Rate Maximization in Wireless Powered Communication Systems with Non-Ideal Circuit Power Consumption

Ivana Nikoloska, Zoran Hadzi-Velkov, Hristina Chingoska

Abstract—**The key concern in battery-powered communication is the limited power availability and the need for battery replacement. Energy harvesting (EH) wireless communication has promised to tackle these issues successfully by devising optimal policies that take into account the harvested energy causality. This task is particularly challenging if the processing energy cost, caused by the non-ideal circuit consumption of the EH devices, is incorporated into these policies, together with the RF transmit power at the output of these devices. In this paper, we consider a point-to-point communications system with RF energy harvesting, which consists of a base station (BS) that broadcasts RF energy, and an EH user (EHU) that harvests this energy and transmits information to the BS. The information transmitter employs "harvest-then-transmit" protocol, such that the EHU in each information transmission spends the total amount of the energy harvested from the BS during the preceding RF broadcast. For such system, we propose a novel transmission scheme that optimizes the BS transmit power and the time sharing between the BS and EHU transmissions. The numerical results depict the achievable average rates of the proposed scheme. Increasing the EHU's processing cost significantly deteriorates the achievable rate, and, therefore, should certainly be considered in the protocol design.**

Index Terms—**Energy harvesting, Wireless power transfer, Processing cost, Point-to-point links, Power and time allocation.**

I. Introduction

Recent advances in ultra-low power wireless communications and energy-harvesting technologies have made self-sustainable devices feasible. Typically, the major concern for these devices is battery life and replacement. Applying energy harvesting techniques to these devices can significantly extend battery life and sometimes even entirely eliminate the need for a battery [1]-[2]. To maximize the system performance, the EH transmitters should adapt their output powers based on the energy harvested up to the time of transmission (causality constraint) [3]-[4]. Ambient energy in the form of man-made electromagnetic radiation is abundant regardless of the system's location (i.e. indoor or outdoor systems) or time of day. The radio frequency energy can be easily found in surroundings as it is used widely by many applications like television broadcasting, telecommunication, microwave etc. It is ubiquitous and free and highly efficient. Harvesting the RF radiation is an approach known as wireless power transfer (WPT) [5]-[6]. The WPT can be realized in the form of a simultaneous wireless information and power transfer (SWIPT) from the same transmitter [7], or, alternatively, the energy and information can be transmitted over orthogonal (either in time or frequency) channels. The latter option gives rise to the so called wireless powered communications networks (WPCNs) [8], which typically rely on time-division multiple access (TDMA).

In order to develop WPCNs, the network nodes must rely on new ultra-low power communication schemes that allow them to make the best use of the small amounts of ambient energy they have at their disposal. In [8], the authors determine the optimal TDMA scheme among the half-duplex nodes (either BS or EHUs), depending on the channel fading states. The optimal time-sharing in WPCNs where one BS operating in full-duplex broadcasts wireless energy to a set of distributed users in downlink and at the same time receives independent information from the users via time-division-multiple-access (TDMA) in uplink, was studied in [9]. The paper [10] studies the WPCN with full-duplex nodes, where the BS is equipped with two antennas. The authors in [11], consider WPCNs, where the nodes choose between two power levels, a constant desired power, or lower power when its EH battery has stored insufficient energy. The paper [12], studies relaying systems with RF energy harvesting.

In this paper, we propose a novel transmission scheme, which optimally adapt the BS transmit power and the duration of the EH and IT phases in each TDMA epoch. The scheme incorporates the constant processing energy cost, denoted by p_c, such that the total power consumption by the EHU includes both the processing and RF transmit powers. The proposed scheme drastically outperforms schemes which only employ optimal time allocation among the network nodes.

II. System Model

As depicted in Fig. 1a, we consider a point-to-point link consisting of a half-duplex BS and a half-duplex EHU, which

Ivana Nikoloska is with the Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University, Rugjer Boshkovik bb, 1000 Skopje, R. Macedonia, E-mail: ivanan@feit.ukim.edu.mk

Zoran Hadzi-Velkov is with the Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University, Rugjer Boshkovik bb, 1000 Skopje, R. Macedonia, E-mail: zoranhv@feit.ukim.edu.mk

Hristina Chingoska is with the Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University, Rugjer Boshkovik bb, 1000 Skopje, R. Macedonia, E-mail: cingoska@feit.ukim.edu.mk

This is an extended version of the paper "Performance of Communication Systems with RF Energy-Harvesting and Processing Cost" presented at 12th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services - TELSIKS 2015, held in October 2015 in Nis, Serbia.

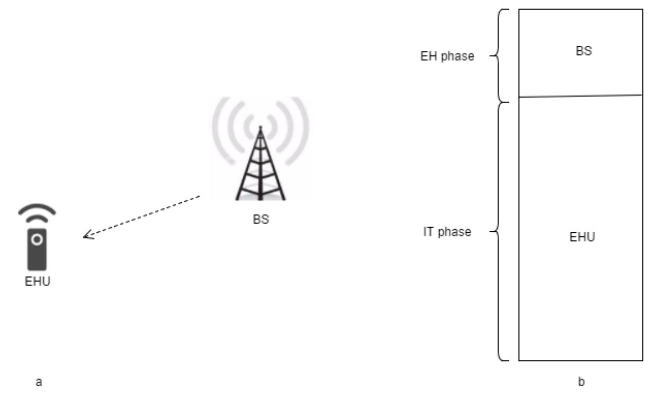

Fig. 1: (a) Point-to-point EHU-BS, link (b) TDMA epoch/frame structure

operate in a fading environment. The BS broadcasts RF energy to the EHU, whereas the EHU transmits information back to the BS. The EHU is equipped with rechargeable EH batteries that harvest the RF energy broadcasted from the BS. The IT from the EHU to the BS (IT phase), and the WPT from the BS to the EHU (EH phase) are realized as successive signal transmissions using TDMA over a common channel, where each TDMA frame/epoch is of duration T. Each (TDMA) epoch consists of an EH phase and an IT phase (Fig. 1b).

The channel between the BS and the EHU is a quasi-static block fading channel, which is constant during a single block but changes independently from one block to the next. The duration of one fading block is assumed equal to T, and one block coincides with a single epoch. In epoch i, the fading power gains of the BS-EHU channel is denoted by x_i'. For convenience, these gains are normalized by the additive white gaussian noise (AWGN) power, yielding $x_i = x_i'/N_0$ with an average value of $\Omega = E[x_i']/N_0$, where $E[\cdot]$ denotes expectation. The channels are assume to be reciprocal, i.e., in epoch i, the gains of BS-EHU and EHU-BS channels are the same.

In epoch i, the BS transmit power is denoted by p_i, the duration of the EH phase is $\tau_{0i}T$ and the duration of the IT phase is $(1-\tau_{0i})T$. We assume that p_i satisfies an average power constraint P_{avg} (i.e., $E[p_i\tau_{0i}] = P_{avg}$), and a maximum power constraint P_{max} (i.e., $0 \le p_i \le P_{max}$).

A. Processing Cost

In practical EH transmitters, besides their transmit power, an additional power is also consumed by its non-ideal electric circuitry (e.g., AC/DC converter, analog RF amplifier, processor etc.), denoted as the *processing energy cost* [13]. In short range communications, as in most wireless sensor networks, where inter-node distances are less than 10m, processing energy consumption can be comparable to the transmission energy [14]. We consider the following practical model for the total power consumption of the EHU:

$$p_t = \begin{cases} P_S + p_c, & P_S > 0 \\ 0, & P_S \le 0, \end{cases} \tag{1}$$

where P_S is the EHU's transmit power.

The amount of harvested power by the EHU is

$$E_i = N_0 p_i \, x_i \, \tau_{0i} \, T \tag{2}$$

which is completely spent in the successive IT of duration $(1-\tau_{0i})T$ as

$$E_i = (P_S(i) + p_c)(1-\tau_{0i})T \tag{3}$$

Thus, the EHU's transmit power in epoch i is given by

$$P_S(i) = \frac{N_0 p_i x_i \tau_{0i}}{1-\tau_{0i}} - p_c, \tag{4}$$

and the achievable information rate in this epoch is given by $R_S(i) = (1-\tau_{0i})\log(1 + P_S(i)x_i)$. We aim at maximizing the EHU's average throughput, given by

$$\bar{R} = \lim_{M\to\infty} \frac{1}{M}\sum_{i=1}^{M} R_S(i). \tag{5}$$

III. Joint Power and Time Allocation

We aim at maximizing the achievable rate by optimizing $P_S(i)$ and τ_{0i}. Therefore, we define the following optimization problem:

$$\begin{aligned} &\max_{P_S(i),\tau_i,\forall i} \frac{1}{M}\sum_{i=1}^{M}(1-\tau_{0i})\log(1+P_S(i)x_i) \\ \text{s.t.}\quad & C1: \quad \frac{1}{M}\sum_{i=1}^{M}\frac{1-\tau_{0i}}{x_i}(P_S(i)+p_c) \le N_0 P_{avg} \\ & C2: \quad (1-\tau_{0i})(P_S(i)+p_c) \le N_0 P_{max}\tau_{0i}x_i \\ & C3: \quad P_S(i) \ge 0 \\ & C4: \quad 0 < \tau_{0i} \le 1. \end{aligned} \tag{6}$$

Due to the products and ratios of the optimization variables, (6) is not a convex optimization problem. After introducing the change of variables,

$$\theta_i = 1 - \tau_{0i} \tag{7}$$

and

$$\alpha_i = (1-\tau_{0i})P_S(i)/x_i \tag{8}$$

problem (6) is transformed into a convex optimization problem,

$$\begin{aligned} &\max_{\alpha_i,\theta_i,\forall i} \frac{1}{M}\sum_{i=1}^{M}\theta_i\log\left(1+\frac{\alpha_i x_i^2}{\theta_i}\right) \\ \text{s.t.}\quad & \bar{C}1': \quad \frac{1}{M}\sum_{i=1}^{M}\left(\alpha_i + \frac{\theta_i p_c}{x_i}\right) \le N_0 P_{avg} \\ & \bar{C}2': \quad \alpha_i + \theta_i\left(\frac{p_c}{x_i} + N_0 P_{max}\right) \le N_0 P_{max} \\ & \bar{C}3': \quad \alpha_i \ge 0 \\ & \bar{C}4': \quad 0 \le \theta_i < 1. \end{aligned} \tag{9}$$

The solution of the optimization problem (6) is given by the following Theorem:

Theorem 1. *The optimal BS transmit power is given by*

$$p_i^* = \begin{cases} P_{max}, & 0 < \frac{\tau_{0i} N_0 P_{max}}{1-\tau_{0i}} - \frac{p_c}{x_i} < \frac{1}{\lambda} - \frac{1}{x_i^2} \\ 0, & \text{otherwise.} \end{cases} \tag{10}$$

The optimal duration of the EH phase, τ_{0i}^*, is given by,

$$\tau_{0i}^* = 1 - \frac{N_0 x_i^2 P_{max}}{N_0 x_i^2 P_{max} + x_i p_c - 1} \left(1 + \frac{1}{W\left(\frac{N_0 x_i^2 P_{max} + x_i p_c - 1}{e^{1-\lambda P_{max}}}\right)} \right)^{-1}, \tag{11}$$

where $W(\cdot)$ denotes the Lambert W function. The constant λ is found from $(1/M)\sum_{i=1}^{M} p_i^* \tau_{0i}^* = P_{avg}$.

Proof: Please refer to Appendix A. ∎

Note, when setting $p_c = 0$, the optimal solution for this optimization problem becomes:

The optimal BS transmit power is given by

$$p_i^* = \begin{cases} P_{max}, & x_i^2 > \lambda \\ 0, & \textit{otherwise}. \end{cases} \tag{12}$$

The optimal duration of the EH phase, τ_{0i}^*, is given by,

$$\tau_{0i}^* = 1 - \frac{N_0 x_i^2 P_{max}}{N_0 x_i^2 P_{max} - 1} \left(1 + \frac{1}{W\left(\frac{N_0 x_i^2 P_{max} - 1}{e^{1-\lambda P_{max}}}\right)} \right)^{-1}, \tag{13}$$

.

The constant λ is found from $(1/M)\sum_{i=1}^{M} p_i^* \tau_{0i}^* = P_{avg}$. Interestingly, the condition in (10), collapses down to a much simpler form, given in (12), as shown in Appendix B.

IV. Practical Implementation Algorithm

The policy proposed in Theorem 1, is difficult to implement in practice, since the values of the Lagrangian multipliers are not known in advance when the PDFs of the fading channels are unknown. In this section, we propose an online policy in which the actual value of λ is replaced by its estimate in epoch i, $\hat{\lambda}(i)$. Therefore Eqs. (10)-(11) become:

$$\hat{p}_i^* = \begin{cases} P_{max}, & 0 < \frac{\tau_{0i} N_0 P_{max}}{1-\tau_{0i}} - \frac{p_c}{x_i} < \frac{1}{\hat{\lambda}(i)} - \frac{1}{x_i^2} \\ 0, & \textit{otherwise}. \end{cases} \tag{14}$$

$$\hat{\tau}_{0i}^* = 1 - \frac{N_0 x_i^2 P_{max}}{N_0 x_i^2 P_{max} + x_i p_c - 1} \left(1 + \frac{1}{W\left(\frac{N_0 x_i^2 P_{max} + x_i p_c - 1}{e^{1-\hat{\lambda}(i) P_{max}}}\right)} \right)^{-1}, \tag{15}$$

Now, the optimal values of the BS output power $\hat{p}_i^*$ and the duration of the EH phase $\hat{\tau}_{0i}^*$ are estimates of p_i^* and τ_{0i}^*, since they are based on the estimate of the value of the Lagrangian multiplier. The estimate of λ is calculated by applying the *stochastic gradient descent* method according to [15, Section III.C], as

$$\hat{\lambda}_0(i) = \hat{\lambda}_0(i-1) + \beta_0 \left(\frac{1}{i-1} \sum_{n=1}^{i-1} \hat{p}_n \hat{\tau}_{0n} - P_{avg} \right), \tag{16}$$

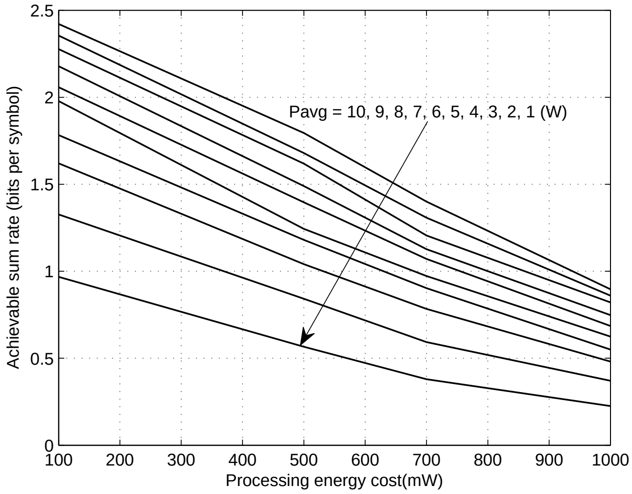

Fig. 2: Maximum achievable throughput for different values of the processing energy cost

where β_0 is an arbitrary small step size, and the average is estimated from the previous $i-1$ epochs, as $\frac{1}{i-1}\sum_{n=1}^{i-1}(\cdot)$. What makes this algorithm attractive is its capability to adapt to sudden changes in channel statistic. The algorithm rapidly "learns" this changes and is able to converge to a new optimum.

V. Numerical Results

We illust1llustrates the achievable rate in a point to point link for different values of the processing cost. As expected the rate decreases with the increase of the processing energy cost. Even more, for smaller values of the average BS output power, increasing the p_c decreases the rate up to one quarter of its value at $100nW$. This illustrates the crippling effect processing energy cost has on this kind on communication. However, the performance of of the proposed practical algorithm, can not be surpassed in such scenarios, when p_c is taken into account.

Fig 3. presents the achievable rate for different values of the BS output power. The increase in rate is again noticeable for as p_c becomes smaller. As previously stated, when $p_c = 0$, the optimal solution collapses down to Eqs. (12)-(13) and this is the maximum achievable rate in an energy harvesting point-to-point system.

As a benchmark we apply the optimal time allocation scheme, according to [8], which maximizes the uplink sum-rate of the WPCN by optimizing the durations of the EH and IT phases, for fixed BS output power in all epochs (i.e., $p_i = P_{avg}$). Eqs. (12)-(13) can be seen as an extension of this benchmark. Note, that, the optimal time allocation scheme does not take into account the processing energy cost. Still, when we set $p_c = 0$, we can illustrate the superior performances of joint power and time allocation (Fig. 4) compared to the optimal time allocation given in [8].

VI. Conclusion

In this paper, we optimize a point-to-point wireless powered communication system with non-ideal circuit power consump-

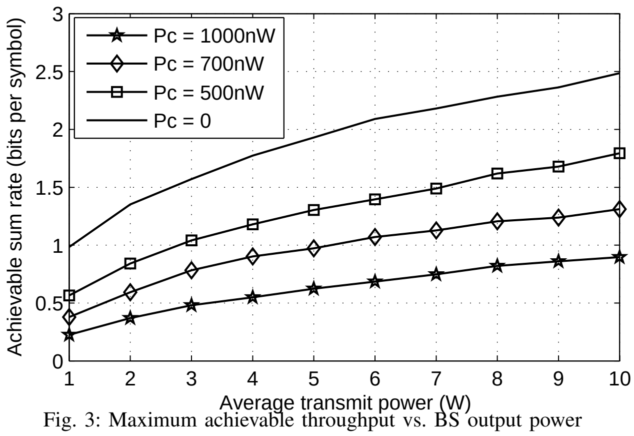

Fig. 3: Maximum achievable throughput vs. BS output power

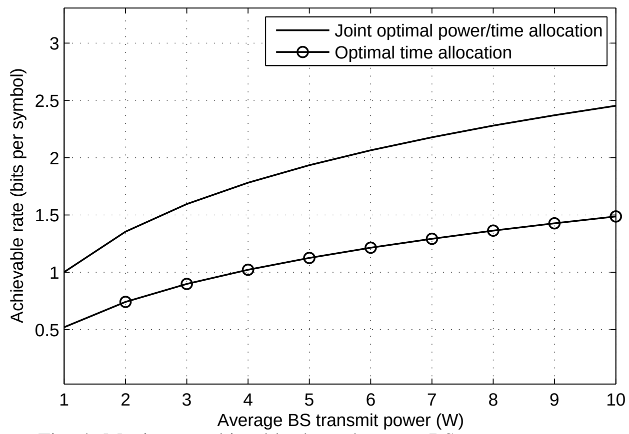

Fig. 4: Maximum achievable throughput vs. BS output power

tion. We proposed a transmission scheme that jointly optimizes the BS transmit power allocation and the time-sharing in the dynamic TDMA frame. This scheme can be also efficiently used for practical scenarios, when the processing cost is considered. The proposed algorithm for practical implementation is capable of iteratively finding the optimal resource allocation even when the fading channel distribution is unknown a priori. Numerical results show that the proposed scheme outperforms the existing schemes in the literature. In the future, we aim to generalize this scheme for wireless powered communication networks with an arbitrary number of users.

Appendix A
Proof of theorem 1

The Lagrangian of problem (9) can be written as

$$\begin{aligned} L''(\alpha_i,\theta_i,\lambda) &= \theta_i \log\left(1+\frac{\alpha_i x_i^2}{\theta_i}\right) \\ &-\lambda\left(\alpha_i+\theta_i\frac{p_c}{x_i}-\bar{P}N_0\right)+\mu_i\alpha_i \\ -q_i\left(\alpha_i+\theta_i\left(\frac{p_c}{x_i}+P_{max}N_0\right)-P_{max}N_0\right) \\ &+\upsilon_i\theta_i-\gamma_i(\theta_i-1) \end{aligned} \tag{17}$$

where λ is associated with $C1'$, μ_i with $C2'$, q_i with $C3'$, and υ_i and γ_i with $C4'$ in problem (9). By differentiating Eq.(17) with respect to α_i and θ_i, we get

$$\frac{\partial L''}{\partial \alpha_i} = \frac{x_i^2}{1+\frac{\alpha_i x_i^2}{\theta_i}} - \lambda + \mu_i - q_i = 0, \tag{18}$$

$$\begin{aligned} \frac{\partial L''}{\partial \theta_i} &= \log\left(1+\frac{\alpha_i x_i^2}{\theta_i}\right) - \frac{\alpha_i x_i^2}{\theta_i+\alpha_i x_i^2} \\ -\lambda\frac{p_c}{x_i} &- q_i\left(\frac{p_c}{x_i}+P_{max}N_0\right)+\upsilon_i-\gamma_i=0 \end{aligned} \tag{19}$$

According to KKT conditions, the complementary slackness should be satisfied, $\forall i$:

$$\begin{aligned} \mu_i\alpha_i = q_i(\alpha_i+\theta_i\left(\frac{p_c}{x_i}+P_{max}N_0\right)-P_{max}N_0) = \\ \upsilon_i\theta_i=\gamma_i(\theta_i-1)=0 \end{aligned} \tag{20}$$

where $\mu_i \geq 0, q_i \geq 0, \upsilon_i \geq 0$ and $\gamma_i \geq 0$. If we consider the previous expressions together with the complementary slackness conditions we can conclude that:

Case 1: When $\alpha_i = 0$, from the definition of α_i, θ_i is also 0. Naturally, no power is allocated in epoch i, i.e. $p_i = 0$.

Case 2: When $0 < \alpha_i < N_0 P_{max}(1-\theta_i) - p_c\frac{\theta_i}{x_i}$, then the slackness conditions require $\mu_i = 0$ and $q_i = 0$. From Eq.(18) follows that

$$\alpha_i = \theta_i\left(\frac{1}{\lambda}-\frac{1}{x_i^2}\right), \tag{21}$$

and from Eq.(19) follows that

$$\log\left(\frac{x_i^2}{\lambda}\right) - 1 + \frac{\lambda}{x_i^2} - \lambda\frac{p_c x_i}{x_i^2} = 0 \tag{22}$$

which can not hold for arbitrary i. Therefore we can conclude that the optimal p_i, can not be in the interval $(0, P_{max})$.

Case 3: When $\alpha_i = N_0 P_{max}(1-\theta_i) - p_c\frac{\theta_i}{x_i}$, then $0 < \theta_i < 1$, $q_i > 0$ and $\mu_i = 0$. Therefore, from Eq.(18) we get

$$q_i = \frac{x_i^2}{1 - x_i p_c + \frac{P_{max}(1-\theta_i)N_0 x_i^2}{\theta_i}} - \lambda > 0. \tag{23}$$

By using the expression for q, we can compute the condition under which $p_i = P_{max}$.

Then, by using Eq.(19) and replacing α_i with $N_0 P_{max}(1-\theta_i) - p_c\frac{\theta_i}{x_i}$, we can finally obtain the following transcendental equation,

$$\begin{aligned} \log\left(1 - x_i p_c + \frac{N_0 P_{max}\, x_i^2\, \tau_{0i}}{1-\tau_{0i}}\right) + N_0\lambda P_{max} \\ = \frac{N_0 P_{max}\, x_i^2}{(1-\tau_{0i})(1-x_i p_c) + N_0 P_{max}\, x_i^2\, \tau_{0i}}, \end{aligned} \tag{24}$$

whose closed form solution can be found by applying the definition of the Lambert W function and is given by (11).

A. Lambert W function

The Lambert W function, also called the omega function or product logarithm, is a set of functions, namely the branches of the inverse relation of $f(z) = ze^z$ where e^z is the exponential function and z is any complex number [16], i.e.

$$z = f^{-1}(ze^z) = W(ze^z). \tag{25}$$

By substituting the above equation in $z' = ze^z$, we get the defining equation for the W function (and for the W relation in general) as

$$z' = W(z')e^{W(z')} \tag{26}$$

for any complex number z'. Setting

$$y = 1 - x_i p_c + \frac{N_0 P_{max}\, x_i^2\, \tau_{0i}}{1 - \tau_{0i}}, \tag{27}$$

(24) can be rewritten in the form of (26), finally yielding (11). The Lambert W function is integrated as a special function in numerous software packages, like Matlab or Maple. It has many applications, ranging from biochemistry, to modeling of fading channels [17] and cooperative methods of power allocation [18].

Appendix B
Sufficient condition for (12)

The condition in (12) is obtained from the following inequality condition:

$$0 < \frac{\tau_{0i} N_0 P_{max}}{1 - \tau_{0i}} < \frac{1}{\lambda} - \frac{1}{x_i^2}, \tag{28}$$

or, equivalently

$$\frac{1 - \tau_{0i}}{\tau_{0i}} \left(\frac{1}{\lambda} - \frac{1}{x_i^2} \right) > N_0 P_{max} > 0, \tag{29}$$

or, equivalently

$$0 < \tau_{0i} < \frac{\frac{1}{\lambda} - \frac{1}{x_i^2}}{N_0 P_{max} + \frac{1}{\lambda} - \frac{1}{x_i^2}}. \tag{30}$$

In order to satisfy the constraint $0 < \tau_{0i} < 1$, (30) suggest the following additional condition:

$$\lambda < x_i^2. \tag{31}$$

If (31) is satisfied, τ_{0i}^*, always satisfies the conditions (28)-(30). In order to prove this, we define the an auxiliary function, as

$$\begin{aligned} f(\tau_{0i}) &= \frac{N_0 P_{max} x_i^2}{1 - \tau_{0i} + N_0 P_{max} x_i^2 \tau_{0i}} - N_0 \lambda P_{max} \\ &- \log\left(1 + \frac{N_0 P_{max} x_i^2 \tau_{0i}}{1 - \tau_{0i}}\right). \end{aligned} \tag{32}$$

Note that (32), originates from the transcendental equation, whose closed form is given by (13). Let us assume that (31) is satisfied. If we now set set τ_{0i} to the lower bound of (30), we have

$$f(0) = N_0 P_{max}(x_i^2 - \lambda) > 0. \tag{33}$$

Then, if we set τ_{0i} to the upper bound of (30), we obtain

$$f\left(\frac{\frac{1}{\lambda} - \frac{1}{x_i^2}}{N_0 P_{max} + \frac{1}{\lambda} - \frac{1}{x_i^2}} \right) = 1 - \frac{\lambda}{x_i^2} - \log\left(\frac{x_i^2}{\lambda}\right) < 0. \tag{34}$$

Since $f(\tau_{0i})$ is decreasing in τ_{0i} and changes the sign at the lower and upper bounds of (30), we conclude that $f(\tau_{0i}) = 0$, is always between these bounds. Therefore, assuming (31), the conditions (28)-(30) are always satisfied by the solution of (13).

References

[1] D. Gunduz, K. Stamatiou, N. Michelusi, and M. Zorzi, ”Designing Intelligent Energy Harvesting Communication Systems,” *IEEE Commun. Magazine*, vol. 52, no. 1, pp. 210-216, January 2014.

[2] C. K. Ho, and R. Zhang, ”Optimal Energy Allocation for Wireless Communications with Energy Harvesting Constraints,” *IEEE Trans. Signal Proccessing*, vol. 60, no. 9, pp. 4808-4818, May 2012.

[3] I. Krikidis, T. Charalambous, and J. S. Thompson, ”Stability Analysis and Power Optimization for Energy Harvesting Cooperative Networks,” *IEEE Signal Processing Letters*, vol. 19, no. 1, pp. 20-23, November 2011.

[4] Z. Ding, and H. V. Poor, ”Cooperative Energy Harvesting Networks with Spatially Random Users,” *IEEE Signal Processing Letters*, vol. 20, no. 12, pp. 1211-1214, October 2013.

[5] L. R. Varshney, ”Transporting Information and Energy Simultaneously”, *Proc. IEEE ISIT*, pp. 1612-1616, July 2008.

[6] P. Grover, and A. Sahai, ”Shannon Meets Tesla: Wireless Information and Power Transfer,” *Proc. IEEE ISIT*, pp. 2363- 2367, June 2010.

[7] R. Zhang, and C. K. Ho, ”MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989-2001, May 2013.

[8] H. Yu, and R. Zhang, ”Througnput Maximization in Wireless Powered Communication Networks,” *IEEE Trans. Wireless Commun.*, vol 13, no. 1, pp. 418-428, January 2014.

[9] H. Ju, and R Zhang, ”Optimal Resource Allocation in Full-Duplex Wireless-Powered Communication Network,” *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3528-3540, October 2014.

[10] X. Kang, C. Keong Ho, and S. Sun, ”Optimal Time Allocation for Dynamic-TDMA-Based Wireless Powered Communication Networks,” *Proc. IEEE Globecom 2014, Signal Processing for Communications Symposium*, December 2014.

[11] He (Henry) Chen, et al., ”Harvest-then-Cooperate: Wireless-Powered Cooperative Communications”, arXiv: 1404.4120v2, March 2015.

[12] R. Morsi, D. S. Michalopoulos, and R. Schober, ”Performance Analysis of Wireless Powered Communication with Finite/Infinite Energy Storage,” arXiv: 1410.1805v2, October 2014.

[13] O. Orhan, D. Gunduz, and E. Erkip, ”Throughput Maximization for an Energy Harvesting Communication System with Processing Cost,” *Information Theory Workshop (ITW)* pp. 84-88, 03 September 2012.

[14] S. Cui, A. J. Goldsmith, and A. Bahai, ”Energy-Constrained Modulation Optimization,” *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2349-2360, September 2005.

[15] X. Wang, and N. Gao, ”Stochastic Resource Allocation over Fading Multiple Access and Broadcast Channels”, *IEEE Trans. Info. Theory*, vol. 56, no. 5, pp. 2382-2391, May 2010.

[16] R. M. Corless, G. H. Gonnet, D. E.G. Hare, D. J. Jeffrey, and D. E. Knuth, ”On the Lambert W Function”, *Adv. Computational Math.*, vol. 5, no. 1, pp. 329-359, January 1996.

[17] C. Tellambura and D. Senaratne, ”Accurate Computation of the MGF of the Lognormal Distribution and its Application to sum of Lognormals”, *IEEE Trans. Commun.*, vol. 58, no. 5, pp. 1568-1577, May 2010.

[18] D. Wu, Y. Cai, L. Zhou, and J. Wang, ”A Cooperative Communication Scheme Based on Coalition Formation Game in Clustered Wireless Sensor Networks”, *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 1190-1200, March 2012.