game.

**Proof:** To prove Lemma 1, we need to show that for all \(j\) it satisfies 1) \(\mathbb{E}[Z_j] < \infty\) and 2) \(\mathbb{E}[Z_{j+1} | Z_j = z_j, \cdots, Z_1 = z_1] = z_j\) \[11\]. Condition 1 holds from the assumption that \(L_\psi\) (the number of bets) is finite. For condition 2), we have for each \(k\)
\[
E[Z_{j+1} | Z_j = z_j, \cdots, Z_0 = z_0] = z_k^l + \mathbb{E} \left[ Q_k^l - E_k^l \right] + \sum_{j=1}^{k} \left( \mu_k T \left[ 1 - \psi_k \right] \right) \left( \mu_k - \lambda_k^\psi \right) T = z_k^l,
\]
where \(1_{\psi_k}^l\) is an indicator function that equals 1 if \(X_k^l \geq C\) and 0 otherwise. This completes the proof.

Then, the following Martingale Stopping Theorem \[11\] could be used to derive the expected network lifetime.

**Proposition 1 (Martingale Stopping Theorem):** Let \(\{Z_j, j \geq 0\}\) be a Martingale and \(W\) a stopping time that depends only on the value of \(Z_j\). If \(\mathbb{E}[|Z_W|] < \infty\), then \(\mathbb{E}[Z_W] = \mathbb{E}[Z_0]\).

In our case, \(W\) corresponds to the number of bets until \(X_k^l < 0\) for some \(Z_k^l\). For an initial state \(Z_0\), we have
\[
\mathbb{E} \left[ \sum_{k=1}^{K} Z_k^l \right] = \mathbb{E} \left[ \sum_{k=1}^{K} \left( \mu_k \right) + \sum_{k=1}^{K} Y_k^l \right] = \sum_{k=1}^{K} x_k^l \triangleq \varepsilon_0, \tag{5}
\]
where \(x_k^l\) is the value of \(X_0^l\), and \(\varepsilon_0\) denotes the initial sum-energy of the WDs. Similarly, at the end of the \(W\)-th bet, we have
\[
\mathbb{E} \left[ \sum_{k=1}^{K} Z_k^l \right] = \mathbb{E} \left[ \sum_{k=1}^{K} \lambda_k^\psi \right] + \mathbb{E} \left[ \sum_{k=1}^{K} Y_k^l \right] \triangleq \varepsilon_0 + \mathbb{E}[W] T \sum_{k=1}^{K} \mu_k - \sum_{k=1}^{K} \left( 1 - \alpha_k^\psi \right) \lambda_k^\psi, \tag{6}
\]
where \(\alpha_k^\psi\) denotes the probability that the battery of the \(k\)-th WD is fully- or overcharged, and \(\varepsilon_0 \triangleq \mathbb{E} \left[ \sum_{k=1}^{K} X_k^l \right]\) denotes the expected residual sum-energy achieved by policy \(\psi\). From Proposition 1, we could infer that the right-hand sides of (5) and (6) are equal. With simple calculations, the expected stopping time conditioned on \(\varepsilon_0\) is obtained as
\[
\mathbb{E}[L_\psi | \varepsilon_0] = \mathbb{E}[W] T = \frac{\varepsilon_0 - \varepsilon_0^\psi}{\sum_{k=1}^{K} \mu_k - \sum_{k=1}^{K} \left( 1 - \alpha_k^\psi \right) \lambda_k^\psi}. \tag{7}
\]
We notice that \(\mathbb{E}[L_\psi | \varepsilon_0]\) is always positive by our assumption that the total energy harvesting rate is smaller than the consumption rate, i.e., \(\sum_{k=1}^{K} \lambda_k^\psi \leq \sum_{k=1}^{K} \mu_k, \forall \psi \in \pi\). Besides, the network lifetime expression in (3) for conventional battery-powered wireless sensor network is a special case of ours when \(\lambda_k^\psi = 0\), i.e., WPT is not used.

### 3.3 Charging Policy Analysis

To prolong the expected network lifetime in (7), a charging policy \(\psi\) should produce
1) low total residual energy \(\varepsilon_0^\psi\);
2) high total energy harvesting rate \(\sum_{k=1}^{K} \lambda_k^\psi\);
3) and low overcharging probabilities \(\alpha_k^\psi\).

For condition 1), the ideal scenario is for all the WDs to have zero residual energy simultaneously. In this case, the optimal charging policy is the max-min approach, i.e., maximizing the minimum residual energy among the WDs after each energy transmission block. For the second condition, the optimal policy is the max-rate approach, i.e., maximizing the total harvested energy by all the WDs in each transmission block. For the third condition, the optimal policy is the min-max approach, i.e., minimizing the maximum residual energy among the WDs after each transmission block. In a practical wireless powered network, however, the above three charging policies may conflict with each other. For instance, the max-rate approach is strongly biased towards nearby WDs with high average channel gains. The power allocation of the max-min approach, however, is in favor of WDs that are far-away
from the EN with smaller channel gains. This simple
efficiency tradeoff indicates that the three objectives could not
be satisfied by a single-criterion charging policy in general.

To balance the three objectives, we therefore consider a
multi-criteria approach. Our observation is that overcharging
only occurs to close-to-capacity WDs. Thus, the EN should
apply a min-max criterion to the close-to-capacity WDs, to
discourage allocating power to the sub-channels that may lead
to overcharge in the coming transmission block(s). Besides,
using max-min approach to charge the currently close-to-outage WDs could effectively reduce $\epsilon^w_k$, because otherwise
larger amount of energy will be harvested by the WDs of
moderate/high energy levels in the subsequent transmission
block(s), leading to higher $\epsilon^w_k$. For those WDs of moderate
energy levels, the max-rate approach is most suitable, because
charging them with the highest efficiency does not have
immediate effect to either $\alpha^w_k$’s or $\epsilon^w_k$, but could effectively
enhance the sum charging rate $\sum_{k=1}^{K} \lambda^w_k$.

The above analysis motivates a multi-criteria charging con-
control method that jointly considers the CSI and BSI. However,
a practical question arises on how to efficiently feed back
CSI/BSI to the EN in an energy-constrained broadband system
with a large number of WDs and sub-channels. To tackle this
problem, we propose in the following a simple yet efficient
charging control protocol based on limited CSI/BSI feedback.

IV. PROPOSED PROTOCOL

In this section, we propose a multi-criteria charging control
protocol using a limited CSI feedback mechanism. The proto-
col operates in the following steps and is illustrated in Fig. 1.

Without causing confusions, we omit the transmission block
index $j$ in this section for the brevity of notation.

1) At the beginning of a transmission block, the EN sends
pilot signals on the $N$ sub-channels. Then, each WD $k$
estimates its own sub-channel power gains, i.e., $h_{k,i}$’s;

2) Depending on the residual energy $X_k$, each WD $k$ sends
back to the EN orthogonal narrowband pilot signals on
its $M_k$ strongest sub-channels, with

$$M_k = \begin{cases}
    m_i, & X_k \leq \tau_i, \\
    m_m, & \tau_i < X_k \leq \tau_h, \\
    m_h, & X_k > \tau_h,
\end{cases} \quad (8)$$

where $m_h \leq m_m \leq m_i$ are positive integers, and $0 < \tau_i, \tau_h < C$ are two predetermined energy thresholds. The
subset of sub-channels reported by WD $k$ is denoted by
$\mathcal{M}_k$, $k = 1, \ldots, K$.

3) Here, we assume that the channel estimation by the
EN is perfect. Besides the knowledge of the channel
gains, i.e., $\{h_{k,i} | i \in \mathcal{M}_k, i = 1, \ldots, N, k = 1, \ldots, K\}$, the EN is also aware of the quantized BSI of each WD
by counting the number of pilots sent by the WDs, i.e., $\mathcal{M}_k$’s. The EN then optimizes its transmit power
allocation on all the sub-channels using a policy detailed later in (9).

4) The WDs harvest RF energy in the remaining transmis-
sion block. Then, the iteration repeats from Step 1).

Instead of sending pilots on all the sub-channels, each WD
only reports on a small subset of sub-channels with the largest
channel gains, which significantly reduces the energy cost.
The intuition behind is that transmit power is in general only
distributed to relatively strong sub-channels, thus the knowledge
of weak sub-channels’ CSI has marginal effect to the power
allocation solution. Although consuming more energy to send
pilots on a larger number of sub-channels, from (8), a WD
of lower residual energy could in fact benefit from a more
favorable power allocation due to the better knowledge
of CSI by the EN. On the other hand, the number of pilots
sent by a WD also contains partial BSI indicating the energy
level, which will be exploited by our proposed power control.
In addition, the values of $\{m_i, m_m, m_h\}$ could be tuned in
different scenarios, e.g., setting $m_m = m_h = 0$ such that a
WD sends energy request only when it is close to outage. The
impact of these parameters will be shown by simulations.

The knowledge of CSI and BSI enables a multi-criteria
charging policy as discussed in Section III.C. In particular,
from the values of $M_k$’s, the EN is aware of the subsets of WDs in low, moderate and high residual energy levels, denoted by $N_l, N_m$ and $N_h$, respectively. We design the EN to allocate transmit power $P_i$ to the $i$-th sub-channel, $i = 1, \ldots, N$, by solving the following linear programming (LP) problem:

$$\begin{array}{ll}
\text{maximize} & \sum_{k \in N_l} \hat{Q}_k + c_1 \sum_{k \in N_m} \hat{Q}_k - c_2 \max_{k \in N_h} \hat{Q}_k \\
\text{subject to} & \sum_{i=1}^{N} P_i = P_0, \quad P_i \geq 0, \quad i = 1, \ldots, N,
\end{array} \quad (9)$$

where $\hat{Q}_k$ denotes the estimated harvested energy by the $k$-th
WD, given by $\hat{Q}_k = \eta T \cdot \sum_{i=1}^{N} P_i \hat{h}_{k,i}$, where

$$\hat{h}_{k,i} = \begin{cases}
\hat{h}_{k,i}, & i \in \mathcal{M}_k, \\
\mathbb{E} [h_{k,i} | h_{k,i} \leq \min_{j \in \mathcal{M}_k} h_{k,j}], & i \notin \mathcal{M}_k.
\end{cases} \quad (10)$$

The three terms in the objective of (9) denote the weighted
energy harvested by WDs in $N_l, N_m$ and $N_h$, respectively. $c_1$ and $c_2$ are two positive weights set for balancing the three
terms. Specifically, the first term maximizes the minimum
harvested energy of the close-to-outage WDs. The second
term maximizes the total harvested energy by the WDs with
moderate energy level. The last term discourages the EN to
charge the close-to-capacity WDs. Generally speaking, a larger
(smaller) \( c_1 \) would enhance the energy harvesting efficiency (fairness). A larger \( c_2 \) would increase the penalty to charge the WDs that are close-to-capacity. In general, \( c_1 \) and \( c_2 \) are set much smaller than 1 to ensure that priority is given to the close-to-outage WDs.

Note that from (10), \( Q_k \) is calculated using both the explicit CSI reported on \( \mathcal{M}_k \), and the implicit CSI for those sub-channels not reported by WD \( k \). In (10), we use conditional expectation to calculate \( h_{k,i} \) given that the channel gains of unreported sub-channels are lower than the known channel gains in \( \mathcal{M}_k \). Then, the calculation of \( h_{k,i} \) for \( i \notin \mathcal{M}_k \) is determined by the distribution of \( h_{k,i} \)'s. Denote \( t_k \triangleq \min_{i \in \mathcal{M}_k} h_{k,i} \). For instance, the estimate is \( h_{k,i} = h^l + t_k/2 \) if \( h_{k,i} \)'s are independent and uniformly distributed within \([h^l, h^b]\). If \( h_{k,i} \)'s follow independent exponential distribution with mean \( h_0 \), the estimate is \( h_{k,i} = t_k + h_0 - t_k/(1 - e^{-t_k/h_0}) \).

The proposed charging control protocol incurs low implementation cost. All the computations are borne by the EN, while each energy-constrained WD only needs to send out limited number of pilots based on the measurement of channel gains and its own residual energy level.

### V. Performance Evaluation

In this section, we evaluate the performance of the proposed multi-criteria charging (MCC) control algorithm. Unless otherwise stated, the parameters used in all simulations are listed in Table I, which correspond to a typical indoor sensor/RFID network. Without loss of generality, the path loss exponent is 2, such that the path loss is roughly 37.7 dB at 2 meters from the EN. In practice, multiple ENs are needed to cover a large area, which is beyond the scope of this paper and will be considered in our future work. The wireless channel power gains follow exponential distributions with mean obtained from the path loss model. Here, we consider an i.i.d. energy consumption model where a WD consumes 28 mW power with probability 0.25 within a block, and no power with probability 0.75. In this case, the average energy consumption rate is 7 mW, where a fully-charged battery will be depleted in about 2.5 hours without WPT. The initial battery level of all WDs is 80% of the capacity, and \( \eta = 1 \) is assumed.

For the proposed MCC algorithm, we set \( \{\tau_l, \tau_h\} = \{2, 4, 5, 4\} \) mAh and \( \{m_l, m_m, m_h\} = \{4, 2, 1\} \). That is, a WD with less than 40% of the battery capacity will report the 4 best sub-channels, while those with more than 90% battery will report 1 sub-channel. Otherwise, a WD will report on 2 sub-channels. Besides, we set \( c_1 = 0.2 \) and \( c_2 = 0.1 \) in (9). We have also considered three single-criterion based benchmark schemes for comparison, including

### Table I

| Parameter                  | Value |
|----------------------------|-------|
| EN Tx power                | 1 W   |
| Center frequency           | 915 MHz |
| No. of SCs                 | 50    |
| SC bandwidth               | 10 kHz |
| Tx antenna gain            | 2.5   |
| Rx antenna gain            | 2     |
| Path loss exponent         | 2     |
| Tx block length            | 100 ms |
| Battery voltage            | 3 V   |
| Battery capacity           | 6 mAh |

![Fig. 2. Comparisons of average network lifetime vs. distance spread d.](image-url)
For fair comparison, we deploy the same charging control method to prolong the lifetime of a wireless powered multiuser broadband system. The proposed charging policy is efficiently implemented using a limited CSI feedback mechanism embedded with partial CSI. Simulations results show that the proposed charging control could significantly increase the network lifetime under a fixed transmit power constraint, and is also power efficient to achieve self-sustainable network operations.

VI. CONCLUSIONS

In this paper, we have proposed a novel multi-criteria charging control method to prolong the lifetime of a wireless powered multiuser broadband system. The proposed charging policy is efficiently implemented using a limited CSI feedback mechanism embedded with partial CSI. Simulations results show that the proposed charging control could significantly increase the network lifetime under a fixed transmit power constraint, and is also power efficient to achieve self-sustainable network operations.

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