Optimal Power and Time Allocation for WPCNs With Piece-Wise Linear EH Model

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Abstract—We propose a novel transmission protocol for harvest-then-transmit wireless powered communication networks, which takes into account the non-linearity of the energy harvesting (EH) process at the EH users and maximizes the sum rate in the uplink. We assume a piece-wise linear EH model and provide expressions for the optimal transmit power of the base station (BS), the duration of the EH phase, and the duration of the uplink information transmission phases of the users. The obtained solution provides insight regarding the significance of the non-linear EH model on the optimal resource allocation. Simulations unveil the growing impact of the saturation effect, which occurs for high received radio frequency powers, as the average and the maximum instantaneous transmit powers of the BS increase.

Index Terms—Energy harvesting, WPCN, non-linear EH model, resource allocation.

I. INTRODUCTION

WIRELESS powered communication networks (WPCNs) are a new type of wireless network that combines wireless information and power transfer (SWIPT) system for resource allocation for a multi-antenna simultaneous wireless information and power transfer (SWIPT) system for a practical non-linear EH model, where the EH characteristic is approximated via curve fitting. A comparison of several nonlinear EH models can be found in [6]. The design and resource allocation of WPCNs are affected by the non-linearity of practical EH circuits, and algorithms designed based on the linear EH model can lead to a significant performance loss due to model mismatch [5]–[8]. References [5] and [7] show that the saturation of practical EH circuits is responsible for this performance loss. Additionally, incorporating the saturation effect into the EH model appears particularly important for maximizing the sum rate in the uplink of WPCNs. In particular, [2, Th. 1], which assumes the linear EH model, suggests that the BS should transmit with the maximum possible power when the channel conditions are favorable. As a result, in practice, many of the EHU may be in saturation due to their non-linear EH circuit. Although the EH model in [5] shows a very good match with measurement data, its application for EH resource allocation design leads to complicated optimization problems, solvable only via iterative numerical algorithms. These algorithms do not reveal the influence of the non-linearity on optimal resource allocation. To address this issue, in this letter, we adopt a simple piece-wise linear approximation of the non-linear EH characteristic and analyze its influence on the optimal power and time allocation of harvest-then-transmit WPCNs. The motivation for using a piece-wise linear EH model is two-fold: first, it is analytically tractable, and second, it captures the saturation behavior of practical EH circuits. The piece-wise linear EH model has been already employed in the context of outage performance analysis of relay systems [9], [10] and secure communication [11], but not in the context of resource allocation.

II. SYSTEM MODEL AND SUM RATE MAXIMIZATION

We consider a WPCN, which consist of a single BS and K EHU, employing Time Division Multiple Access (TDMA). All nodes are equipped with a single antenna, and operate in the half-duplex mode. The transmission time is divided into M epochs of equal duration T, each containing a single TDMA frame. Each TDMA frame is divided into an EH phase, and K information transfer (IT) phases. In epoch i, the duration of the EH phase is denoted by τ(i)T, whereas the duration of the successive IT phases of all EHU are denoted by τ(i)T, . . . τ(1)T, τ(0)T, respectively, where τ(i)T are time-sharing parameters which are dimensionless quantities satisfying 0 ≤ τ(i) ≤ 1 and τ(0)T + K k=1 τ(k)T = 1. We assume that all wireless links exhibit frequency non-selective block fading, i.e., the channel coefficients are constant in each slot but change from one slot to the next, where each slot corresponds to one epoch. In epoch i, the fading power gain of the BS − EHUk channel is x(i) and we normalize its value by the power of the additive white Gaussian noise (AWGN) at the receiver, N0, to obtain x(i) = x(i)/N0 with average value E[k]x(i) = E[k]x(i)/N0, where E[·] denotes expectation. For convenience, the downlink and uplink channels are assumed to be reciprocal and the BS is assumed to have full channel

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state information in each epoch. The instantaneous transmit power of the BS is denoted by $p_0(i)$ and satisfies the average power constraint $P_{\text{avg}}$, i.e., $E[p_0(i)\tau_0(i)] = P_{\text{avg}}$.

A. EH Model

The EHU s are equipped with rechargeable batteries and employ a harvest-then-transmit mechanism, i.e., they charge their batteries in the EH phase and then transmit information in the corresponding IT phases during which they spend all of their harvested energy.

The EH process can be modelled by a piece-wise linear EH characteristic, which implies that the RF-DC (direct current) conversion curve consists of a linear part corresponding to the linear regime of operation, and a constant (saturation) part corresponding to saturated regime of operation. Therefore, the harvested power of EHU $k$ is modeled as:

$$P_{\text{HK}}k = \begin{cases} \eta_k P_{\text{in}}, & \eta_k P_{\text{in}} \leq P_{\text{HK}}k \\ P_{\text{HK}}k, & \text{otherwise} \end{cases}$$

where $P_{\text{HK}}k$ is the peak amount of power that can be harvested by EHU $k$ and $\eta_k$ denotes the EH efficiency ($0 < \eta_k < 1$). Thus, the harvested energy of EHU $k$ in epoch $i$ is given by

$$E_k(i) = T \cdot \min\{N_0 \eta_k x_k(i) p_0(i) \tau_0(i), P_{\text{HK}}k \tau_0(i)\}.$$ 

Therefore, its transmit power during the IT phase is $P_k(i) = E_k(i)/(\tau_k(i)T)$, and its achievable rate is $r_k(i) = \tau_k(i) \log(1 + P_k(i) x_k(i))$. The average achievable rate of EHU $k$ is $R_k = \lim_{M \to \infty} \frac{1}{M} \sum_{i=1}^{M} r_k(i)$.

B. Unconstrained Instantaneous BS Transmit Power

Here, we aim at maximizing the sum rate in the uplink subject to an average power constraint at the BS:

$$\text{maximize} \quad \frac{1}{M} \sum_{i=1}^{M} \sum_{k=1}^{K} P_k(i) x_k(i) \log \left(1 + \frac{\eta_k x_k(i)}{\tau_k(i)} \right) \times \min\{N_0 \eta_k x_k(i) p_0(i) \tau_0(i), P_{\text{HK}}k \tau_0(i)\} \quad \text{s.t.} \quad C_1: \frac{1}{M} \sum_{i=1}^{M} p_0(i) \tau_0(i) \leq P_{\text{avg}} \quad C_2: \tau_0(i) + \sum_{k=1}^{K} \tau_k(i) = 1, \forall i \quad C_3: 0 \leq p_0(i), \forall i.$$ 

The optimal solution of problem $Q_0$ is given in the following theorem.$^1$

**Theorem 1:** In each epoch $i$, we relabel the EHU s such that:

$$\frac{P_{H1}}{N_0 \eta_1 x_1(i)} < \frac{P_{H2}}{N_0 \eta_2 x_2(i)} < \ldots < \frac{P_{HK}}{N_0 \eta_K x_K(i)}.$$ 

Such relabeling does not affect the objective function which only depends on the sum of the rates of all EHU s.

In each epoch $i$, the optimal power allocation at the BS, $p_0(i)$, if greater than 0, inverts the channel of one of the EHU s, the index of which we denote by $s^*$, such that the harvested power of this EHU is exactly on the boundary between the linear and the saturated part of the EH characteristic curve, i.e., the harvested power is $P_{\text{HK}}s^* = \eta_{s^*} p_0(i) N_0 x_{s^*}(i) = P_{\text{HK}}s^*$. Index $s^*$ is determined as follows:

$$s^* = \left\{ 1 \leq s \leq K : \frac{A_{s-1}(i)}{\lambda} > z_{s-1} \text{ and } \frac{A_s(i)}{\lambda} < z_s \right\}$$

where

$$A_s(i) = \sum_{m=s+1}^{K} N_0 \eta_m x_m(i), \quad B_s(i) = \sum_{n=1}^{s} P_{\text{HK}}n x_n(i),$$

$$z_s = (B_s(i) - 1)/W((B_s(i) - 1)/e).$$

$W(\cdot)$ is the Lambert-W function, and $\lambda$ is chosen such that equality holds in $\text{C1}$. Thus, the optimal power allocation at the BS is:

$$p_0(i) = \begin{cases} \frac{P_{\text{HK}}s^*}{(N_0 \eta_{s^*} x_{s^*}(i))}, & A_0(i) > \lambda \\ 0, & \text{otherwise} \end{cases}$$

Therefore, the harvested power of the EHU s with indices $n \in S_0^* = \{1, 2, \ldots, s^* - 1\}$ are in the saturation regime, i.e., the harvested powers are $P_{\text{HK}}n$, respectively, whereas the harvested powers of the EHU s with indices $m \in S_1^* = \{s^* + 1, s^* + 2, \ldots, K\}$ are in the linear regime, i.e., the harvested powers are $P_{\text{HK}}m = \eta_m p_0(i) N_0 x_m(i)$, respectively.

The optimal duration of the IT phase of the EHU s in the linear regime is given by

$$\tau_n(i) = \frac{p_0(i) N_0 \eta_m x_m(i) \tau_0(i)}{(C_s(i) - 1)},$$

and the optimal duration of the IT phase of the EHU s in the saturated regime is given by

$$\tau_0(i) = \frac{1 + \frac{p_0(i) A_s(i)}{C_s(i) - 1} + B_s(i)}{C_s(i) - 1}.$$ 

Constant $C_s(i)$ is obtained as the solution to the following transcendental equation:

$$\log(C_s(i)) = \frac{C_s(i) - 1}{C_{s^*}(i)} + \frac{\lambda P_{\text{HK}}s^*}{N_0 \eta_{s^*} x_{s^*}(i)} = \frac{1}{C_{s^*}(i)} \left( \frac{P_{\text{HK}}s^* A_{s^*}(i)}{\eta_{s^*} x_{s^*}(i) N_0 + B_{s^*}(i)} \right).$$

**Proof:** Please refer to the Appendix.

C. Constrained Instantaneous BS Transmit Power

Let us assume that, apart from the average power constraint $P_{\text{avg}}$, the instantaneous transmit power of the BS is limited to $P_{\text{M}}$. In this case, $C_3$ of $Q_0$ is replaced by the following constraint:

$$\hat{C}_3 : 0 \leq p_0(i) \leq P_{\text{M}}, \forall i,$$

leading to a new optimization problem:

$$Q_1 : \text{Identical to } Q_0 \text{ with } C_3 \text{ replaced by } \hat{C}_3$$

The solution of problem $Q_1$ is given in the following theorem:

**Theorem 2:** In epoch $i$, let us relabel the EHU s as

$$\frac{P_{H1}}{N_0 \eta_1 x_1(i)} < \frac{P_{H2}}{N_0 \eta_2 x_2(i)} < \ldots < \frac{P_{\text{HK}}}{N_0 \eta_K x_K(i)} < \frac{P_{\text{HK}+1}}{N_0 \eta_{K+1} x_{K+1}(i)} < \ldots < \frac{P_{\text{HK}}}{N_0 \eta_K x_K(i)},$$

$^1$ We note that if the non-linear EH model [5, eq. (4), (5)] is applied instead of the piece-wise linear model in (1), the resulting sum-rate maximization problem is non-convex, and does not permit an efficient solution. Applying an exhaustive search is computationally infeasible, since we assume $M \to \infty$. 


If \( g \geq s^g \), then Theorem 1 applies. Otherwise, let \( m \in G_1 = \{1, 2, \ldots, g\} \) and \( n \in G_2 = \{g+1, \ldots, K\} \). In this case, the optimal BS transmit power is \( p_0(i) = P_M \), and, \( \tau_m(i), \tau_n(i), \) and \( \tau_0(i) \) are obtained from (10), (11), and (12), respectively, with \( C_{r'}(i) \) replaced by \( C_g(i) \), where \( C_g(i) \) is given by:

\[
\log(C_g(i)) - \frac{C_g(i) - 1}{C_g(i)} + \lambda P_M = \frac{PMAk(i) + B_g(i)}{C_g(i)}. \tag{17}
\]

**Proof:** Due to the constrained space and the similarity with the proof of Theorem 1, we give only a sketch of the proof. The problem is again solved using the dual Lagrangian method. For each epoch \( i \), the new constraint \( C_3 \) introduces another Lagrangian multiplier \( \gamma(i) \), whose value is greater than 0 when \( p_0(i) > P_M \). As long as \( p_0(i) \leq P_M \), we have \( \gamma(i) = 0 \) and the solution of \( Q_i \) remains the same as the solution of \( Q_0 \). When the solution of \( Q_0 \) is such that \( p_0(i) > P_M \) then the right hand side of \( C_3 \) is satisfied with equality, so \( \gamma(i) > 0 \) and \( p_0(i) \) becomes \( p_0(i) = P_M \). In this case, the stations with \( PH_k/(N_0n_kx_k(i)) < P_M \) are in saturation and all other EUs in the linear regime, as seen from (16). The optimal \( \tau_0(i) \) and \( \tau_k(i) \) are found following [2, Appendix] while taking into account that some of the stations can be in the saturated regime.

**III. Numerical Results**

In this section, we assume a WPCN with Rayleigh fading channels, with \( E[x_k^2(i)] = 10^{-3} D_k \) , where \( D_k \) is the distance between the BS and EHU \( k \). We assume a peak power constrained BS, and EUs placed on a circle around the BS at a radius of 10 m. For the proposed and the baseline resource allocation schemes, in our simulations, the harvested powers of all EUs are determined according to the practical EH characteristic curve in [4, Fig. 5(b)] obtained from measurements performed on EH circuits at 1 MΩ load. The proposed resource allocation scheme (denoted as "Proposed resource allocation") is based on Theorem 2. The parameters of the corresponding piece-wise linear EH model are obtained by fitting the two segments of the piece-wise curve to the measured characteristic in [4, Fig. 5(b)], such that the slope of the linear part is determined by incident power levels lower than the value at which the power efficiency starts to decline rapidly (\(-16 \) dBm). This leads to \( \eta_k = 0.2 \) and \( PH_k = 9.2 \mu W, \forall k \). We employ two baselines for performance comparison. Baseline 1 is a WPCN which employs the power and time allocation that is optimal for the linear EH model [2, Th. 1] with \( \eta_k = 0.2 \). Baseline 2 applies a constant power and time allocation scheme: in each epoch, the BS transmits with power \( p_0(i) = P_M \), the EH phase duration is set to \( \tau_0(i) = P_{avg}/P_M \) (such that C1 is satisfied with strict equality to ensure a fair comparison), and the IT phases are of equal duration \( \tau_k(i) = (1 - \tau_0(i))/K, \forall k \).

Fig. 1 shows the sum rates of the WPCNs obtained with different resource allocation schemes. Fig. 1 a) reveals that for small values of \( P_{avg} \), the sum rate difference between the proposed resource allocation scheme and Baseline 1 is negligible, since for small values of \( P_{avg} \) all EUs operate in the linear regime for most of the time. As \( P_{avg} \) increases, Baseline 1 uses the BS power less efficiently compared to the proposed resource allocation scheme, yielding lower sum rates. Baseline 2 yields the worst results since no optimization is applied. Fig. 1 a) also reveals that a larger number of EUs leads to a higher sum rate. This effect is caused by the larger amount of energy that can be harvested with more EUs due to the broadcast nature of the wireless channel.

![Fig. 1](image-url)

**IV. Conclusion**

In this letter, we proposed a communication protocol that maximizes the uplink sum rate of WPCNs while taking into account the non-linearity of the EH RF-DC conversion through a piece-wise linear model. When the maximum instantaneous transmit power of the BS is limited, the optimal protocol requires the BS to adapt its transmit power such that the harvested power of a certain EHU is exactly on the boundary between the linear regime and the saturated regime of the EHU’s EH characteristic. The proposed protocol outperforms the optimal protocol for a linear EH model since the latter forces the BS to transmit with maximum power causing a waste of power due to the saturation of the harvested power.

**Appendix**

**Proof of Theorem 1**

After substituting \( e(i) = p_0(i) \tau_0(i) \) and representing the function \( \min\{0, \eta_k x_k(i) e(i), P_{avg} \tau_0(i) \} \) by its epigraph using the auxiliary variable \( e_k(i) \), we obtain the following equivalent convex problem:

\[
\text{Maximize} \quad \sum_{i=1}^{M} \sum_{k=1}^{K} \tau_k(i) \log(1 + \frac{e_k(i)}{\tau_k(i) x_k(i)}) \quad \tag{18}
\]

s.t. \( C_1 : \quad \frac{1}{M} \sum_{i=1}^{M} e(i) \leq P_{avg} \)

\( C_2 : \quad \tau_0(i) + \sum_{k=1}^{K} \tau_k(i) = 1, \forall i \)

\( C_3 : \quad 0 \leq e(i), \forall i \)

\( C_4 : \quad e_k(i) \leq N_0 \eta_k x_k(i) e(i), \forall k, i \)

\( C_5 : \quad e_k(i) \leq P_{avg} \tau_0(i), \forall k, i \)
The Lagrangian of problem (18) is given by:

\[
L = \sum_{i=1}^{M} \sum_{k=1}^{K} \frac{\tau_k(i)}{M} \log \left( 1 + \frac{e_k(i)}{\tau_k(i)} x_k(i) \right) + \lambda \left( P_{avg} - \frac{1}{M} \sum_{i=1}^{M} e(i) \right) - \sum_{i=1}^{M} \beta(i)(e_k(i) - P_{Hk} \tau_0(i)) - \sum_{i=1}^{M} e(i) \left( \tau_0(i) + \sum_{k=1}^{K} \tau_k(i) - 1 \right)
\]

where \(\lambda, \varepsilon(i), \mu_k(i), \alpha_k(i),\) and \(\beta_k(i)\) are the Lagrangian multipliers associated with \(\mathcal{C}_1 - \mathcal{C}_5\), respectively. In epoch \(i\), the slackness conditions must be satisfied for each \(k\):

\[
0 = \mu(i)e(i) = \alpha_k(i)(e_k(i) - N_0 n_k x_k(i)e(i)) = \beta_k(i)(e_k(i) - P_{Hk} \tau_0(i))
\]

After differentiating \(L\) with respect to \(\tau_k(i), e_k(i), e(i),\) and \(\tau_0(i)\), and setting the result equal to zero, we get:

\[
\log \left( 1 + \frac{e_k(i)}{\tau_k(i)} x_k(i) \right) - \frac{\varepsilon_k(i)}{\varepsilon(i)} \frac{\tau_k(i)}{x_k(i)} - \varepsilon(i) = 0 \quad (21)
\]

\[
-\alpha_k(i) - \beta_k(i) + \frac{x_k(i)}{\tau_k(i)} = 0 \quad (22)
\]

\[
-\lambda + \mu(i) + \sum_{k=1}^{K} \alpha_k(i) N_0 n_k x_k(i) = 0 \quad (23)
\]

\[
-\varepsilon(i) + \sum_{k=1}^{K} \beta_k(i) P_{Hk} = 0 \quad (24)
\]

From (21), we see that the BS receives the signals from all EHU with the same signal-to-noise ratio (SNR) equal to \(C(i) - 1, i.e.,\n
\[
e_k(i)x_k(i)/\tau_k(i) = C(i) - 1, 1 \leq k \leq K, \quad (25)
\]

where \(C(i)\) satisfies \(C(i) > 1\), and from (22), we obtain:

\[
x_k(i)/\alpha_k(i) + \beta_k(i) = C(i), 1 \leq k \leq K. \quad (26)
\]

Now, assume that a single EHU, which is given index \(s\), simultaneously satisfies \(\mathcal{C}_4\) and \(\mathcal{C}_5\) with equality. Due to (4), the EHU whose harvested power falls into the linear part of the EH model have indices \(m \in S_1 = \{1, 2, \ldots, s\}\) and the EHUs whose harvested power falls into the saturation part have indices \(n \in S_2 = \{s+1, s+2, \ldots, K\}\). Due to (20), we have \(\alpha_s(i) > 0, \beta_s(i) > 0, \alpha_m(i) > 0, \beta_m(i) > 0, \) and \(\beta_n(i) > 0\). From (25), we therefore obtain:

\[
\alpha_m(i) = \frac{x_m(i)}{C_s(i)}, \quad \beta_m(i) = \frac{x_m(i)}{C_s(i)}, \quad \alpha_s(i) + \beta_s(i) = \frac{x_s(i)}{C_s(i)}. \quad (27)
\]

There is exactly one solution for (29), (30), \((\beta_s(i), C_s(i)),\) such that \(0 < \beta_s(i) < 1\). To see this, we define an equation \(f(z, a) = \log(z) - (z - 1 - a)/z\) which has root \(z^* = (a - 1)/(W(e^{-(a-1)})^{-1})\) for \(a > 0\) and \(z^*_1 = 1\) for \(a = 0\). From (29), we know that \(C_s(i)\) is an increasing function of \(\beta_s(i)\) and from (30), \(C_s(i)\) is a linearly decreasing function of \(\beta_s(i)\). Thus, since when setting \(\rho = 0 = 1,\) we respectively obtain:

\[
A_s(i)/\lambda > z_{s-1} \quad (31)
\]

After differentiating \(L\) with respect to \(\tau_k(i), e_k(i), e(i),\) and \(\tau_0(i)\), and setting the result equal to zero, we get:

\[
\log \left( 1 + \frac{e_k(i)}{\tau_k(i)} x_k(i) \right) - \frac{\varepsilon_k(i)}{\varepsilon(i)} \frac{\tau_k(i)}{x_k(i)} - \varepsilon(i) = 0 \quad (21)
\]

\[
-\alpha_k(i) - \beta_k(i) + \frac{x_k(i)}{\tau_k(i)} = 0 \quad (22)
\]

\[
-\lambda + \mu(i) + \sum_{k=1}^{K} \alpha_k(i) N_0 n_k x_k(i) = 0 \quad (23)
\]

\[
-\varepsilon(i) + \sum_{k=1}^{K} \beta_k(i) P_{Hk} = 0 \quad (24)
\]

\[
\beta_s(i) = \beta_s(i) x_s(i) C_s(i). \quad (29)
\]

Based on (21), (23), and (24), we obtain the following set of equations with two unknowns \((\rho_s(i), C_s(i)),\)

\[
\log(C_s(i)) - C_s(i) - 1 = \rho_s(i) P_{Hs} x_s(i) + B_{s-1}(i) \quad (29)
\]

There is exactly one solution for (29), (30), \((\beta_s(i), C_s(i)),\) such that \(0 < \beta_s(i) < 1\). To see this, we define an equation \(f(z, a) = \log(z) - (z - 1 - a)/z\) which has root \(z^* = (a - 1)/(W(e^{-(a-1)})^{-1})\) for \(a > 0\) and \(z^*_1 = 1\) for \(a = 0\). From (29), we know that \(C_s(i)\) is an increasing function of \(\rho_s(i)\) and from (30), \(C_s(i)\) is a linearly decreasing function of \(\beta_s(i)\). Thus, since when setting \(\rho = 0 = 1,\) we respectively obtain:

\[
A_s(i)/\lambda > z_{s-1} \quad (31)
\]

\[
\rho_s(i) = \rho_s(i) x_s(i) C_s(i). \quad (29)
\]

\[
\log(C_s(i)) - C_s(i) - 1 = \rho_s(i) P_{Hs} x_s(i) + B_{s-1}(i) \quad (29)
\]

\[
C_s(i) = (A_s(i) + C_s(i)(N_0 n_s x_s(i)^2)/\lambda) \quad (30)
\]

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