SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER IN LOW-LATENCY RELAYING NETWORKS WITH NONLINEAR ENERGY HARVESTING

(Invited Paper)

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ABSTRACT

This work studies a simultaneous wireless information and power transfer (SWIPT)-enabled relaying network, where a power splitting protocol is applied at the relay before energy harvesting (EH). Due to low-latency requirements, the transmissions are operated with short blocklength codes. We aim at providing a reliability-oriented network design, while for the first time, the finite blocklength (FBL) impact and a realistic nonlinear EH process are jointly considered. In particular, we characterize the overall error probability of the considered network, and formulate the problem minimizing the overall error probability by optimally choosing the power splitting ratio. However, the formulated problem is non-convex due to the nonlinear EH process (which is also non-convex), thus making it challenging to be solved optimally. To tackle this difficulty, we propose a three-step approach to obtain an efficient solution. We first introduce two auxiliary variables, with the assistance of which we reformulate the problem. Then, we apply a convex approximation technique to tightly approximate the problem (at each local point/solution), based on which an efficient iterative algorithm (updating the local point) is finally proposed approaching a high-quality sub-optimal solution. Simulation results are provided to validate the convergence of the proposed algorithm and evaluate the performance in comparison to benchmarks with linear EH.

Index Terms— simultaneous wireless information and power transfer (SWIPT), relaying network, power splitting, nonlinear energy harvesting (EH), finite blocklength (FBL).

1. INTRODUCTION

Future wireless networks are expected to support high speed, low-latency and high reliability transmissions while connecting a massive number of smart devices, e.g., enabling applications in the Internet of Things (IoT) [1], such as industrial control, autonomous driving, cyber-physical systems, E-health, haptic feedback in virtual and augmented reality, smart grid, and remote surgery [2]. To guarantee the low-latency requirement, data transmissions are operated using short blocklength codes, which makes the transmission perform differently from existing results [3–5] conducted under the assumption of an infinite blocklength (IBL), i.e., assuming the transmissions to be arbitrarily reliable at the Shannon's capacity. In the finite blocklength (FBL) regime, a considerable error probability exists even if the coding rate is set to be lower than the Shannon capacity. Accurate FBL models are developed addressing the relationship between the error probability and the coding rate in peer to peer transmissions under additive white Gaussian noise (AWGN) channels [6] and quasi-static fading channels [7, 8]. The FBL performance of a relaying network is characterized in [9, 10].

Moreover, energy harvesting (EH) is well-known to be a promising technology to prolong the lifetime of the IoT network [11–14]. For non-relaying wireless powered EH networks, the energy consumption model is characterized in [15] and the energy efficiency is maximized by resource allocation in [16–18]. To explore the cooperative gain of relaying, a strategy called simultaneously wireless information and power transfer (SWIPT)-enabled relaying is introduced [19], where the source sends signals carrying both energy and information at the same time to the relay and the relay forwards the information to the destination based on the harvested energy. Different protocols of SWIPT are investigated in [20] for relaying networks. The corresponding error probability of these protocols is discussed in [21] within a large-scale relay network. The authors in [22] have studied the reliability in a cooperative decode-and-forward relaying network. Most existing studies conducted for SWIPT-enabled relaying are under the IBL assumption, which makes the results inaccurate for a low-latency scenario. Nevertheless, recent work in [23] derives the FBL performance of a SWIPT-enabled relaying transmission, while ignoring the nonlinearity [24] in the EH process. To the best of our knowledge, an accurate performance modeling and a system design are still missing for SWIPT-enabled relaying networks under the consideration of the impacts of FBL codes in the communication process and the nonlinearity in the EH process. In this work, we study a SWIPT-enabled relaying network in the FBL regime, where a power splitting (PS) protocol is applied at the relay. Under the assumption of a nonlinear EH process, we minimize the overall error probability by designing an optimal PS ratio.

The rest of this paper is organized as follows: In Section 2, we describe the system using a nonlinear EH model and a FBL performance model. Then, the problem is stated in Section 3. We reformulate the problem based on two auxiliary variables and propose an iterative algorithm in Section 4. Finally, our work is validated through simulation results in Section 5 and concluded in Section 6.

2. PRELIMINARIES

In this section, we first describe the system and subsequently review the FBL performance model for a peer to peer transmission.

2.1. System Description

We consider a two-hop relaying network including a source (S), a relay (R) and a destination (D). A data packet with a size of k bits is

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required to be transmitted ultra reliably in a short transmission period with a length of N symbols. In particular, the transmission from the source to the destination is divided into two hops, respectively, through two links, i.e., link S-R and link R-D. In the first hop, the relay performs EH and decodes the data packet which is transmitted from the source. If the relay decodes successfully, it forwards the packet to the destination in the second hop. We denote by n_1 and n_2 the blocklengths (numbers of symbols) in the two hops, i.e., $n_1 + n_2 = N$. Then, the corresponding time lengths of the two hops are $n_1 T_0$ and $n_2 T_0$, where T_0 represents the time length of a symbol.

Recall that the network is required to support highly reliable transmissions. Hence, we reasonably assume that the line-of-sight (LoS) paths for both links always exist. In addition, the channels of two links are assumed to independently experience a quasi-static Nakagami-m fading, where m is the shape factor. In other words, the channels are constant within one transmission period and vary independently to the next. We denote by β_1 and β_2 the constant channel gains of the two links. The transmit power is indicated by P_s and the noise power of two links are represented by σ_1 and σ_2, respectively. In addition, denote by $\alpha \in (0,1)$ the PS ratio at the relay. Hence, a portion of received power, i.e., $\alpha\beta_1 P_s$, is applied for decoding, which yields the following signal-to-noise ratio (SNR)

$$\gamma_1 = \frac{\alpha\beta_1 P_s}{\sigma_1}. \quad (1)$$

The remaining energy is converted to direct-current (DC) power via a nonlinear EH process. According to [25], the nonlinearity of the EH process can be generalized by an implicit function. By introducing the Taylor expansion of nonlinearity in diode, we can obtain an implicit relation between output harvested current I_{out} and the received RF power Q_{rf}:

$$e^{\frac{R_{\text{L}} I_{\text{out}}}{n v_t}} (I_{\text{out}} + I_{\text{s}}) \approx \sum\nolimits_{j=0}^{n'_o} \alpha_j Q_{\text{rf}}^j, \quad (2)$$

where R_L, n, v_t and I_s respectively denote the load resistance, the ideality factor, the thermal voltage and the reverse bias saturation current of diode. The truncation order n'_o is a positive integer which can be sufficiently large and determinate the accuracy of the nonlinear EH model. In addition, all the factors α_j are positive. The harvested power P_{eh} is clearly a function of output current I_{out}, namely $P_{eh} = I_{\text{out}}^2 R_L$, which implies that the charged power P_{eh} is also an implicit nonlinear function of received power Q_{rf}. We denote by $\mathcal{F}_{\text{nl}}(Q_{\text{rf}})$ this nonlinear function, i.e., $P_{\text{eh}} = \mathcal{F}_{\text{nl}}(Q_{\text{rf}})$. Therefore, the harvested power at relay (R) is given by $\mathcal{F}_{\text{nl}}[(1-\alpha)\beta_1 P_s]$, as the power for harvesting is $Q_{\text{rf}} = (1-\alpha)\beta_1 P_s$. The total harvested energy at relay is $n_1 T_0 \mathcal{F}_{\text{nl}}[(1-\alpha)\beta_1 P_s]$. As a result, we can formulate the SNR γ_2 for link R-D as

$$\gamma_2 = \frac{\beta_2 n_1 T_0 \mathcal{F}_{\text{nl}}[(1-\alpha)\beta_1 P_s]}{n_2 T_0 \sigma_2} = \frac{\beta_2 n_1 \mathcal{F}_{\text{nl}}[(1-\alpha)\beta_1 P_s]}{n_2 \sigma_2}. \quad (3)$$

3. PROBLEM STATEMENT

In the following, we study the FBL performance of an SWIPT-enabled relaying network supporting high reliability transmissions. The transmission via each link is required to be reliable enough, i.e., the error probability is lower than a threshold ε_{th}, where in general we assume $\varepsilon_{\text{th}} \ll 10^{-1}$. Recall that the data packet likely has a considerable amount of bits. Hence, it should be mentioned that an ultra reliable transmission cannot be guaranteed if the received SNR at either R or D is extremely low, e.g., $\gamma_i < \gamma_{\text{th}} = 0\,\text{dB}, i = 1, 2$. In the considered work, as both the S-R and R-D links have the LoS paths, this extremely low SNR case can be ignored, i.e., we assume that $\gamma_i \geq \gamma_{\text{th}} = 0\,\text{dB}, i = 1, 2$ always holds to facilitate the derivations in our analytical model.

In the following, we study and optimize the reliability of the considered network. Let $i = 1$ indicate the link S-R and $i = 2$ represents the link R-D. Then, with blocklength n_i and data packet size k, the corresponding coding rate is given by $r_i = \frac{k}{n_i}$. According to [6], the error probability ϵ_i for the transmission via link i is

$$\epsilon_i = \mathcal{P}(\gamma_i, r_i, n_i) = Q\left(\sqrt{\frac{n_i}{V_i}}(\log_2(1+\gamma_i) - r_i)\ln 2\right), \quad (4)$$

where $Q^{-1}(\cdot)$ is the inverse of Q-function $Q(w) = \int_w^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$ and where $V_i = 1 - \frac{1}{(1+\gamma_i)^2}$ is the channel dispersion of link i.

The overall error probability of the two-hop transmission is

$$\epsilon_0 = \epsilon_1 + (1-\epsilon_1)\epsilon_2 = \epsilon_1 + \epsilon_2 - \epsilon_1\epsilon_2. \quad (5)$$

Recall that $\epsilon_0 \leq \varepsilon_{\text{th}} \ll 0.1$ and clearly $\epsilon_0 \geq \epsilon_i$ holds. Hence, we have $\epsilon_i \ll 0.1, \forall i \in \{1, 2\}$, i.e., the term $\epsilon_1\epsilon_2$ is much lower than terms ϵ_1 and ϵ_2. By ignoring the high-order term $\epsilon_1\epsilon_2$, the overall error probability can be approximated as

$$\epsilon_0 \approx \epsilon_1(\gamma_1) + \epsilon_2(\gamma_2). \quad (6)$$

Then, the original problem for our error probability minimization is formulated as

$$\begin{aligned} \text{(OP)}: \min_{\alpha} \quad & \epsilon_1(\gamma_1) + \epsilon_2(\gamma_2) && (7a)\\ s.t. \quad & \gamma_i \geq 1, \forall i \in \{1, 2\}, && (7b)\\ & r_i \leq \log_2(1+\gamma_i), \forall i \in \{1, 2\}, && (7c)\\ & 0 < \alpha < 1. && (7d) \end{aligned}$$

The constraint (7c) indicates that the coding rate r_i must be smaller than the Shannon capacity to guarantee a reliable transmission. Note that the objective function in (OP) is obviously not convex in α. Thus, the problem (OP) cannot be efficiently solved by the standard tools for convex problem. Moreover, the SNR of link R-D, namely γ_2, is a complicated function over α, which is built through an implicit function $\mathcal{F}_{nl}$ and makes the problem more complex to be analyzed and solved.

4. RELIABILITY-ORIENTED DESIGN

Problem (OP) is non-convex, thus making it challenging to be solved optimally. To tackle this difficulty, we propose in this section a three-step approach to obtain an efficient solution. We first reformulate the problem after introducing two auxiliary variables. Then, we solve the problem in an iterative way: by applying a convex approximation technique [26], we tightly approximate the problem at the local point in each iteration. Finally, an efficient iterative algorithm is proposed approaching a high-quality solution.

4.1. Problem Reformulation

In this subsection, we introduce two auxiliary variables x and y, with the assistance of which we reformulate problem (OP).

We first introduce auxiliary variable x as $x = \frac{1}{1-\alpha} \in (1, +\infty)$. Hence, the SNR for link S-R γ_1 given in (1) is represented as

$$\gamma_1 = \frac{\beta_1 P_s}{\sigma_1}(1 - \frac{1}{x}). \quad (8)$$

Then, we have Lemma 1 addressing the relationship between the error probability and x:

Lemma 1. *With given coding rate r_1 and blocklength n_1, the error probability $\epsilon_1 = \epsilon_1(\gamma_1(x))$ is convex in $x(>0)$ when $\gamma_1(x) \geq 1$.*

Proof. According to Proposition 1 in [23], with given r_1 and n_1, $\epsilon_1(\gamma_1)$ is convex in γ_1, i.e., $\frac{d^2\epsilon_1}{d\gamma_1^2} \geq 0$, when $\gamma_1 \geq 1$. Additionally, it is obvious that a higher SNR leads to a lower error probability, i.e., $\frac{d\epsilon_1}{d\gamma_1} < 0$. Therefore, we have the second-order derivative of ϵ_1 over variable x to be

$$\begin{aligned}\frac{d^2\epsilon_1}{dx^2} =& \frac{d\left(\frac{d\epsilon_1}{d\gamma_1}\frac{d\gamma_1}{dx}\right)}{dx} = \frac{d^2\epsilon_1}{d\gamma_1^2}\left(\frac{d\gamma_1}{dx}\right)^2 + \frac{d\epsilon_1}{d\gamma_1}\frac{d^2\gamma_1}{dx^2} \\ =& \frac{d^2\epsilon_1}{d\gamma_1^2}\left(\frac{\beta_1 P_s}{\sigma_1 x^2}\right)^2 + \frac{d\epsilon_1}{d\gamma_1}\frac{-2\beta_1 P_s}{\sigma_1 x^3} > 0. \end{aligned} \tag{9}$$

Thus, error probability ϵ_1 is convex in $x > 0$. □

Further, we introduce the second variable y as the transmit power at the relay in forwarding the data packet to the destination. Then, the corresponding SNR γ_2 given in (3) can be represented as

$$\gamma_2 = \frac{\beta_2 y}{\sigma_2}. \tag{10}$$

According to Proposition 1 in [23], error probability $\epsilon_2 = \epsilon_2(\gamma_2(y))$ is convex in y when $\gamma_2(y) \geq 1$. In addition, the relay transmits power y is limited by the harvested energy, which indicates

$$y \leq \frac{n_1}{n_2}\mathcal{F}_{\rm nl}[(1-\alpha)\beta_1 P_s] = \frac{n_1}{n_2}\mathcal{F}_{\rm nl}[\frac{\beta_1 P_s}{x}]. \tag{11}$$

With the assistance of x and y, Problem (OP) can be equivalently reformulated as

$$\begin{aligned}
(\text{P1}): \min_{x,y} \quad & \epsilon_0(x,y) = \epsilon_1(\gamma_1(x)) + \epsilon_2(\gamma_2(y)) && \text{(12a)}\\
s.t. \quad & x > 1, && \text{(12b)}\\
& x \geq \frac{1}{1 - \frac{\sigma_1}{\beta_1 P_s}\max\{1, 2^{r_1}-1\}}, && \text{(12c)}\\
& y \geq \frac{\sigma_2}{\beta_2}\max\{1, 2^{r_2}-1\}, && \text{(12d)}\\
& y \leq \frac{n_1}{n_2}\mathcal{F}_{\rm nl}[\frac{\beta_1 P_s}{x}]. && \text{(12e)}
\end{aligned}$$

In particular, constraint (12b) is derived from (7d) and the constraints (12c)-(12d) are reformulated according to (7b)-(7c). By solving problem (P1), an optimal x can be determined, based on which we can further obtain the optimal PS ratio α which is actually the optimal solution to problem (OP).

4.2. Convex Approximation

Note that the objective function and constraints of problem (P1) are convex except constraint (12e), i.e., the problem cannot be directly handled by convex optimization tools. In this subsection, we apply a convex approximation technique [26] to tightly approximate the problem. Notice that by introducing auxiliary variable x, the RF power for harvesting at relay is reformulated as

$$Q_{\rm rf} = \frac{\beta_1 P_s}{x}. \tag{13}$$

It can be easily proven that $Q_{\rm rf}(x)$ satisfies the sufficient condition

$$Q''_{\rm rf}(x)Q_{\rm rf}(x) - \left(Q'_{\rm rf}(x)\right)^2 \geq 0. \tag{14}$$

Therefore, according to Theorem 2 in [25], we obtain the conclusion that $\mathcal{F}_{\rm nl}[\frac{\beta_1 P_s}{x}]$ is convex in x. Based on the property of convexity, we obtain the following approximation at a local value $x^{(r)}$:

$$\begin{aligned}\mathcal{F}_{\rm nl}[\frac{\beta_1 P_s}{x}] \geq & -\mathcal{F}'_{\rm nl}[\frac{\beta_1 P_s}{x^{(r)}}]\frac{\beta_1 P_s}{(x^{(r)})^2}(x - x^{(r)}) + \mathcal{F}_{\rm nl}[\frac{\beta_1 P_s}{x^{(r)}}] \\ \triangleq & f^{(r)}(x). \end{aligned} \tag{15}$$

Function $f^{(r)}(x)$ is clearly a concave function and the equality holds when $x = x^{(r)}$. By replacing $\mathcal{F}_{\rm nl}[\frac{\beta_1 P_s}{x}]$ with $f^{(r)}(x)$, the problem (P1) is approximated to a convex one (P2):

$$\begin{aligned}
(\text{P2}): \min_{x,y} \quad & \epsilon_1(\gamma_1(x)) + \epsilon_2(\gamma_2(y)) && \text{(16a)}\\
s.t. \quad & \text{(12b), (12c), (12d)}, \\
& y \leq \frac{n_1}{n_2} f^{(r)}(x). && \text{(16b)}
\end{aligned}$$

Note that the feasible set of (P2) is always a subset of the feasible set in (P1) according to (15), and (P2) can be efficiently solved by convex tools, such as CVX. Next, we will propose an algorithm for problem (P1) by iteratively solving the convex problem (P2).

4.3. Iterative Algorithm

For the iterative algorithm, we first initialize a feasible local point $(x^{(0)}, y^{(0)})$ for problem (P1) and set the iteration index $r = 0$.

In the r-th iteration, we build the convex approximation (P2) for problem (P1) based on the local point $(x^{(r)}, y^{(r)})$. As the local point is also a feasible point in (P2), where the feasibility is already guaranteed in the process of the convex approximation, a point with better performance can be found by solving convex problem (P2). Then, the better point will be directly applied as the local point in the next iteration, i.e., in iteration $(r+1)$.

By repeating the iterations, the performance, namely the overall error probability, will be constantly improved. As the error probability is generally lower-bounded, the iterative algorithm will eventually converge to a suboptimal point. And consequently, a suboptimal PS ratio α for (OP) can be built from the solution.

The complete algorithm is described in Algorithm 1.

Algorithm 1 : Iterative Algorithm.

a) Initialize a local point $(x^{(0)}, y^{(0)})$ for (P1).
b) Set iteration index $r = 0$.
c) Build convex problem (P2) based on local point $(x^{(r)}, y^{(r)})$.
d) Solve (P2) and get optimal solution $(x^{(r)\star}, y^{(r)\star})$.
e) **If** $\epsilon_0(x^{(r)}, y^{(r)}) - \epsilon_0(x^{(r)\star}, y^{(r)\star}) <$ threshold λ_{th}
  Define PS ratio $\alpha = 1 - 1/x^{(r)\star}$.
  Return.
Else
  $(x^{(r+1)}, y^{(r+1)}) = (x^{(r)\star}, y^{(r)\star})$.
  $r = r + 1$.
  Back to c).
End

5. SIMULATION RESULTS

In this section, we present the simulation results to evaluate the convergence and performance of our proposed algorithm. Moreover, compared to the design with linear EH model, we show the advantage of our proposed design based on the nonlinear EH model and

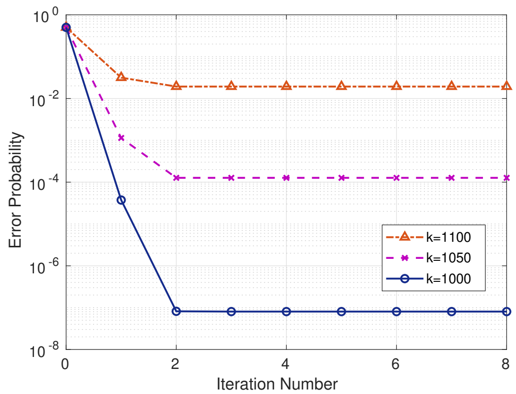

Fig. 1. Error probability over iterations with different packet sizes k.

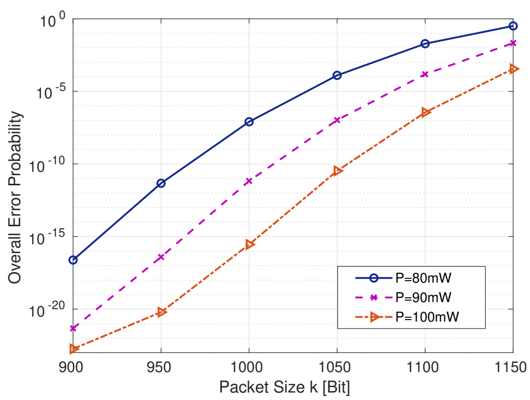

Fig. 2. Error probability over packet size with different transmit power P_s.

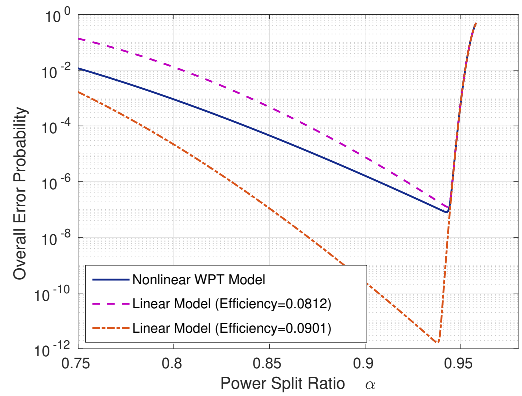

Fig. 3. Error probability over the PS ratio with different EH models.

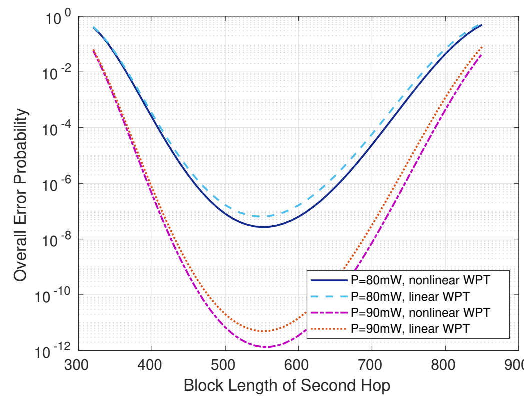

Fig. 4. Error probability over optimal α with different EH model.

declare the necessity of considering the non-linearity in EH. For all the simulations, we have the following default set-up parameters: $P=80mW$, $\sigma_1=\sigma_2=-45dBm$, $n_1=800$, $n_2=500$, $k=1000$.

We first investigate in Fig. 1 the convergence behavior of our proposed algorithm with different transmit power P_s. Clearly, the error probability is reduced after each iteration and converges within a small number of iterations. In addition, a relatively high error probability is observed when a larger data packet is transmitted. Next, in Fig. 2 we show the optimized error probability over packet size k with different transmit powers P_s. We learn that when the transmit power P_s increases, the network is apparently improved and a lower error probability results as shown in the figure.

Moreover, we study the effect of the non-linearity of our EH model on the system reliability in Fig. 3, where the work for PS ratio optimization based on a linear EH model in [23] is also presented as a benchmark. As expected, compared to the results of the proposed design based on the nonlinear EH model, the performance of the design following a Linear EH model is observed to be harmful in the PS ratio optimization. In particular, the optima are very sharp in the PS ratio, i.e., a small deviation in the PS ratio, which leads to a big loss in reliability. The optimal performance (based on the optimal PS ratio) under different EH models is further compared in Fig. 4. From the figure, with different setups of n_2, we find that the error probabilities of our proposed solution are always lower than the error probabilities of the linear EH model. In other words, the inaccuracy of the EH model leads to a significant performance error/loss in the reliability optimization, which confirms the necessity of this work.

6. CONCLUSION

In this paper, we study a SWIPT-enabled relaying network in the FBL regime, where the EH process follows a nonlinear model. A reliability-oriented design is provided, aiming at minimizing the overall error probability by optimizing the PS ratio of the SWIPT process at the relay. As the formulated problem is highly non-convex due to the nonlinearity of the EH, the problem is challenging to be solved optimally. To tackle this difficulty, we propose a three-step approach to obtain an efficient solution. We first introduce two auxiliary variables, with the assistance of which we reformulate the problem. Then, we apply a convex approximation technique to tightly approximate the problem, based on which an efficient iterative algorithm is finally proposed approaching to a high-quality solution. The simulation results validate the convergence of our design and the performance advantages in comparison to the designs following a linear EH model. Our results confirm that ignoring non-linearity in the EH model introduces a significant performance loss. Finally, it should be mentioned that the three-step approach provided in this work can potentially be extended to further WPT network designs following the nonlinear model.

7. ACKNOWLEDGEMENT

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