Spectral and Energy Efficient Wireless Powered IoT Networks: NOMA or TDMA?

Qingqing Wu, Wen Chen, Derrick Wing Kwan Ng, and Robert Schober

Abstract—**Wireless powered communication networks (WPCNs), where multiple energy-limited devices first harvest energy in the downlink and then transmit information in the uplink, have been envisioned as a promising solution for the future Internet-of-Things (IoT). Meanwhile, non-orthogonal multiple access (NOMA) has been proposed to improve the system spectral efficiency (SE) of the fifth-generation (5G) networks by allowing concurrent transmissions of multiple users in the same spectrum. As such, NOMA has been recently considered for the uplink of WPCNs based IoT networks with a massive number of devices. However, simultaneous transmissions in NOMA may also incur more transmit energy consumption as well as circuit energy consumption in practice which are critical for energy constrained IoT devices. As a result, compared to orthogonal multiple access schemes such as time-division multiple access (TDMA), whether the SE can be improved and/or the total energy consumption can be reduced with NOMA in such a scenario is still unknown. To answer this question, we first derive the optimal time allocations for maximizing the SE of a TDMA-based WPCN (T-WPCN) and a NOMA-based WPCN (N-WPCN), respectively. Subsequently, we analyze the total energy consumption as well as the maximum SE achieved by these two networks. Surprisingly, it is found that N-WPCN not only consumes more energy, but also is less spectral efficient than T-WPCN. Simulation results verify our theoretical findings and unveil the fundamental performance bottleneck in multiuser NOMA systems.**

I. Introduction

As reported in [1], the number of connected devices will skyrocket to 30 billion by 2025, giving rise to the well known "Internet-of-Things (IoT)". With such a huge number of IoT devices, the lifetime of networks becomes a critical issue and the conventional battery based solutions may no longer be sustainable due to the high cost in battery replacements as well as environmental concerns. As a result, wireless power transfer, which enables energy harvesting from ambient radio frequency (RF) signals, is envisioned as a promising solution for powering massive IoT devices [2]. However, due to the significant signal attenuation in wireless communication channels, the harvested RF energy at the devices is generally limited. Therefore, how to efficiently utilize the scarce harvested energy becomes particularly crucial for realizing sustainable and scalable IoT networks. To this end, a "harvest and then transmit" protocol is proposed in [3] for wireless powered communication networks (WPCNs), where devices first harvest energy in the downlink (DL) for wireless energy transfer (WET) and then transmit information signals in the uplink (UL) for wireless information transmission (WIT). To improve the spectral efficiency (SE), this work is

Qingqing Wu and Wen Chen are with Department of Electronic Engineering, Shanghai Jiao Tong University, email: {wu.qq, wenchen}@sjtu.edu.cn. Derrick Wing Kwan Ng is with the School of Electrical Engineering and Telecommunications, The University of New South Wales, Australia, email: w.k.ng@unsw.edu.au. Robert Schober is with the Institute for Digital Communications, Friedrich-Alexander-University Erlangen-Nürnberg (FAU), email: robert.schober@fau.de.
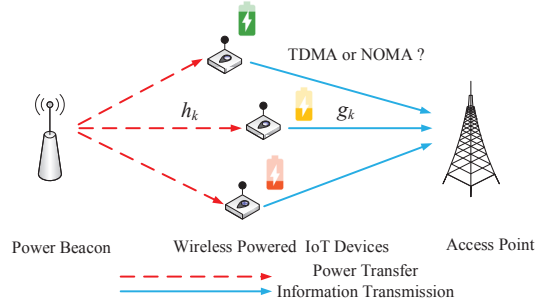

Fig. 1. System model of a wireless powered IoT network.

further extended to a full-duplex communication network in [4] where devices can harvest energy and transmit information at the same time. However, it may not be feasible to implement the full-duplex functionality in IoT devices due to the resulting high complexity, energy consumption, and cost. As a result, the most recent narrowband IoT (NB-IoT) standard requires NB-IoT devices to support only the half-duplex protocol for simplicity [1].

Meanwhile, non-orthogonal multiple access (NOMA) has been proposed to improve the SE as well as user fairness by allowing multiple users simultaneously to access the same spectrum. With successive interference cancellation (SIC) performed at the receiver, NOMA has been demonstrated superior to orthogonal multiple access (OMA) in terms of ergodic sum rates [5]. As such, NOMA is recently pursued for UL WIT in WPCNs as [6] and [7], where the decoding order of users is exploited to enhance the throughput fairness among users. However, the conclusions drawn in [5] are only applicable for the DL scenario and may not hold for UL IoT networks with energy constrained devices. Furthermore, [6] and [7] focus only on balancing the individual throughput of the users without considering the system SE. Last, the circuit power consumption of the users is ignored in [3], [6], [7] which, however, is comparable to the transmit power for short-range IoT applications, such as wearables devices. As multiple users access the same spectrum simultaneously in NOMA, the circuit energy consumption of each user increases inevitably, which may contradict a fundamental design requirement of future IoT networks, i.e., ultra low power consumption [8]. For example, in NOMA-based WPCN (N-WPCN) with a fixed total available harvested energy, if devices consume more circuit energy than in time-division multiple access (TDMA)-based WPCN (T-WPCN), then less energy will be left for signal transmission. As a result, a natural question arise: Does NOMA improve the SE and/or reduce the total energy consumption of such wireless powered IoT networks in practice compared to TDMA?

Driven by the above question, we make the following contributions in this paper. 1) By taking into account the circuit power

consumption, we first derive the optimal time allocation for the SE maximization problem for T-WPCN, based on which, the corresponding problem for N-WPCN can be cast into the single user case for T-WPCN; 2) we prove that N-WPCN in general requires a longer DL WET time duration than T-WPCN, which implies that N-WPCN is more energy demanding; 3) we prove that N-WPCN in general achieves a lower SE than T-WPCN. Given 2) and 3), NOMA may not be a good candidate for wireless powered IoT networks in practice.

II. System Model and Problem Formulation

A. System Model

We consider a WPCN, which consists of one power beacon (PB), $K > 1$ wireless-powered IoT devices, and one information access point (AP), as shown in Fig. 1. The total available transmission time is denoted by $T_{\max}$. The "harvest and then transmit" protocol [3] is adopted where the devices first harvest energy from the signal sent by the PB and then transmit information to the AP. To compare the upper bound performance of T-WPCN and N-WPCN, we assume that perfect channel state information (CSI) is available for resource allocation. The DL channel gain between the PB and device $k \in \{1, 2, \ldots, K\}$, and the UL channel gain between device k and the AP are denoted by h_k and g_k, respectively.

During DL WET, the PB broadcasts the energy signal with a constant transmit power P_E and time τ_0. The energy harvested from the noise and the received UL WIT signals from other devices are assumed to be negligible, since both the noise power and device transmit power are much smaller than the transmit power of the PB in practice [3]. Thus, the amount of harvested energy at device k can be expressed as

$$E_k^h = \eta_k P_E h_k \tau_0, \tag{1}$$

where $\eta_k \in (0, 1]$ is the constant energy conversion efficiency of device k. During UL WIT, device k transmits its information signal to the AP with transmit power p_k. Along with the transmit power, each device also consumes a constant power for the circuit operation such as the RF chain, denoted by $p_{c,k} \geq 0$. For the multiple access scheme in UL WIT, we consider two schemes, i.e., TDMA and NOMA. For T-WPCN, device k exclusively accesses the spectrum for a duration of τ_k, while for N-WPCN, all the devices access the spectrum simultaneously for a duration of $\bar{\tau}_1$. Then, the energy consumed by device k during UL WIT for T-WPCN and N-WPCN can be expressed as $(p_k + p_{c,k})\tau_k$ and $(p_k + p_{c,k})\bar{\tau}_1$, respectively. Denote $\gamma_k = \frac{g_k}{\sigma^2}$ as the normalized UL channel gain of device k, where σ^2 is the additive white Gaussian noise power at the AP. Without loss of generality, we assume that the normalized UL channel gains are sorted in ascending order, i.e., $0 < \gamma_1 \leq \gamma_2 \cdots \leq \gamma_K$.

B. T-WPCN and Problem Formulation

For T-WPCN, the achievable throughput of device k in bits/Hz can be expressed as

$$r_k = \tau_k \log_2 (1 + p_k \gamma_k). \tag{2}$$

Then, the system throughput of T-WPCN is given by

$$R_{\text{TDMA}} = \sum_{k=1}^{K} r_k = \sum_{k=1}^{K} \tau_k \log_2(1 + p_k \gamma_k). \tag{3}$$

Accordingly, the SE maximization problem is formulated as

$$\underset{\tau_0, \{\tau_k\}, \{p_k\}}{\text{maximze}} \quad \sum_{k=1}^{K} \tau_k \log_2 (1 + p_k \gamma_k) \tag{4a}$$

$$\text{s.t.} \quad (p_k + p_{c,k}) \tau_k \leq \eta_k P_E h_k \tau_0, \ \forall k, \tag{4b}$$

$$\tau_0 + \sum_{k=1}^{K} \tau_k \leq T_{\max}, \tag{4c}$$

$$\tau_0 \geq 0, \ \tau_k \geq 0, \ p_k \geq 0, \ \forall k. \tag{4d}$$

In problem (4), (4b) is the energy causality constraint which ensures that the energy consumed for WIT does not exceed the total energy harvested during WET. (4c) and (4d) are the total time constraint and the non-negativity constraints on the optimization variables, respectively.

C. N-WPCN and Problem Formulation

For N-WPCN, since all the K devices share the same spectrum, SIC is employed at the AP to eliminate multiuser interference [5]. Specifically, for detecting the message of the k-th device, the AP first decodes the message of the i-th device, $\forall i < k$, and then removes this message from the received signal, in the order of $i = 1, 2, \ldots, k-1$. The message of the i-th user, $\forall i > k$, is treated as noise. Hence, the achievable throughput of device k in bits/Hz in N-WPCN can be expressed as

$$r_k = \bar{\tau}_1 \log_2 \left(1 + \frac{p_k \gamma_k}{\sum_{i=k+1}^{K} p_k \gamma_k + 1} \right). \tag{5}$$

Then, the system throughput of T-WPCN is given by

$$R_{\text{NOMA}} = \sum_{k=1}^{K} r_k = \bar{\tau}_1 \log_2 \left(1 + \sum_{k=1}^{K} p_k \gamma_k \right). \tag{6}$$

Accordingly, the SE maximization problem is formulated as

$$\underset{\tau_0, \bar{\tau}_1, \{p_k\}}{\text{maximize}} \quad \bar{\tau}_1 \log_2 \left(1 + \sum_{k=1}^{K} p_k \gamma_k \right) \tag{7a}$$

$$\text{s.t.} \quad (p_k + p_{c,k}) \bar{\tau}_1 \leq \eta_k P_E h_k \tau_0, \ \forall k, \tag{7b}$$

$$\tau_0 + \bar{\tau}_1 \leq T_{\max}, \tag{7c}$$

$$\tau_0 \geq 0, \ \bar{\tau}_1 \geq 0, \ p_k \geq 0, \ \forall k. \tag{7d}$$

Similar to problem (4), (7b), (7c), and (7d) represent the energy causality constraint, total time constraint, and non-negativity constraints, respectively.

III. T-WPCN or N-WPCN for IoT Networks?

In this section, we first derive the optimal solutions to problems (4) and (7), respectively. Then, we theoretically analyze and compare the system energy consumed and the SE achieved by both T-WPCN and N-WPCN.

A. Optimal Solution for T-WPCN

It can be shown that each device will deplete all of its energy at the optimal solution, i.e., constraint (4b) holds with equality, since otherwise p_k can be always increased to improve the

objective value such that (4b) is active. Thus, problem (4) is simplified to the following

$$\underset{\tau_0,\{\tau_k\}}{\text{maximize}} \quad \sum_{k=1}^{K} \tau_k \log_2\left(1 - p_{c,k}\gamma_k + \frac{\eta_k P_E h_k \gamma_k}{\tau_k}\tau_0\right) \quad \text{(8a)}$$

$$\text{s.t.} \quad \tau_0 + \sum_{k=1}^{K} \tau_k \leq T_{\max}, \quad \text{(8b)}$$

$$\tau_0 \geq 0, \ \tau_k \geq 0, \ \forall k. \quad \text{(8c)}$$

It is easy to verify that problem (8) is a convex optimization problem and also satisfies the Slater's condition. Thus, the optimal solution can be obtained efficiently by applying the Lagrange dual method. To this end, we need the Lagrangian function of problem (8) which can be written as

$$\mathcal{L}(\tau_0,\{\tau_k\}) = \sum_{k=1}^{K} \tau_k \log_2\left(1 - p_{c,k}\gamma_k + \frac{\eta_k P_E h_k \gamma_k}{\tau_k}\tau_0\right)$$
$$+ \lambda\left(T_{\max} - \tau_0 - \sum_{k=1}^{K}\tau_k\right), \quad \text{(9)}$$

where $\lambda \geq 0$ is the Lagrange multiplier associated with (8b). (8c) is naturally satisfied since the PB is activated in the DL and each user is scheduled in the UL. Taking the partial derivative of $\mathcal{L}$ with respect to τ_0 and τ_k, respectively, yields

$$\frac{\partial \mathcal{L}}{\partial \tau_0} = \sum_{k=1}^{K} \frac{\eta_k P_E h_k \gamma_k \log_2(e)}{1 - p_{c,k}\gamma_k + x_k} - \lambda, \quad \text{(10)}$$

$$\frac{\partial \mathcal{L}}{\partial \tau_k} = \log_2(1 - p_{c,k}\gamma_k + x_k) - \frac{x_k \log_2(e)}{1 - p_{c,k}\gamma_k + x_k} - \lambda, \quad \text{(11)}$$

where $x_k = \frac{\eta_k P_E h_k \gamma_k}{\tau_k}\tau_0, \forall k$. Since $\tau_0 > 0$ and $\tau_k > 0$, $\forall k$, always hold at the optimal solution, we have $\frac{\partial \mathcal{L}}{\partial \tau_0} = 0$ and $\frac{\partial \mathcal{L}}{\partial \tau_k} = 0$, $\forall k$. As a result, the optimal values of x_k, $\forall k$, can be obtained by solving the following equations

$$\mathcal{G}_k(x_k^*) \triangleq \log_2(1 - p_{c,k}\gamma_k + x_k^*) - \frac{x_k^* \log_2(e)}{1 - p_{c,k}\gamma_k + x_k^*}$$
$$- \sum_{k=1}^{K} \frac{\eta_k P_E h_k \gamma_k \log_2(e)}{1 - p_{c,k}\gamma_k + x_k^*} = 0, \forall k. \quad \text{(12)}$$

It can be shown that (8b) is active at the optimal solution, i.e., $\tau_0 + \sum_{k=1}^{K}\tau_k = \tau_0 + \sum_{k=1}^{K} \frac{P_E h_k \eta_k \gamma_k}{x_k^*}\tau_0 = T_{\max}$. With x_k^*, $\forall k$, from (12), the optimal time allocation for T-WPCN is given by

$$\tau_0^* = \frac{T_{\max}}{1 + \sum_{k=1}^{K} \frac{\eta_k P_E h_k \gamma_k}{x_k^*}}, \quad \text{(13)}$$

$$\tau_k^* = \frac{\eta_k P_E h_k \gamma_k}{x_k^*}\tau_0^*, \forall k. \quad \text{(14)}$$

B. Optimal Solution for N-WPCN

Similarly, problem (7) can be simplified to the following problem:

$$\underset{\tau_0,\bar{\tau}_1}{\text{maximize}} \quad \bar{\tau}_1 \log_2\left(1 - \sum_{k=1}^{K} p_{c,k}\gamma_k + \frac{\sum_{k=1}^{K}\eta_k P_E h_k \gamma_k}{\bar{\tau}_1}\tau_0\right)$$
$$\text{(15a)}$$

$$\text{s.t.} \quad \tau_0 + \bar{\tau}_1 \leq T_{\max}, \quad \text{(15b)}$$

$$\tau_0 \geq 0, \ \bar{\tau}_1 \geq 0. \quad \text{(15c)}$$

It is interesting to observe that problem (15) has the same structure as problem (8) when $K = 1$ with only minor changes in constant terms. As such, the proposed solution for T-WPCN can be immediately extended to N-WPCN. Specifically, the optimal time allocation for N-WPCN is given by

$$\tau_0^\star = \frac{T_{\max}}{1 + \frac{\sum_{k=1}^{K}\eta_k P_E h_k \gamma_k}{x^\star}}, \quad \bar{\tau}_1^\star = \frac{\sum_{k=1}^{K}\eta_k P_E h_k \gamma_k}{x^\star}\tau_0^\star, \quad \text{(16)}$$

where $x^\star$ is the unique root of

$$\mathcal{G}(x^\star) \triangleq \log_2\left(1 - \sum_{k=1}^{K} p_{c,k}\gamma_k + x^\star\right) - \frac{x^\star \log_2(e)}{1 - \sum_{k=1}^{K} p_{c,k}\gamma_k + x^\star}$$
$$- \frac{\sum_{k=1}^{K}\eta_k P_E h_k \gamma_k \log_2(e)}{1 - \sum_{k=1}^{K} p_{c,k}\gamma_k + x^\star} = 0. \quad \text{(17)}$$

The proposed solutions in Sections III-A and B serve as the theoretical foundation for the comparison between T-WPCN and N-WPCN.

C. TDMA versus NOMA

For notational simplicity, we first denote by $E_{\text{NOMA}}^\star$ and E_{TDMA}^* the total energy consumption of T-WPCN and N-WPCN at the optimal solutions to problem (8) and (15), respectively. The corresponding spectral efficiencies are denoted by $R_{\text{NOMA}}^\star$ and $R_{\text{TDMA}}^\star$, respectively. Now, we introduce the following theorem.

Theorem 1: At the optimal solution, 1) the DL WET time of N-WPCN in (13) is greater than or equal to that of T-WPCN in (16), i.e., $\tau_0^\star \geq \tau_0^*$; 2) the energy consumption of N-WPCN is larger than or equal to that of T-WPCN, i.e.,

$$E_{\text{NOMA}}^\star \geq E_{\text{TDMA}}^*, \quad \text{(18)}$$

where "=" holds when $p_{c,k} = 0, \ \forall k$.

Proof: Since $\sum_{k=1}^{K} p_{c,k}\gamma_k \geq p_{c,k}\gamma_k$, it is easy to show that $x^\star \geq x_k^*$, $\forall k$, from (17) and (12), where "=" holds when $p_{c,k} = 0, \ \forall k$. Then, it follows from (13) and (16) that $\tau_0^\star \geq \tau_0^*$. Furthermore, since each device depletes all of its harvested energy, then the total energy consumption of N-WPCN and T-WPCN satisfies $E_{\text{NOMA}}^\star = P_E \tau_0^\star \geq E_{\text{TDMA}}^* = P_E \tau_0^*$. ∎

Theorem 1 implies that N-WPCN is more energy demanding than T-WPCN in terms of the total energy consumption. This is fundamentally due to simultaneous transmissions of multiple devices during UL WIT, which thereby leads to more circuit energy consumption. Furthermore, since $\tau_0^\star \geq \tau_0^*$, more energy is also wasted during DL WET for N-WPCN than for T-WPCN. Next, we compare the SE of the two networks.

Theorem 2: The maximum SE of T-WPCN is greater than or equal to that of N-WPCN, i.e.,

$$R_{\text{TDMA}}^* \geq R_{\text{NOMA}}^\star, \quad \text{(19)}$$

where "=" holds when $p_{c,k} = 0, \ \forall k$.

Proof: Assume that $\{\tau_0^\star, \bar{\tau}_1^\star\}$ achieves the maximum SE of problem (15), $R_{\text{NOMA}}^\star$. Then, we construct a new solution $\{\widetilde{\tau}_0, \{\widetilde{\tau}_k\}\}$ satisfying $\widetilde{\tau}_0 = \tau_0^\star$ and $\sum_{k=1}^{K}\widetilde{\tau}_k = \bar{\tau}_1^\star$ such that

all devices achieve the same signal-to-noise ratio (SNR) in T-WPCN, i.e.,

$$\text{SNR} = \frac{\eta_k P_E h_k \widetilde{\tau}_0 - p_{c,k}\widetilde{\tau}_k}{\widetilde{\tau}_k}\gamma_k = \frac{\eta_m P_E h_m \widetilde{\tau}_0 - p_{c,m}\widetilde{\tau}_m}{\widetilde{\tau}_m}\gamma_m$$

$$= \frac{\sum_{k=1}^{K}(\eta_k P_E h_k \widetilde{\tau}_0 - p_{c,k}\widetilde{\tau}_k)\gamma_k}{\sum_{k=1}^{K}\widetilde{\tau}_k}, \forall m \neq k. \quad (20)$$

It can be verified that the constructed solution is also a feasible solution to problem (8). Denote the SE achieved by the optimal solution $\{\tau_0^*, \{\tau_k^*\}\}$ and the constructed solution $\{\widetilde{\tau}_0, \{\widetilde{\tau}_k\}\}$ as R_{TDMA}^* and $\widetilde{R}_{\text{TDMA}}$, respectively. Then, it follows that

$$R_{\text{TDMA}}^* \geq \widetilde{R}_{\text{TDMA}}$$
$$= \sum_{k=1}^{K}\widetilde{\tau}_k \log_2\left(1 + \frac{\eta_k P_E h_k \widetilde{\tau}_0 - p_{c,k}\widetilde{\tau}_k}{\widetilde{\tau}_k}\gamma_k\right)$$
$$= \sum_{k=1}^{K}\widetilde{\tau}_k \log_2\left(1 + \frac{\sum_{m=1}^{K}(\eta_m P_E h_m \widetilde{\tau}_0 - p_{c,m}\widetilde{\tau}_m)\gamma_m}{\sum_{m=1}^{K}\widetilde{\tau}_m}\right)$$
$$\overset{(a)}{\geq} \bar{\tau}_1^\star \log_2\left(1 + \frac{\sum_{m=1}^{K}(\eta_m P_E h_m \tau_0^\star - p_{c,m}\bar{\tau}_1^\star)\gamma_m}{\bar{\tau}_1^\star}\right)$$
$$= R_{\text{NOMA}}^\star, \quad (21)$$

where inequality "(a)" holds due to $0 < \widetilde{\tau}_k < \bar{\tau}_1^\star, \forall k$, and equality holds when $p_{c,k} = 0, \forall k$. Thus, if $\exists k, p_{c,k} > 0$, it follows that $R_{\text{TDMA}}^* > R_{\text{NOMA}}^\star$. Next, we prove that when $p_{c,k} = 0, \forall k$, the constructed solution is the optimal solution to problem (8), i.e., $\tau_0^* = \widetilde{\tau}_0$ and $\tau_k^* = \widetilde{\tau}_k$. The SE of T-WPCN is given by

$$R_{\text{TDMA}} = \sum_{k=1}^{K}\tau_k \log_2\left(1 + \frac{\eta_k P_E h_k \gamma_k}{\tau_k}\tau_0\right)$$
$$\overset{(b)}{\leq} \sum_{k=1}^{K}\tau_k \log_2\left(1 + \frac{\sum_{m=1}^{K}\eta_m P_E h_m \gamma_m}{\sum_{m=1}^{K}\tau_m}\tau_0\right)$$
$$= (1-\tau_0)\log_2\left(1 + \frac{\sum_{m=1}^{K}\eta_m P_E h_m \gamma_m}{1-\tau_0}\tau_0\right)$$
$$\overset{(c)}{\leq} (1-\tau_0^\star)\log_2\left(1 + \frac{\sum_{m=1}^{K}\eta_m P_E h_m \gamma_m}{1-\tau_0^\star}\tau_0^\star\right)$$
$$= R_{\text{NOMA}}^\star, \quad (22)$$

where "(b)" holds due to the concavity of the logarithm function and "=" holds when $\frac{\eta_k P_E h_k \gamma_k}{\tau_k}\tau_0 = \frac{\eta_m P_E h_m \gamma_m}{\tau_m}\tau_0, \forall k$, which is exactly the same as (20) for $p_{c,k} = 0, \forall k$. Thus, we have $\tau_k^* = \widetilde{\tau}_k$. Equality in "(c)" is due to the optimality of $\bar{\tau}_0^\star$ for N-WPCN. Thus, it follows that $\tau_0^* = \bar{\tau}_0^\star = \widetilde{\tau}_0$. ∎

Theorem 2 answers the question raised in the introduction regarding to the SE comparison of T-WPCN and N-WPCN. Specifically, TDMA in general achieves a higher SE than NOMA for wireless powered IoT devices. This seems contradictory to the conclusion of previous works, e.g. [5], which have shown that NOMA always outperforms OMA schemes such as TDMA. Such a conclusion, however, was based on the conventional transmit power limited systems where more transmit power is always beneficial for improving the SE by leveraging SIC. To show this, suppose that the transmit power of device k is limited by p_k and the energy causality constraints in (4) are removed.

By setting $\tau_0 = 0$ in (4c), we have

$$R_{\text{TDMA}} = \sum_{k=1}^{K}\tau_k \log_2(1 + p_k\gamma_k)$$
$$\overset{(d)}{\leq} \sum_{k=1}^{K}\tau_k \log_2\left(1 + \sum_{m=1}^{K}p_m\gamma_m\right)$$
$$= T_{\max}\log_2\left(1 + \sum_{k=1}^{K}p_k\gamma_k\right) = R_{\text{NOMA}}, \quad (23)$$

where strict inequality "(d)" holds if $p_k > 0, \forall k$. Accordingly, $E_{\text{TDMA}} = \sum_{k=1}^{K}\tau_k p_k \leq \sum_{k=1}^{K}T_{\max}p_k = T_{\max}\sum_{k=1}^{K}p_k = E_{\text{NOMA}}$. This suggests that the SE gain achieved by NOMA in transmit power limited systems is at the expense of more energy consumption. In fact, if the total available energy of each device is constrained, i.e., for energy limited systems, NOMA has no performance gain over TDMA in terms of SE as shown in Theorem 2. More importantly, when the circuit power consumption is taking into account for practical IoT devices, NOMA achieves a strictly lower SE than TDMA. Recall that the key principle of NOMA for enhancing the SE is to allow devices to access the same spectrum simultaneously. This, however, inevitably leads to more circuit energy consumption, which is particularly detrimental to IoT devices that are energy limited in general.

Remark 1: As shown in Theorems 1 and 2, since N-WPCN consumes more energy but achieves a lower SE than T-WPCN in general, it is concluded that NOMA may not be a good option for practical IoT networks[1].

IV. NUMERICAL RESULTS

This section provides simulation results to demonstrate the effectiveness of the proposed solutions and validate our theoretical findings. There are 10 IoT devices randomly and uniformly distributed inside a disc with the PB in the center. The carrier frequency is 750 MHz and the bandwidth is 180 kHz as in the NB-IoT scenario [8]. The reference distance is 1 meter and the maximum service distance is 5 meters. The AP is located 50 meters away from the PB. Both the DL and UL channel power gains are modeled as $10^{-3}\rho^2 d^{-\alpha}$ [3] where ρ^2 arising from the Rayleigh fading is an exponentially distributed random variable with unit mean and d is the link distance. The path loss exponent is set as $\alpha = 2.2$. Without loss of generality, it is assumed that all IoT devices have identical parameters which are set as $\eta_k = 0.9$ and $p_{c,k} = 0.1$ mW, $\forall k$. Other important parameters are set as $\sigma^2 = -117$ dBm, $P_E = 40$ dBm, and $T_{\max} = 0.1$ s, unless specified otherwise.

A. SE versus PB Transmit Power

Fig. 2 illustrates the achievable throughput and energy consumption versus the PB transmit power, respectively. For comparison, two baseline schemes adopting TDMA and NOMA respectively are considered, where $\tau_0 = \frac{T_{\max}}{2}$ is set for both of them. This corresponds to the case that only $E_k^h = \frac{\eta_k P_E h_k T_{\max}}{2}$ Joule of energy is available for device k, i.e., energy constrained IoT networks. Yet, the UL WIT is still optimized for maximizing the SE. In Fig. 2 (a), the throughputs of both T-WPCN

[1]We note that NOMA may still be an appealing technology for delay-sensitive applications and for user fairness provisioning [7].
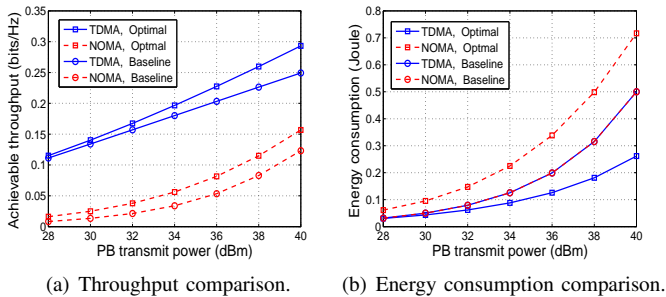
Fig. 2. Throughput and energy consumption versus PB transmit power.

Fig. 3. Throughput and energy consumption versus device circuit power.

and N-WPCN improve with P_{E}. This is intuitive since with larger P_{E}, the wireless powered IoT devices are able to harvest more energy during the DL WET and hence achieve a higher throughput in UL WIT. In addition, the baseline schemes suffer from a throughput loss in both TDMA and NOMA compared to the corresponding optimal scheme due to the fixed time allocation for DL WET, which implies that optimizing the DL WET duration is also important for maximizing the SE of wireless powered IoT networks. Furthermore, as suggested by Theorem 2, T-WPCN outperforms N-WPCN significantly and the performance gap between them becomes larger as P_{E} increase. This is because larger P_{E} will reduce the DL WET time and thereby leave more time for UL WIT. Since all the devices in N-WPCN are scheduled simultaneously for UL WIT, the circuit energy consumption will be significantly increased compared to that of T-WPCN, which thus leads to a larger performance gap. Fig. 2 (b) shows that N-WPCN is in general more energy demanding compared to T-WPCN for the optimal scheme, which verifies our theoretical finding in Theorem 1. Since $\tau_0 = \frac{T_{\max}}{2}$ is set for both the two baseline schemes, they have the same total energy consumption. In addition, when $P_{\mathrm{E}} = 28$ dBm, the energy consumption of optimal N-WPCN is close to that of optimal T-WPCN, which implies that device k, $\forall k$, basically harvests a similar amount of energy in the DL of T-WPCN and N-WPCN. As such, the substantial SE loss in Fig. 2 (a) indicates that a significant portion of the harvested energy is consumed by the circuit rather than for signal transmission, due to the simultaneous transmission feature of NOMA.

B. SE versus Device Circuit Power

Fig. 3 illustrates the throughput and energy consumption versus the device circuit power consumption, respectively. Several observations are made as follows. First, for $p_{\mathrm{c},k} = 0$ in Fig. 3 (a) and (b), T-WPCN and N-WPCN achieve the same throughput and energy consumption for $K = 10$ and $K = 50$, which coincides with our findings in Theorems 1 and 2. Second, for $K = 10$ and $K = 50$, the throughput and energy consumption for T-WPCN moderately decreases and increases with $p_{\mathrm{c},k}$, respectively, while those for N-WPCN decreases and increases sharply with $p_{\mathrm{c},k}$, respectively. This suggests that the performance of N-WPCN is sensitive to $p_{\mathrm{c},k}$. In fact, for T-WPCN, when a device suffers from a worse DL channel condition, the corresponding harvested energy is also less. Then, the device will be allocated a short UL WIT duration such that the energy causality constraint is satisfied. However, for N-WPCN, since all devices transmit in the UL simultaneously, to meet the energy causality of all the devices,
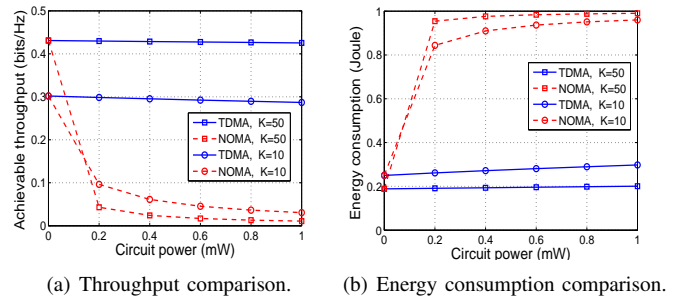
i.e., $(p_k + p_{\mathrm{c},k})\,\bar\tau_1 \le \eta_k P_{\mathrm{E}} h_k \tau_0 = \eta_k P_{\mathrm{E}} h_k (1 - \bar\tau_1),\ \forall k$, it follows that $\bar\tau_1 \le \frac{\eta_k P_{\mathrm{E}} h_k}{p_k + p_{\mathrm{c},k} + \eta_k P_{\mathrm{E}} h_k} \le \frac{\eta_k P_{\mathrm{E}} h_k}{p_{\mathrm{c},k} + \eta_k P_{\mathrm{E}} h_k},\ \forall k$. As can be seen, the UL WIT duration $\bar\tau_1$ is always limited by the worst DL channel gain of all devices for $p_{\mathrm{c},k} > 0$, a phenomenon termed "user bottleneck problem". In addition, concurrent transmissions also lead to higher circuit energy consumption. As a result, the throughput and energy consumption of N-WPCN are significantly reduced and increased, respectively, as $p_{\mathrm{c},k}$ increases. Third, given the "user bottleneck problem", it is expected that when K increases from 10 to 50, the performance of N-WPCN decreases in both Fig. 3 (a) and (b). In contrast, for T-WPCN, since the UL WIT duration of each user can be individually allocated based on the DL and UL channel gains of each device, multiuser diversity can be exploited to improve the performances as K increases from 10 to 50.

V. CONCLUSIONS

In this paper, we have answered a fundamental question: Does NOMA improve the SE and/or reduce the total energy consumption of the wireless powered IoT networks? By taking into account the circuit energy consumption of the IoT devices, we have found that N-WPCN is neither spectral efficient nor energy efficient, compared to T-WPCN. This suggests that NOMA may not be a practical solution for wireless IoT networks with energy constrained devices. The case with user fairness consideration is an interesting topic for future work.

REFERENCES

[1] "Nokia: Optimizing LTE for the internet of things," [Online] Available: https://novotech.com/docs/default-source/default-document-library/lte-m-optimizing-lte-for-the-internet-of-things.pdf?sfvrsn=0.
[2] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. Schober, "An overview of sustainable green 5G networks," *IEEE Wireless Commun. Mag.*, 2017, [Online] Available: https://arxiv.org/abs/1609.09773.
[3] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 418–428, Jan. 2014.
[4] ——, "Optimal resource allocation in full-duplex wireless-powered communication network," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3528 – 3540, Oct. 2014.
[5] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, "On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users," *IEEE Signal Process. Lett.*, vol. 21, no. 12, pp. 1501–1505, Jul. 2014.
[6] P. D. Diamantoulakis, K. N. Pappi, Z. Ding, and G. K. Karagiannidis, "Wireless-powered communications with non-orthogonal multiple access," *IEEE Trans. Wireless Commun.*, vol. 15, no. 12, pp. 8422–8436, Dec. 2016.
[7] H. Chingoska, Z. Hadzi-Velkov, I. Nikoloska, and N. Zlatanov, "Resource allocation in wireless powered communication networks with non-orthogonal multiple access," *IEEE Wireless Commun. Lett.*, vol. 5, no. 6, pp. 684–687, Dec. 2016.
[8] Y.-P. E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, and H. S. Razaghi, "A primer on 3GPP narrowband internet of things," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 117–123, Mar. 2017.