# AN ONLINE ALGORITHM FOR THROUGHPUT MAXIMIZATION OF WIRELESS POWERED COMMUNICATION NETWORKS

*Wei-Chiang Li, Hsin-Shan Hsieh and Chong-Yung Chi*

Institute of Communications Engineering & Department of Electrical Engineering,
National Tsing Hua University, Hsinchu, Taiwan 30013
E-mail: weichiangli@gmail.com, s102064522@m102.nthu.edu.tw, cychi@ee.nthu.edu.tw

**ABSTRACT**

Optimizing the system performance of a wireless powered communication network (WPCN) has been extensively studied recently, by incorporating space, frequency and/or time diversity of the channel, etc. However, the time diversity, inherently imposes the causality constraint on the channel state information (CSI) in the system design. Hence development of effective and efficient online algorithms for optimizing the system performance is essential but challenging. In this paper, a WPCN with two single-antenna access points (APs) and a single-antenna user, wherein the "harvest and then transmit" over multiple time blocks is considered for the resource allocation (time and power in each time block) by maximizing the system throughput rate. To this end, a low-complexity online algorithm is proposed. Some simulation results are provided to support its efficacy.

***Index Terms*—** Wireless energy transfer, time diversity, online algorithm, throughput maximization.

## 1. INTRODUCTION

Energy harvesting has drawn extensive attention in recent years, due to perpetual energy supply for a conventional energy-constrained network to prolong its life time. Among a variety of energy resources, radio frequency (RF) enabled wireless energy transfer (WET) technology can particularly provide more stable, and more controllable energy than others, such as solar and wind, [1, 2]. As a result, the wireless powered communication network (WPCN) has become an appealing research topic. In a general WPCN [3], a hybrid access point (H-AP) provides the information transmission and energy transmission simultaneously to a set of distributed user terminals in the downlink (DL) phase, and the wireless powered user terminals transmit information in the uplink (UL) phase using the energy harvested in the DL phase.

The research of WPCN can be roughly divided into two categories. The first considers the rate-energy trade-off for the simultaneous wireless information and power transfer (SWIPT) in the DL phase of WPCNs, and has been extensively studied under different system models and channel settings [3, 4, 5, 6, 7]. The other is the transmission design for the "harvest-then-transmit" (i.e., user terminals harvest energy in the DL phase, and then transmit information using the harvested energy in the UP phase), which is the focus of this paper. The time allocation, the power control, and beamforming design for the DL-UL phases have fundamental impact on the throughput performance of the user terminals. In [8], a WPCN consisting of one single-antenna H-AP and multiple single-antenna user terminals is considered. It is assumed that the user terminals transmit their independent information to the H-AP by time-division-multiple-access (TDMA), and both the sum-rate maximization problem and min-rate maximization problem are considered. This work is further extended to the MISO system, where the H-AP is equipped with multiple antennas [9]. In the presence of Gaussian CSI error that is inevitable in practical systems, the authors of [10] consider joint time allocation and energy beamforming design for a MISO WPCN system to maximize the sum-rate subject to signal-to-noise ratio (SNR) outage probability constraints.

The related works in the literature mostly focus on exploiting the spatial diversity provided by multiple antennas. However, the time diversity has not yet been well studied for WPCN. Since the energy harvested in current time block can be stored in the energy storage device (ESD) for future use, properly designed time allocation and power control over several time blocks experiencing different channel fading can well be expected to further improve the performance of WPCN. To the best of our knowledge, there is only one work [11] in the literature that considers a throughput maximization problem for the time allocation and power control over a finite horizon of time for a WPCN consisting of one single-antenna H-AP and multiple single-antenna users. However, the work [11] only deals with the ideal case that the CSI for all time blocks are known a priori, which is not very realistic due to the causality of CSI not taken into account. So far, the development of online algorithms is still an open problem. In view of this, we consider this problem for a WPCN consisting two single-antenna APs and one single-antenna user subject to the causal CSI. Because it turns out to be an intractable nonconvex problem, we propose an online algorithm to obtain a suboptimal solution. The proposed algorithm can be efficiently implemented by simple bisection search and golden section search [12]. Some simulation results are provided to demonstrate its efficacy.

## 2. SIGNAL MODEL AND PROBLEM STATEMENT

We consider a WPCN consisting of two single-antenna APs and a single-antenna user. One of the APs is for DL wireless energy transfer, referred to as energy-AP (E-AP); the other is for UL wireless information transmission, referred to as information-AP (I-AP)[1]. To exploit the time diversity of fading channel, we consider the energy transfer and information transmission over $N$ consecutive time blocks of independent channel fading states. The DL channel from E-AP to user and the UL channel to I-AP in the $n$th time block are assumed to be qusi-static flat fading channels and are denoted by $g_n$ and $h_n$, respectively. Except for an energy storage device (ESD) in form of rechargeable battery, the user is assumed to have no other

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[1]The WPCN with one H-AP and one user is a special case of this model.

power resource. Thus, the user needs to harvest energy from the E-AP in the DL phase for its information transmission in the UL phase. Since the user cannot receive energy and transmit information simultaneously, we adopt the "harvest-then-transmit" protocol [8], in which a transmission time block is divided into DL phase and UL phase in order. Specifically, in the $n$th time block, $(1-\tau_n)T$ $(0<\tau_n<1)$ amount of time is assigned to E-AP for energy transfer, and the remaining $\tau_n T$ amount of time is for the user terminal to transmit information to I-AP.

In the DL phase of the $n$th time block, the E-AP transfers energy to user with DL transmit power budget $P$. With the transmit signal denoted by $x_n^{dl}$, the DL transmit power from the E-AP is

$$\mathbb{E}[|x_n^{dl}|^2] = p_n^{dl} \leq P. \tag{1}$$

In the $n$th time block, the received signal at the user can be written as (for energy receivers, the receiver noise is negligible in practice)

$$y_n^{dl} = g_n x_n^{dl}. \tag{2}$$

As a result, the energy harvested by the user in the DL phase of the $n$th time block is

$$E_n = \eta\mathbb{E}[|y_n^{dl}|^2] = \eta p_n^{dl}|g_n|^2(1-\tau_n)T, \quad n=1,\dots,N, \tag{3}$$

where $0 \leq \eta \leq 1$ is the factor of energy conversion efficiency at the receiver.

For the UL phase of the $n$th time block, the signal transmitted from the user terminal to I-AP is denoted by

$$x_n^{ul} = \sqrt{p_n^{ul}} s_n^{ul}, \tag{4}$$

where $p_n^{ul}$ is the transmit power and the independent and identically distributed information-carrying signal $s_n^{ul} \sim \mathcal{CN}(0,1)$ (complex Gaussian with zero mean and unity variance) is assumed. Moreover, for the information transmission, there is additional energy consumption by the user terminal circuit, denoted by $P_c$ [13], which is relatively independent of transmit power and assumed to be constant over all the time blocks. Assuming infinite capacity for the ESD at the user terminal, the available UL transmit power in the UL phase of the $n$th time block is given by

$$\bar{P}_n^{ul} = \frac{E_n + E_n^{\text{left}}}{\tau_n T} = \frac{\eta p_n^{dl}|g_n|^2(1-\tau_n)T + E_n^{\text{left}}}{\tau_n T}, \ \forall n, \tag{5}$$

where $E_n^{\text{left}} = \sum_{i=1}^{n-1} E_i - \sum_{i=1}^{n-1}(p_i^{ul}+P_c)\tau_i T$ is the energy left from the previous time blocks. Hence, the transmit power in the UL phase is constrained by $p_n^{ul} + P_c \leq \bar{P}_n^{ul}$. The received signal at the I-AP in the $n$th time block of the UL phase is given by

$$y_n^{ul} = h_n x_n^{ul} + z_n, \tag{6}$$

where $z_n \sim \mathcal{CN}(0,\sigma^2)$ is the additive white Gaussian noise (AWGN) at the I-AP. Then, the SNR for decoding the signal $s_n$ can be expressed as

$$\bar{\gamma}_n = \frac{p_n^{ul}|h_n|^2}{\sigma^2}. \tag{7}$$

We assume $T=1$ and $\eta=1$ without loss of generality. As a result, the achievable rate (in bps/Hz) for information transmission in the $n$th time block can be expressed as

$$R_n = \tau_n \log_2\left(1 + \frac{p_n^{ul}|h_n|^2}{\sigma^2}\right). \tag{8}$$

Notice that the optimal throughput performance, i.e., maximizing $\sum_{n=1}^{N} R_n$, relies on joint optimization of the DL-UL time allocation $\tau_n$ and the power allocation $p_n^{ul}$ over the $N$ blocks. In the following sections, we propose an optimal offline optimization method and a practical online optimization method. This offline optimization is obviously not very practical since non-causal CSI is required, but it can serve as a performance upper bound to the proposed online method, where the CSI-causality constraint is imposed.

## 3. OFFLINE OPTIMIZATION

Assuming all the CSIs known a priori, the offline throughput maximization problem for the considered WPCN can be formulated as

$$\max_{p_n^{dl}, p_n^{ul}, \tau_n, \forall n} \sum_{n=1}^{N} \tau_n \log_2\left(1 + \frac{p_n^{ul}|h_n|^2}{\sigma^2}\right) \tag{9a}$$

$$s.t. \ 0 \leq p_n^{dl} \leq P, \quad p_n^{ul} \geq 0, \ \forall n, \tag{9b}$$

$$\sum_{i=1}^{n} \tau_i(p_i^{ul}+P_c) \leq \sum_{i=1}^{n} p_i^{dl}|g_i|^2(1-\tau_i), \ \forall n, \tag{9c}$$

$$0 \leq \tau_n \leq 1, \ \forall n, \tag{9d}$$

where (9c) is the UL power constraint deduced from (5), (3) and the constraint $p_n^{ul} + P_c \leq \bar{P}_n^{ul}$. Obviously, problem (9) is a non-convex optimization problem, due to its non-concave objective function and non-convex constraint (9c). Nevertheless, it can be reformulated as a convex problem by the change of variables $\tilde{p}_n^{dl} = (1-\tau_n)p_n^{dl}$ and $\tilde{p}_n^{ul} = \tau_n p_n^{ul}$, so can be efficiently solved using the standard convex solver CVX [14].

## 4. ONLINE OPTIMIZATION

For online optimization, we assume that only the CSI of the current time block, say $g_n$ and $h_n$, are known, and the CSI of the future time blocks $\{g_i, h_i\}_{i=n+1}^{N}$ are unknown and random with known probability distribution. Therefore, at each time block $n$, we consider the problem of maximizing the throughput of the current time block plus the expected throughput of the future time blocks, i.e.,

$$\max_{p_n^{dl}, p_n^{ul}, \tau_n} \ \tau_n \log_2\left(1 + \frac{p_n^{ul}|h_n|^2}{\sigma^2}\right) + \mathbb{E}\left[\sum_{i=n+1}^{N} \breve{\tau}_i \log_2\left(1 + \frac{\breve{p}_i^{ul}|\mathcal{H}_i|^2}{\sigma^2}\right)\right] \tag{10a}$$

$$s.t. \ 0 \leq p_n^{dl} \leq P, \quad p_n^{ul} \geq 0, \tag{10b}$$

$$\tau_n(p_n^{ul}+P_c) \leq p_n^{dl}|g_n|^2(1-\tau_n) + E_{n-1}^{\text{left}}, \tag{10c}$$

$$0 \leq \tau_n \leq 1, \tag{10d}$$

where $\{\breve{\tau}_i, \breve{p}_i^{ul}, \mathcal{H}_i\}_{i=n+1}^{N}$ are the time allocation, power allocation, and CSI in the UL phase of the future time blocks, and are modeled as random variables in the current time block.

### 4.1. Problem Reformulation

By introducing the slack variable $s_n \geq 0$ (the total energy left at the $n$th time block), one can rewrite constraint (10c) as

$$\tau_n(p_n^{ul}+P_c) + s_n = p_n^{dl}|g_n|^2(1-\tau_n) + E_{n-1}^{\text{left}}, \ s_n \geq 0.$$

Then, constraints (10c) and (10d) translate to

$$0 \leq \tau_n = \frac{p_n^{dl}|g_n|^2 + E_{n-1}^{\text{left}} - s_n}{p_n^{ul} + p_n^{dl}|g_n|^2 + P_c} \leq 1, \ s_n \geq 0.$$

Moreover, it can be observed from (10b) and (10c) that the optimal DL power must be $p_n^{dl} = P$. Hence, problem (10) can be reformulated as[2]

$$\max_{p_n^{ul}, s_n} \frac{P|g_n|^2 + E_{n-1}^{\text{left}} - s_n}{p_n^{ul} + P|g_n|^2 + P_c} \log_2\left(1 + \frac{p_n^{ul}|h_n|^2}{\sigma^2}\right) + \mathbb{E}\left[\frac{P|\mathcal{G}_{n+1}|^2 + s_n - \breve{s}_{n+1}}{\breve{p}_{n+1}^{ul} + P|\mathcal{G}_{n+1}|^2 + P_c} \log_2\left(1 + \frac{\breve{p}_{n+1}^{ul}|\mathcal{H}_{n+1}|^2}{\sigma^2}\right)\right] + \mathbb{E}\left[\sum_{i=n+2}^{N} \frac{P|\mathcal{G}_i|^2 + \breve{s}_{i-1} - \breve{s}_i}{\breve{p}_i^{ul} + P|\mathcal{G}_i|^2 + P_c} \log_2\left(1 + \frac{\breve{p}_i^{ul}|\mathcal{H}_i|^2}{\sigma^2}\right)\right] \tag{11a}$$

$$s.t.\ 0 \le P|g_n|^2 + E_{n-1}^{\text{left}} - s_n \le p_n^{ul} + P|g_n|^2 + P_c, \tag{11b}$$

$$s_n \ge 0, \quad p_n^{ul} \ge 0. \tag{11c}$$

### 4.2. Conservative Approximation

It is obvious that the optimal transmission strategy for the future blocks, i.e., $\{\breve{p}_i^{ul}, \breve{s}_i\}_{i=n+1}^N$, depends on how much energy is left for the current time block, i.e., $s_n$, which makes problem (11) intractable. To find a tractable suboptimal solution to problem (11), we assume that in the next future time block, the user terminal does not perform energy harvesting from E-AP, and use up all the remaining energy to transmit information, i.e.,

$$\breve{p}_{n+1}^{ul} = \max\{s_n - P_c, 0\},$$
$$\breve{s}_{n+1} = 0.$$

Note that $\breve{p}_{n+1}^{ul} = 0$ is for the case that the energy left $s_n$ at the current time block is below the circuit power consumption $P_c$. Under this assumption, the third term in the objective function of (11) becomes independent of the unknown variables $p_n^{ul}$ and $s_n$, and hence problem (11) can be simplified as

$$\max_{p_n^{ul}, s_n} \frac{P|g_n|^2 + E_{n-1}^{\text{left}} - s_n}{p_n^{ul} + P|g_n|^2 + P_c} \log_2\left(1 + \frac{p_n^{ul}|h_n|^2}{\sigma^2}\right) + \mathbb{E}\left[\frac{P|\mathcal{G}_{n+1}|^2 + s_n}{\max\{s_n - P_c, 0\} + P|\mathcal{G}_{n+1}|^2 + P_c} \log_2\left(1 + \frac{\max\{s_n - P_c, 0\}|\mathcal{H}_{n+1}|^2}{\sigma^2}\right)\right] \tag{12}$$

$$s.t.\ (11b), (11c).$$

To solve problem (12), one needs to consider two cases, $s_n \ge P_c$ and $s_n \le P_c$, that are presented respectively below.

**<u>Case I</u>** ($s_n \ge P_c \Rightarrow \breve{p}_{n+1}^{ul} = s_n - P_c$)

$$\max_{p_n^{ul}, s_n} \frac{P|g_n|^2 + E_{n-1}^{\text{left}} - s_n}{p_n^{ul} + P|g_n|^2 + P_c} \log_2\left(1 + \frac{p_n^{ul}|h_n|^2}{\sigma^2}\right) + \mathbb{E}\left[\log_2\left(1 + \frac{(s_n - P_c)|\mathcal{H}_{n+1}|^2}{\sigma^2}\right)\right] \tag{13a}$$

$$s.t.\ 0 \le P|g_n|^2 + E_{n-1}^{\text{left}} - s_n \le p_n^{ul} + P|g_n|^2 + P_c, \tag{13b}$$

$$s_n \ge P_c, \quad p_n^{ul} \ge 0. \tag{13c}$$

[2]Noticing that, by definition, $s_n = E_n^{\text{left}}$, we have replaced $E_i^{\text{left}}$ by $s_i$ for all $i \ge n$, and have used $\breve{s}_i$ for all $i \ge n+1$ to emphasize that they are random variables. Analogous to UL channels, the future DL channels are denoted by $\mathcal{G}_i$ for $i \ge n+1$.

**<u>Case II</u>** ($s_n \le P_c \Rightarrow \breve{p}_{n+1}^{ul} = 0$)

$$\max_{p_n^{ul}, s_n} \frac{P|g_n|^2 + E_{n-1}^{\text{left}} - s_n}{p_n^{ul} + P|g_n|^2 + P_c} \log_2\left(1 + \frac{p_n^{ul}|h_n|^2}{\sigma^2}\right) \tag{14a}$$

$$s.t.\ 0 \le P|g_n|^2 + E_{n-1}^{\text{left}} - s_n \le p_n^{ul} + P|g_n|^2 + P_c, \tag{14b}$$

$$0 \le s_n \le P_c, \quad p_n^{ul} \ge 0. \tag{14c}$$

It is obvious that the optimal value of problem (12) is the maximum of the optimal values of (13) and (14), and the corresponding optimal solution is hence optimal to problem (12).

### 4.3. Efficient Implementation

In this subsection we present an efficient algorithm for solving the nonconvex problems (13) and (14). First, let us consider case I, i.e., problem (13). By the change of variables

$$t_n = \frac{1}{p_n^{ul} + P_c + P|g_n|^2},\ r_n = P|g_n|^2 + E_{n-1}^{\text{left}} - s_n, \tag{15}$$

problem (13) can be equivalently written as

$$\max_{t_n, r_n} t_n r_n \log_2\left(1 + \frac{(1 - t_n(P_c + P|g_n|^2))|h_n|^2}{t_n\sigma^2}\right) + \mathbb{E}\left[\log_2\left(1 + \frac{(P|g_n|^2 + E_{n-1}^{\text{left}} - r_n - P_c)|\mathcal{H}_{n+1}|^2}{\sigma^2}\right)\right] \tag{16a}$$

$$s.t.\ 0 \le t_n \le r_n^{-1}, \tag{16b}$$

$$0 \le t_n \le (P_c + P|g_n|^2)^{-1}, \tag{16c}$$

$$0 \le r_n \le P|g_n|^2 + E_{n-1}^{\text{left}} - P_c. \tag{16d}$$

For ease of exposition, let

$$\alpha(t_n, r_n) = t_n r_n \log_2\left(1 + \frac{(1 - t_n(P_c + P|g_n|^2))|h_n|^2}{t_n\sigma^2}\right),$$

$$\beta(r_n) = \mathbb{E}\left[\log_2\left(1 + \frac{(P|g_n|^2 + E_{n-1}^{\text{left}} - r_n - P_c)|\mathcal{H}_{n+1}|^2}{\sigma^2}\right)\right]$$

Then problem (16) can be expressed as

$$\max_{r_n} f(r_n) \triangleq \left[\max_{0 \le t_n \le \min\left\{\frac{1}{r_n}, \frac{1}{P_c + P|g_n|^2}\right\}} \alpha(t_n, r_n)\right] + \beta(r_n) \tag{17a}$$

$$s.t.\ 0 \le r_n \le P|g_n|^2 + E_{n-1}^{\text{left}} - P_c. \tag{17b}$$

It can be shown that, for fixed $r_n$, $\alpha(t_n, r_n)$ is concave in $t_n$ (the proof is omitted due to space limitations), and hence for any fixed value of $r_n$, $f(r_n)$ can be efficiently evaluated by solving the inner maximization problem using bisection search. Moreover, it can be proved that $f(r_n)$ is a unimodal function of $r_n$. Therefore, the optimal $r_n$ can be efficiently obtained by the golden section search method [12]. The proposed efficient algorithm for solving problem (17) is hence summarized in Algorithm 1. For case II, problem (14) can be analogously reformulated as problem (17) except for $\beta(r_n) = 0$ and constraint (17b) replaced by

$$P|g_n|^2 + E_{n-1}^{\text{left}} - P_c \le r_n \le P|g_n|^2 + E_{n-1}^{\text{left}}.$$

The resulting problem can also be solved by Algorithm 1 with the initial conditions changed to $r_1 := P|g_n|^2 + E_{n-1}^{\text{left}} - P_c$ and $r_2 := P|g_n|^2 + E_{n-1}^{\text{left}}$. After obtaining the optimal $r_n$ and $t_n$, the optimal solution of (12) can be obtained by (15).

**Algorithm 1** Efficient Algorithm for Solving Problem (17)

Set $r_1 := 0$, $r_2 := P|g_n|^2 + s_{n-1}$, $R_G := \frac{\sqrt{5}-1}{2}$ and tolerance $\epsilon > 0$.
**repeat**
  Set $L := r_2 - r_1$.
  Set $r_3 := r_2 - R_G \times L$ and $r_4 := r_1 + R_G \times L$.
  Compute $f(r_3)$ and $f(r_4)$ by bisection search.
  **if** $f(r_3) > f(r_4)$, update $r_2 := r_4$.
  **else** update $r_1 := r_3$.
**until** $|r_2 - r_1| < \epsilon(|r_3| + |r_4|)$
**Output** $r^\star := \frac{r_1+r_2}{2}$ as the optimal solution of problem (17).

## 5. SIMULATION RESULTS AND CONCLUSIONS

In the simulations, the number of time blocks is set to $N = 200$, and the user is randomly allocated in a 4-meter $\times$ 4-meter room. With the center of the square room being the origin, E-AP and I-AP are allocated on $(0.1, 0)$ and $(-0.1, 0)$ respectively. Note that the expectation term in (13a) is approximated by sample average with 200 channel realizations. The distance-dependent pass loss model is given by $P_L = A_0(d_l/d_0)^{-3}$, where $A_0 = 10^{-3}$, $d_l$ denotes the distance between the user and AP and $d_0 = 1$ meter. Considering the Rician fading channel model, the DL channel $g$ and UL channel $h$ can be expressed respectively as

$$g = \sqrt{\frac{K_R}{1+K_R}} g^{\text{LOS}} + \sqrt{\frac{1}{1+K_R}} g^{\text{NLOS}}, \quad (18)$$

$$h = \sqrt{\frac{K_R}{1+K_R}} h^{\text{LOS}} + \sqrt{\frac{1}{1+K_R}} h^{\text{NLOS}}. \quad (19)$$

where $K_R = 3$ denotes the Rician factor, $g^{\text{LOS}} \in \mathbb{C}$ (the set of complex numbers) and $h^{\text{LOS}} \in \mathbb{C}$ are the line of sight (LOS) deterministic components, $g^{\text{NLOS}} \in \mathbb{C}$ and $h^{\text{NLOS}} \in \mathbb{C}$ denote the Rayleigh fading components with zero mean and unity variance.

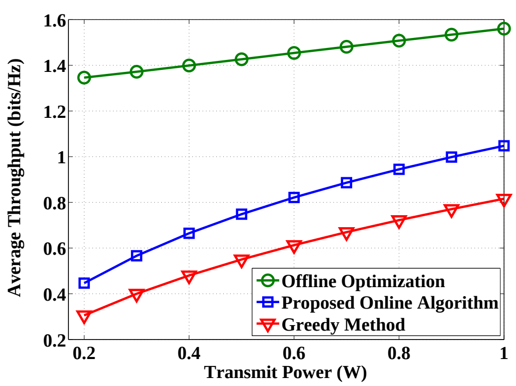


**Fig. 1**. Average throughput performance versus transmit power $P$ of E-AP for $\sigma^2 = 10^{-6}$ (Watt) and $P_c = 10^{-5}$ (Watt).

Figures 1, 2 and 3 show the average throughput performance (versus different transmit power $P$ of E-AP, noise power $\sigma^2$ at I-AP and circuit power $P_c$) of the offline optimization (solving problem (9) using CVX [14]), the proposed online optimization algorithm (Algorithm 1 for solving problem (12)) and a heuristic greedy method, which solves (14) in every time block (without any prediction on the throughput rate for any future time block). Some observations from these three figures are as follows. The average throughput performances of the three methods are better for larger $P$, smaller $\sigma^2$, and smaller $P_c$, and the offline optimization performs best and the greedy method performs worst. The performance gap between the offline optimization and the online optimization is smaller, and that between the latter and the greedy method is larger for larger $P$ (see Fig. 1) and smaller $\sigma^2$ (see Fig. 2). However, Fig. 3 shows that the performance gap between the offline optimization and the online optimization is roughly constant, while that between the online optimization and the greedy method decreases with the circuit power $P_c$, and reduces to zero (due to $s_n < P_c$ for all $n$) as $P_c$ is large.

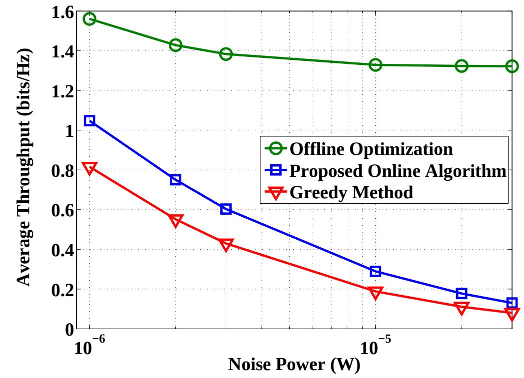


**Fig. 2**. Average throughput performance versus noise power $\sigma^2$ at I-AP for $P = 1$ (Watt), $P_c = 10^{-5}$ (Watt).

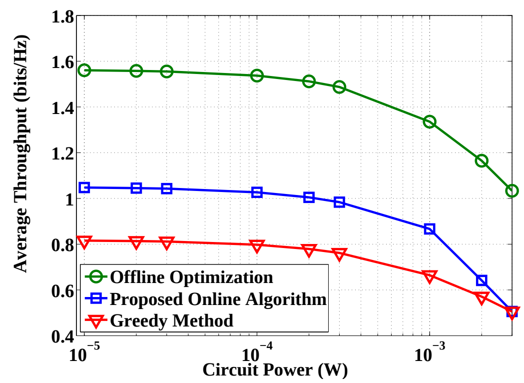


**Fig. 3**. Average throughput performance versus circuit power $P_c$ for $P = 1$ (Watt) and $\sigma^2 = 10^{-6}$ (Watt).

In conclusion, we have presented a low-complexity online optimization method for the throughput maximization of WPCN over multiple independent channel fading states provided by the time diversity. The proposed online optimization method (Algorithm 1), the first algorithm for online processing to the best of our knowledge, significantly outperforms a heuristic greedy method. Though the offline optimization solved by CVX [14], provides a performance upper bound to the proposed online algorithm, the latter performs well with the computation time about ten times less than the former in the presented simulation results. However, the development of more advanced online algorithms to reduce the gap below the performance upper bound is left as a future study.

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