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Performance analysis for wireless-powered IoT networks with hybrid non-orthogonal multiple access

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Abstract

Aim: In this paper, we study a wireless-powered Internet of Things (IoT) network, where a hybrid access point (HAP) charges IoT devices with wireless energy transfer technology (WET) and collects their data by wireless information transfer (WIT).

Methods: To improve spectral efficiency, we propose a hybrid non-orthogonal multiple access (NOMA)-based transmission scheme. On the one hand, NOMA technology is applied for WIT. On the other hand, when some devices transmit data, the HAP can simultaneously charge the other devices, namely concurrent WET and WIT, such that the other devices can harvest more energy to achieve a better rate with some rate loss of these devices due to interference. How to divide devices into the interference and non-interference groups, namely *device grouping*, and how to pair devices, *e.g., device pairing*, becomes critical issues in terms of the achieved network throughput and fairness.

Results: We first formulate the network throughput maximization problem by optimizing the pairing and grouping policies. To simplify the analysis, we then investigate two specific hybrid NOMA-based transmission schemes. In the former, all devices are firstly paired based on the max–min criterion, where the "best" device is paired with the "worst" one, and then grouped in either ascending or descending order; this is referred to as the first-pairing-then-grouping (FPTG) scheme. In the latter, devices are first grouped and then paired; this is referred to as the first-grouping-then-pairing (FGTP) scheme. By applying the order statistics theory, we theoretically analyze the achieved network throughput and derive the corresponding pairing and grouping policies. Furthermore, we study the max–min fairness of the proposed hybrid NOMA-based scheme.

Conclusion: Simulation results validate the significant improvement of the proposed hybrid NOMA-based scheme in terms of network throughput and fairness.

Keywords: Wireless-powered IoT networks, non-orthogonal multiple access, order statistics theory, network throughput, max-min fairness

INTRODUCTION

Radio frequency (RF)-based energy harvesting technology is an emerging potential solution for providing continuous and sustainable energy supply to wireless devices over the air [1,2]. By employing it, a hybrid access point (HAP) charges devices in the downlink via wireless energy transfer (WET) and then collects data information from devices in the uplink, namely wireless information transfer (WIT). This framework is referred to as wireless-powered communication networks (WPCNs), and it is an emerging framework for sustainable wireless networking which has attracted much research attention in the past years.

Recently, many research works have investigated WPCNs [3–8], where the energy harvested from the RF energy source is used for information transmission of wireless devices. In [3], the key network architectures and technologies to build efficient WPCNs are summarized and some challenging research directions are pointed out. In [4], all devices first harvest radio energy broadcasted by the HAP in the downlink (DL), and then send their information to the HAP via the time division multiple access (TDMA) manner in the uplink (UL). The achieved network throughput of a WPCN is maximized in [5] subject to the energy causality, time duration, and quality-of-service (QoS) constraints, where the time allocated to WET and WIT is optimized. These works validate that WPCNs could significantly increase the network throughput and present a valuable opportunity to address the fundamental energy scarcity issue of wireless networks.

Non-orthogonal multiple access (NOMA) is an emerging and effective method to improve spectral efficiency and connectivity [9–11]. In [12], green transportation is introduced, the advantages of using backscatter communication and NOMA in the automotive industry 5.0 are discussed, and a multi-cell optimization framework is proposed to maximize the energy efficiency of a backscatter-enabled NOMA vehicle network. In [13], a joint NOMA optimization framework for small cell networks (SCNET) is proposed by exploiting the concept of multi-objective problems. In particular, the transmit power of the base station (BS) in each small cell is simultaneously optimized to maximize the total capacity and total energy efficiency (EE) of the SCNET. To maximize the network throughput of a WPCN, the NOMA transmission scheme is exploited in [9], where the transmit power of the HAP and the time allocation for WET and WIT are jointly optimized. In [10], two different decoding schemes with/without successive interference cancellation are proposed to maximize network throughput by optimizing the time and power allocation. The benefit of NOMA scheme is validated in [11] concerning network throughput, fairness, and energy efficiency. In [14], half-duplex and asynchronous downlink–uplink transmission are considered. The WET time, transmission power of devices, and decoding order are jointly optimized in [15] for a WPCN with NOMA.

Instead of network throughput, the network fairness issue of wireless-powered communication network is studied in [16–18]. In [16], it is shown that non-orthogonal access using a successive interference canceller (SIC) can significantly improve user fairness by increasing the throughput of cell edge users compared to orthogonal access. In [17], the fairness of uplink non-orthogonal multiple access (NOMA) and orthogonal multiple access (OMA) schemes are compared, and a fairness metric based on Jain's index is proposed to measure the asymmetry of multi-user channels. The single-input single-output (SISO) NOMA system is studied in [19]. The max–min power allocation problem for maximizing the minimum achievable user rate in clustered multiple-input multiple-output (MIMO) NOMA systems is studied in [18]. The authors of [20] designed power allocation algorithms to achieve fairness in NOMA-based cognitive radio (CR) transmissions for secondary users (SUS). However, to the best of our knowledge, most of the existing works in the literature investigate non-orthogonal information transmission, while how to explore the non-orthogonal transmission between WET and WIT as well as between WIT and WIT has not been thoroughly studied yet, which is the inspiration for this paper. In our previous work [21], a fairness-aware NOMA-based scheduling scheme is proposed for a wireless-powered IoT network, where the NOMA for concurrent WET and WIT is exploited, and the NOMA-based WIT is not taken into consideration.

In this paper, we propose a hybrid NOMA-based transmission scheme for wireless-powered IoT networks, in which NOMA for both simultaneous WET and WIT and simultaneous WIT of devices are jointly explored. To realize non-orthogonal WET and WIT, all devices are divided into two groups, namely the interference group and the non-interference group. Non-orthogonal WET and WIT are conducted during the transmission of devices in the former group, such that the WIT of these devices suffers the interference caused by simultaneous transmission. Thus, the device grouping policy becomes a significant issue in maximizing the network throughput and achieving network fairness. Meanwhile, to realize non-orthogonal WIT of devices, conventional NOMA technology is deployed, and the device pairing policy plays an important role. On this basis, we study the achieved throughput under two specific hybrid NOMA-based schemes, namely the first-pairing-then-grouping (FPTG) and first-grouping-then-pairing (FGTP) schemes. Devices are firstly paired based on their channel qualities, and then grouped in the FPTG policy, and vice versa in the FGTP policy. To analyze the achieved performance, we apply order statistics theory, and then optimal pairing and grouping are determined. Subsequently, we analyze the max–min fairness of the hybrid NOMA scheduling scheme by applying the FPTG and FGTP schemes. Devices are transmitted in the uplink in a non-orthogonal way, and the decoding order at the receiver determines the minimum rate of each pair of devices. We maximize the minimum rate of each pair of devices by adjusting the grouping and pairing devices to achieve maximum–minimum fairness. By simulation results, it is validated that significant network throughput gain and fairness are realized by the hybrid NOMA-based scheme.

SYSTEM MODEL AND PROBLEM FORMULATION

System model

In this paper, we study a WPCN, as illustrated in Figure 1, where $2N$ IoT devices are randomly deployed in the communication coverage of a hybrid access point (HAP) with radius r_e. Since IoT devices are energy-constrained, the HAP needs to first charge devices on the downlink by wireless energy transfer (WET) technology and then collect the data information from devices in the uplink, namely WIT. $R_n \in [0, r_e]$ denotes the charging and transmission distance between device n and the HAP.

Block fading channels are considered, which means the channel remains constant in a unit of time but varies in different time blocks. Suppose $L_0 d_0^\alpha / R_n^\alpha$ and g_n denote the large- and small-scale fading coefficients of the link between device n and the HAP, respectively, where L_0 and α denote the path loss and path loss exponent at the reference distance d_0. Meanwhile, the maximum transmit power at the HAP is $\bar{P}_s$. σ^2 denotes the noise variance at the HAP.

Hybrid NOMA transmission scheme

In a WPCN, devices far away from the HAP usually harvest less energy than those close to the HAP, leading to a lower transmission rate. Thus, it is necessary to improve the performance of remote devices with relatively poor channel quality. An alternative method is to supply more energy to devices by a longer WET time while keeping the same information transmission time. To achieve this, we can explore concurrent WET and WIT, namely

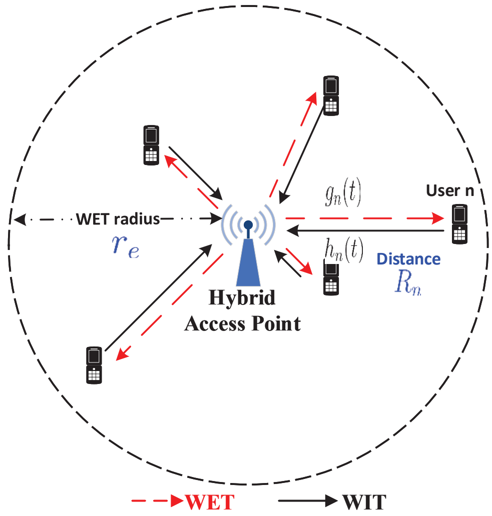

Figure 1. System model of NOMA-based WPCN.

Table 1. Notations and definitions

Notation	Definition
N	Number of IoT devices
r_e	The communication coverage of HAP
P_n	Charging and transmission distance between device n and HAP
α	Path loss exponent
d_0, L_0	Reference distance and reference path loss
g_n, h_n	Small-scale fading of WET and WIT channels
$\bar{P}_s$	Maximum transmit power of the PS
t_0, t_n	Transmission time of WET and WIT slot of device
m	Number of devices in $\mathcal{N}_0$
$\mu_{i,j}$	Whether devices i and j are paired
ν_n	group of device n
P_n	Transmit power of the PS in slot t_n
e_n	Harvested energy of device n in slot t_n
s_0, s_i, s_j	Signals transmitted by the HAP and devices i, j
$y_0^{i,j}$	The received signal at the HAP
z_0	Noise of device
η, σ^2	Energy conversion efficiency, and power of noise
$\gamma_{i,j}(m)$, $r_{i,j}(m)$	SNR and sum rate of paired devices i, j with m interfered devices
$f_R(r)$, $F_R(r)$	pdf and CDF of distance from HAP to device
$r_{(i),(j)}(m)$	Sum rate of ith and jth ordered devices
$f(r_{(i)}, r_{(j)})$	The pdf of ith and jth ordered devices

non-orthogonal energy and information transmission. This is because the energy and information signals are delivered by the HAP and devices, respectively. Note that the energy signal is regarded as an interfering signal that affects the information transmission of IoT devices. Meanwhile, NOMA technology can effectively improve the spectral efficiency and connectivity by allowing concurrent information transmission of multiple devices, such that we incorporate NOMA for WIT into a wireless-powered IoT network. To this end, we propose a hybrid NOMA transmission scheme for a WPCN, in which NOMA for both WIT and concurrent WET and WIT is exploited.

An example of time block structure is presented in Figure 2. The dedicated WET time is denoted as t_0, and the following time is equally divided into N time slots for WIT, where each slot with duration of $(1 - t_0)/N$ is used for the WIT of one pair of NOMA devices. Concerning the NOMA transmission for WIT, how to pair IoT devices becomes a significant issue. Meanwhile, to allow some devices to harvest more energy, WET is concurrently scheduled in the first m slots of NOMA-based WIT. Note that the non-orthogonal WET and WIT in the first m slot of WIT causes self-interference at the HAP, which degrades the rates of $2m$ devices

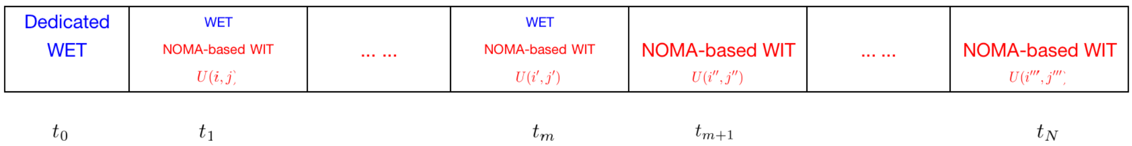

Figure 2. Time structure of NOMA-based WPCN.

scheduled in these slots. Accordingly, another critical issue is how to determine m and decide the group of devices scheduled in the first m slots of WIT.

According to the hybrid NOMA transmission scheme, all devices are divided into two groups, *i.e.,* the interference group of $|\mathcal{N}_0| = 2m$ devices and the non-interference group of $|\mathcal{N}_1| = 2N - 2m$ devices. Therefore, we define a binary $v_n \in \{0, 1\}$ to indicate the group of device n, where $v_n = 0$ means device n belongs to the interference group. For devices $n \in \mathcal{N}_0$, the total WET time is $t_0 + (m-1)(1-t_0)/N$, while, for devices $n \in \mathcal{N}_1$, the WET time is $t_0 + m(1 - t_0)/N$. If $m = 0$, the hybrid NOMA transmission scheme is degraded to the conventional transmission scheme with only NOMA for WIT. It is worth mentioning that, when the dedicated WET time is canceled, namely $t_0 = 0$, our proposed hybrid NOMA transmission scheme is still valid because devices can collect energy at the first m slots ($m > 0$).

In the dedicated WET slot, only the HAP transmits energy to charge all devices, such that the amount of energy harvested by device n is

$$e_{n,0} = \frac{t_0 \eta P_s L_0 d_0^{\alpha} |g_n|^2}{R_n^{\alpha}}, \forall n \in \mathcal{N}, \tag{1}$$

where η is the energy conversion efficiency and $\mathcal{N} = \{1, 2, \cdots, 2N\}$ is the set of devices.

In the WIT slot, according to the NOMA manner, two devices can simultaneously transmit information to the HAP. Define a binary variable $\mu_{i,j} \in \{0, 1\}$ to indicate whether devices i and j are paired for NOMA transmission or not. $\mu_{i,j} = 1$ means they are paired, and otherwise they are not paired. Thus, we have

$$\mu_{i,j} = \begin{cases} 1, & \text{if device i and j are paired,} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Note that, when $\mu_{i,j} = 1$, devices i and j must be in the same group, *i.e.,* $v_i = v_j$.

When devices $i \in \mathcal{N}_0$ and $j \in \mathcal{N}_0$ are paired to deliver their information, the HAP simultaneously transmits energy to charge all devices except devices i and j. Thus, the received signal at device n, $(n \neq i, j)$ is

$$y_n^{i,j} = \sqrt{\frac{\bar{P}_s L_0 d_0^{\alpha}}{R_n^{\alpha}}} g_n s_0 + \sqrt{P_i} h_{i,n} s_i + \sqrt{P_j} h_{j,n} s_l + z_n, \tag{3}$$

where s_0, s_i, and s_j denote the signals transmitted by PS and devices i and j, respectively; $\bar{P}_s$, P_i, and P_j denote the corresponding transmit power of PS and devices i and j; $h_{i,n}$ and $h_{j,n}$ denote the channel gain between devices n and i, j respectively; and z_n is the background noise. Since the transmit power of devices are usually much smaller than that of the HAP, the second and third terms in Equation (3) can be neglected concerning energy harvesting. Therefore, the amount of energy harvested by device i in this slot is

$$e_n^{i,j} = \frac{(1-t_0)}{N} \frac{\eta \bar{P}_s L_0 d_0^\alpha |g_n|^2}{R_n^\alpha}, \forall n \in \mathcal{N}, \text{ and, } n \notin \{i, j\}. \tag{4}$$

Based on the hybrid NOMA transmission scheme, the total WET times for devices in the interference and non-interference groups are $t_0 + (m-1)(1-t_0)/N$ and $t_0 + m(1-t_0)/N$, respectively. Thus, the total amount of harvested energy of device n is given by

$$e_n = \begin{cases} \frac{\eta[Nt_0+(m-1)(1-t_0)]\bar{P}_s L_0 d_0^\alpha |g_n|^2}{NR_n^\alpha}, & n \in \mathcal{N}_0, \\ \frac{\eta[Nt_0+m(1-t_0)]\bar{P}_s L_0 d_0^\alpha |g_n|^2}{NR_n^\alpha}, & n \in \mathcal{N}_1. \end{cases} \tag{5}$$

Given the transmission time $(1-t_0)/N$, the transmit power of device n is

$$P_n = \begin{cases} \frac{\eta[Nt_0+(m-1)(1-t_0)]\bar{P}_s L_0 d_0^\alpha |g_n|^2}{(1-t_0)R_n^\alpha}, & n \in \mathcal{N}_0, \\ \frac{\eta[Nt_0+m(1-t_0)]\bar{P}_s L_0 d_0^\alpha |g_n|^2}{(1-t_0)R_n^\alpha}, & n \in \mathcal{N}_1. \end{cases} \tag{6}$$

When devices i and j send information to the HAP simultaneously, the received signal at the HAP is

$$y_0^{i,j} = \begin{cases} \sqrt{\frac{P_i L_0 d_0^\alpha}{R_i^\alpha}} h_i s_i + \sqrt{\frac{P_j L_0 d_0^\alpha}{R_j^\alpha}} h_j s_j + \sqrt{\bar{P}_s} h_I s_0 + z_0, & i, j \in \mathcal{N}_0, \\ \sqrt{\frac{P_i L_0 d_0^\alpha}{R_i^\alpha}} h_i s_i + \sqrt{\frac{P_j L_0 d_0^\alpha}{R_j^\alpha}} h_j s_j + z_0, & i, j \in \mathcal{N}_1. \end{cases} \tag{7}$$

where h_I denotes the self-interference fading channel and z_0 is the noise with zero mean and variance σ^2 at the HAP. According to the NOMA transmission manner, the sum of signal-to-noise ratio (SINR) of devices i and j is

$$\gamma_{i,j}(m) = \begin{cases} \frac{\eta[Nt_0+(m-1)(1-t_0)]\bar{P}_s L_0^2 d_0^{2\alpha}}{(1-t_0)(P_{s,i}|h_I|^2+\sigma^2)} \cdot \left(\frac{|g_i|^2|h_i|^2}{R_i^\alpha} + \frac{|g_j|^2|h_j|^2}{R_j^\alpha}\right), i, j \in \mathcal{N}_0, \\ \frac{\eta[Nt_0+m(1-t_0)]\bar{P}_s L_0^2 d_0^{2\alpha}}{(1-t_0)\sigma^2} \cdot \left(\frac{|g_i|^2|h_i|^2}{R_i^\alpha} + \frac{|g_j|^2|h_j|^2}{R_j^\alpha}\right), i, j \in \mathcal{N}_1. \end{cases} \tag{8}$$

Thus, the achievable sum rate of paired devices i, j is

$$r_{i,j}(m) = \mathbf{E}\left[t_{i,j} \log_2\left(1 + \gamma_{i,j}(m)\right)\right]. \tag{9}$$

The practical sum rate of devices i, j is $\mu_{i,j}[\nu_i r_{i,j}(m) + (1-\nu_i) r_{i,j}(m)]$, which not only depends on the device paring policy $\mu_{i,j}$ but also relies on the device grouping policy ν_i, ν_j.

THROUGHPUT ANALYSIS OF HYBRID NOMA TRANSMISSION SCHEME

Problem formulation

In this paper, we focus on the network throughput under the hybrid NOMA transmission scheme by optimizing the device grouping and pairing policies. Thus, we can formulate the following network throughput maximization (NTM) problem

$$\max_{\mu,\nu,m} \quad \sum_{i=1}^{2N}\sum_{j=1}^{2N} \mu_{i,j}[\nu_i r_{i,j}(m) + (1-\nu_i) r_{i,j}(m)] \tag{10a}$$

$$s.t. C1 : \sum_{i=1}^{2N} \mu_{i,j} = 1, \forall j \in \mathcal{N}, \tag{10b}$$

$$C2 : \sum_{j=1}^{2N} \mu_{i,j} = 1, \forall i \in \mathcal{N}, \tag{10c}$$

$$C3 : \mu_{i,i} = 0, \forall i \in \mathcal{N}, \tag{10d}$$

$$C4 : \mu_{i,j} = \mu_{j,i}, \forall i, j \in \mathcal{N}, \tag{10e}$$

$$C5 : \mu_{i,j}(\nu_i - \nu_j) = 0, \forall i, j \in \mathcal{N}, \tag{10f}$$

$$C6 : \mu_{i,j} \in \{0, 1\}, \forall i, j \in \mathcal{N}, \tag{10g}$$

$$C7 : \nu_n \in \{0, 1\}, \forall n \in \mathcal{N}. \tag{10h}$$

In the above problem, the first four constraints are the limitation of device pairing policy concerning the NOMA transmission for WIT, which means that a device can be paired with only one other device except itself. Constraint C5 indicates that devices i and j must be in the same group, *i.e.*, $\nu_i = \nu_j$, if they are paired for NOMA transmission, namely $\mu_{i,j} = 0$.

The formulated optimization problem in Equation Equation (10) is an integer nonlinear programming problem, which is difficult to solve. To reduce the complexity, we investigate the achieved performance of two specific hybrid NOMA transmission schemes. In the former, devices are firstly paired based on their channel qualities, and then the device grouping is decided. In the latter, the device grouping policy is given based on their channel qualities, and then the device pairing policy is determined.

First-pairing-then-grouping scheme

In this subsection, the device pairing policy is first determined based on channel qualities, and then the devices are grouped; this is referred to as the first-pairing-then-grouping (FPTG) policy. Concerning the device pairing policy, we first need to sort all devices in descending order by their channel gains, and then pair the ordered devices based on the max–min pairing policy, which is best to maximize throughput. In the max–min policy, the first ordered device is paired with the $2N$th device, the second ordered device is paired with the $2N - 1$th device, and so on. Accordingly, there are N pairs of devices. Given the device pairing policy, the original problem in Equation Equation (10) can be reformulated as

$$\max_{\mu} \quad \sum_{i=1}^{2N}\sum_{j=1}^{2N} \mu^*_{(i),(j)}\nu_{(i)} \cdot r_{(i),(j)} + \mu^*_{(i),(j)}(1-\nu_{(i)}) \cdot r_{(i),(j)} \tag{11a}$$

$$s.t. C1 : \mu^*_{(i),(j)}(\nu_{(i)}-\nu_{(j)})=0, \forall i, j \in \{1, \cdots, 2N\}, \tag{11b}$$

$$C2 : \nu_{(i)} \in \{0, 1\}, \forall i \in \{1, \cdots, 2N\}. \tag{11c}$$

Then, for the device grouping policy, the basic idea is to allow m pairs of the device in the group $\mathcal{N}_0$ to transmit energy and data simultaneously, such that there are in total $\sum_{m=0}^{N} C_N^m = 2^N$ cases with a given device pairing policy. When $m = 0$, there is no concurrent transmission and all devices transmit in orthogonal time slots. For $m > 0$, as m increases, on the one hand, the achievable rate of the device increases due to more energy being collected, and, on the other hand, the rate of the device in $\mathcal{N}_0$ decreases due to the interference of the NOMA transmission. Thus, the key point is to decide the optimal m to maximize the network throughput.

To achieve this, we first need to analyze the achievable rate $r_{(i),(j)}$ of paired and ordered devices. When the HAP uses the maximum power $\bar{P}_s$ to charge devices, the achievable sum rate of the pair of (i, j)th ordered devices is

$$r_{(i),(j)} = \begin{cases} \frac{1-t_0}{N}\mathbf{E}[\log_2(1+\frac{a_{(i)}(m-1+\kappa)a_0}{bR_{(i)}^{2\alpha}}+\frac{a_{(j)}(m-1+\kappa)a_0}{bR_{(j)}^{2\alpha}}), & if\ \nu_{(i)}=0, \\ \frac{1-t_0}{N}\mathbf{E}[\log_2(1+\frac{a_{(i)}(m+\kappa)a_0}{R_{(i)}^{2\alpha}}+\frac{a_j(m+\kappa)a_0}{R_{(j)}^{2\alpha}}), & if\ \nu_{(i)}=1, \end{cases} \quad (12)$$

where $a_0 = \frac{\eta \bar{P}_s L_0^2 d_0^{2\alpha}}{\sigma^2}$, $a_{(i)} = |g_{(i)}|^2 |h_{(i)}|^2$, $a_{(j)} = |g_{(j)}|^2 |h_{(j)}|^2$, $b = 1 + \frac{\bar{P}_s |h_I|^2}{\sigma^2}$, $\kappa = \frac{N t_0}{1-t_0}$, $R_{(i)}$ is the ith smallest value of the communication distance $R_1, \cdots, R_{2N}$ of all devices, *i.e.*, $R_{(1)} \leq \cdots R_{(i)} \leq \cdots R_{(2N)}$. We then calculate the probability density function (pdf) of ordered random variables by applying the order statistic theory to analyze the achievable rate $r_{(i),(j)}$.

Proposition 1 *Let $X_1, X_2, ...X_n$ be n independent identically distributed (i.i.d.) random variables with a pdf of $f_X(x)$ and a cumulative distribution function (CDF) of $F_X(x)$. In general, we consider $X_1, X_2, ...X_n$ in the rth and sth smallest random variables $X_{(r)}$ and $X_{(s)}$, where $1 \leq r < s < n$. Then, the CDF and pdf of $X_{(r)}$ and $X_{(s)}$ are given by*

$$f_{(r),(s)}(x, y) = C_{r,s}[F(x)]^{r-1} f(x) \cdot [F(y) - F(x)]^{s-r-1} f(y)[1 - F(y)]^{n-s},$$

where $C_{r,s} = \frac{n!}{(r-1)!(s-r-1)!(n-s)!}$,

$$F_{(r),(s)}(x, y) = \sum_{i=s}^{n} \sum_{j=r}^{i} \frac{n!}{j!(i-j)!(n-i)!} [F(x)]^j \cdot [F(y) - F(x)]^{i-j} [1 - F(y)]^{n-i}.$$

According to Proposition1, we can calculate the achievable rate for each pair of ordered devices. We suppose that IoT devices are randomly deployed around a HAP with radius r_e. The probability density function (pdf) and cumulative distribution function (CDF) of the transmission distance between the devices and the HAP are $f_R(r) = \frac{2r}{r_e^2}$ and $F_R(r) = \frac{r^2}{r_e^2}$, respectively. Suppose that the pair of ith and jth ordered devices has $R_{(i)} < R_{(j)}$, and then the pdf of the transmission distance of i, j is

$$f(r_{(i)}, r_{(j)}) = C_{i,j} (\frac{r_i^2}{r_e^2})^{i-1} \frac{2r_i}{r_e^2} (\frac{r_i^2 - r_j^2}{r_e^2})^{j-i-1} \frac{2r_j}{r_e^2} (1 - \frac{r_j^2}{r_e^2})^{2N-j},$$

where $C_{i,j} = \frac{2N!}{(i-1)!(j-i-1)!(2N-j)!}$.

Thus, the achievable sum rate of the pair of ith and jth ordered devices in the interference group ($\nu_{(i)} = 0$) can be expressed as

$$r_{(i),(j)} = \frac{(N-1)!(1-t_0)}{(i-1)!(j-i-1)!(2N-j)!} \int_{r_i}^{r_e} \int_0^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{j-i-1} (r_e^2 - r_j^2)^{2N-j}}{r_e^{4N}} \cdot \log_2 \left(1 + \frac{a_{(i)}(m-1+\kappa)a_0}{br_{(i)}^{2\alpha}} + \frac{a_{(j)}(m-1+\kappa)a_0}{br_{(j)}^{2\alpha}}\right) dr_i dr_j, \tag{13}$$

Similarly, the achievable sum rate of ordered devices i and j in the non-interference group ($\nu_{(i)} = 1$) is expressed as

$$r_{(i),(j)} = \frac{(N-1)!(1-t_0)}{(i-1)!(j-i-1)!(2N-j)!} \int_{r_i}^{r_e} \int_0^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{j-i-1} (r_e^2 - r_j^2)^{2N-j}}{r_e^{4N}} \cdot \log_2 \left(1 + \frac{a_{(i)}(m+\kappa)a_0}{r_{(i)}^{2\alpha}} + \frac{a_{(j)}(m+\kappa)a_0}{r_{(j)}^{2\alpha}}\right) dr_i dr_j, \tag{14}$$

In the following part, we consider two cases.

Case I: The first m pairs of devices are grouped in the interference group and the remaining $N - m$ pairs are grouped in the non-interference group. Then, the achievable rate of the pair of $(i, 2N+1-i)$th ordered devices is given by Equation Equation (12), and the achievable network throughput is the total rate of all pairs, which is given by

$$\begin{aligned} r_{\text{sum}}(m) = & \sum_{i=1}^{m} \frac{(1-t_0)(N-1)!}{2(i-1)!(2N-2i)!} \int_{r_i}^{r_e} \int_0^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{2N-2i} (r_e^2 - r_j^2)^{i-1}}{r_e^{4N}} \cdot \log_2 \left(1 + \frac{a_{(i)}(m-1+\kappa)a_0}{br_i^{2\alpha}} + \frac{a_{(j)}(m-1+\kappa)a_0}{br_j^{2\alpha}}\right) dr_i dr_j \\ & + \sum_{i=m+1}^{N} \frac{(1-t_0)(N-1)!}{2(i-1)!(2N-2i)!} \int_{r_i}^{r_e} \int_0^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{2N-2i} (r_e^2 - r_j^2)^{i-1}}{r_e^{4N}} \cdot \log_2 \left(1 + \frac{a_{(i)}(m+\kappa)a_0}{r_i^{2\alpha}} + \frac{a_{(j)}(m+\kappa)a_0}{r_j^{2\alpha}}\right) dr_i dr_j, \end{aligned} \tag{15}$$

Accordingly, the network throughput maximization problem is to determine the optimal m^* according to the following problem

$$m^* = \arg\max_m r_{\text{sum}}(m). \tag{16}$$

To solve this, we study the effect of m on the achieved network throughput. When the number of devices in the interference group $\mathcal{N}_0$ increases from m to $m+1$, it means that the $(m+1, 2N-m)$th ordered pair of devices is moved from the non-interference group $\mathcal{N}_0$ to the interference group $\mathcal{N}_1$ and the incremental network throughput $\Delta r(m) = r_{sum}(m+1) - r_{sum}(m)$ includes not only the gain of devices other than the $(m+1, 2N-m)$ pair but also the loss of the $(m+1, 2N-m)$ pair due to interference. Thus, it can be rewritten as

$$\Delta r(m) = r_{\text{gain}}(m) - r_{\text{loss}}(m), \tag{17}$$

where $r_{\text{gain}}(m)$ and $r_{\text{loss}}(m)$ are given by

$$\begin{aligned} r_{\text{gain}}(m) = &\sum_{i=1}^{m} \frac{(1-t_0)(N-1)!}{2(i-1)!(2N-2i)!} \int_{r_i}^{r_e}\int_{0}^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{2N-2i}(r_e^2 - r_j^2)^{i-1}}{r_e^{4N}} \\ &\cdot \log_2\left(1+\frac{1}{\frac{br_i}{a_{(i)}a_0}+(m-1+\kappa)\frac{a_{(i)}r_j^{2\alpha}+a_{(j)}r_i^{2\alpha}}{a_{(i)}r_j^{2\alpha}}}+\frac{1}{\frac{br_j}{a_{(j)}a_0}+(m-1+\kappa)\frac{a_{(i)}r_j^{2\alpha}+a_{(j)}r_i^{2\alpha}}{a_{(j)}r_i^{2\alpha}}}\right)dr_i dr_j \\ &+ \sum_{i=m+2}^{N} \frac{(1-t_0)(N-1)!}{2(i-1)!(2N-2i)!} \int_{r_i}^{r_e}\int_{0}^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{2N-2i}(r_e^2 - r_j^2)^{i-1}}{r_e^{4N}} \\ &\cdot \log_2\left(1+\frac{1}{\frac{r_i}{a_{(i)}a_0}+(m+\kappa)\frac{a_{(i)}r_j^{2\alpha}+a_{(j)}r_i^{2\alpha}}{a_{(i)}r_j^{2\alpha}}}+\frac{1}{\frac{r_j}{a_{(j)}a_0}+(m+\kappa)\frac{a_{(i)}r_j^{2\alpha}+a_{(j)}r_i^{2\alpha}}{a_{(j)}r_i^{2\alpha}}}\right)dr_i dr_j, \end{aligned} \tag{18}$$

$$\begin{aligned} r_{\text{loss}}(m) = &\frac{(1-t_0)(N-1)!}{2(i-1)!(2N-2i)!} \int_{r_i}^{r_e}\int_{0}^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{2N-2i}(r_e^2 - r_j^2)^{i-1}}{r_e^{4N}} \\ &\cdot \log_2\left(b+\frac{1-b}{1+\frac{a_{(m+1)}a_0(m+\kappa)}{br_{(m+1)}^{(2\alpha)}}+\frac{a_{(2N-m)}a_0(m+\kappa)}{br_{(2N-m)}^{2\alpha}}}\right)dr_i dr_j, \end{aligned} \tag{19}$$

According to Equation (18) and Equation (19), it can be concluded that the throughput gain $r_{\text{gain}}(m)$ decreases monotonically as the number of devices m in $\mathcal{N}_0$ increases, while the throughput loss $r_{\text{loss}}(m)$ increases monotonically with m. Thus, the throughput increment $\Delta r(m)$ decreases monotonically with m. It is easy to derive that the achievable network throughput first increases and then decreases with m.

Case II: The later m pairs of devices are grouped in the interference group and the remainder $N-m$ pairs are grouped in the non-interference group. Thus, the achievable network throughput is expressed as

$$\begin{aligned} r_{\text{sum}}(m) = &\sum_{i=1}^{N-m} \frac{(1-t_0)(N-1)!}{2(i-1)!(2N-2i)!} \int_{r_i}^{r_e}\int_{0}^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{2N-2i}(r_e^2 - r_j^2)^{i-1}}{r_e^{4N}} \\ &\cdot \log_2\left(1+\frac{a_{(i)}(m+\kappa)a_0}{r_i^{2\alpha}}+\frac{a_{(j)}(m+\kappa)a_0}{r_j^{2\alpha}}\right)dr_i dr_j \\ &+ \sum_{i=N-m+1}^{N} \frac{(1-t_0)(N-1)!}{2(i-1)!(2N-2i)!} \int_{r_i}^{r_e}\int_{0}^{r_e} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{2N-2i}(r_e^2 - r_j^2)^{i-1}}{r_e^{4N}} \\ &\cdot \log_2\left(1+\frac{a_{(i)}(m-1+\kappa)a_0}{br_i^{2\alpha}}+\frac{a_{(j)}(m-1+\kappa)a_0}{br_j^{2\alpha}}\right)dr_i dr_j, \end{aligned} \tag{20}$$

In this case, when m increases to $m+1$, it means that the $(N-m)$th pair of devices moves from the non-interference group $\mathcal{N}_1$ to the interference group $\mathcal{N}_0$. As in Case I, the achievable network throughput first increases and then decreases as m increases. When devices with poor channel conditions are interfered with, the throughput gain of the other devices is greater than their throughput loss, which leads to an increase in network throughput. However, if devices with good channel quality are moved to the interfering group, the throughput gain decreases and is smaller than the throughput loss, so the network throughput decreases.

First-grouping-then-pairing scheme

In this subsection, the device grouping policy is first determined based on channel qualities, and then the devices are paired; this is referred to as the first-grouping-then-pairing (FGTP) policy. We first sort all devices in descending order based on their channel gains. Concerning the grouping policy, we consider two cases: **Case I**, the $2m$ devices with good channel conditions are first grouped in the interference group and the remaining $2N-2m$ devices are grouped in the non-interference group; and **Case II**, the last $2m$ devices with poor channel conditions are first grouped in the interference group and the remaining $2N-2m$ devices are grouped in the non-interference group. To maximize the network throughput, the max–min pairing policy is then performed for each group.

Case I: The ith ordered device ($i \leq 2m$) is paired with the $(2m+1-i)$th ordered device in the $\mathcal{N}_0$ group, and the ith ordered device ($i > 2m$) is paired with the $(2N+2m+1-i)$th ordered device in the $\mathcal{N}_1$ group. Then, the achievable sum rate of all paired devices can be obtained:

$$\begin{aligned} r_{\text{sum}}(m)=&\sum_{i=1}^{m}\frac{(1-t_0)(N-1)!}{(i-1)!(2m-2i)!(2N-2m-1-i)!}\int_{r_i}^{r_e}\int_0^{r_e}\frac{4r_i^{2i-1}r_j(r_j^2-r_i^2)^{2m-2i}(r_e^2-r_j^2)^{2N-2m-1-i}}{r_e^{4N}} \\ &\cdot\log_2\Big(1+\frac{a_{(i)}(m-1+\kappa)a_0}{br_i^{2\alpha}}+\frac{a_{(j)}(m-1+\kappa)a_0}{br_j^{2\alpha}}\Big)dr_i dr_j \\ &+\sum_{i=2m+1}^{N+m}\frac{(1-t_0)(N-1)!}{(i-1)!(2N+2m-2i)!(i-2m-1)!}\int_{r_i}^{r_e}\int_0^{r_e}\frac{4r_i^{2i-1}r_j(r_j^2-r_i^2)^{2N+2m-2i}(r_e^2-r_j^2)^{i-2m-1}}{r_e^{4N}} \\ &\cdot\log_2\Big(1+\frac{a_{(i)}(m+\kappa)a_0}{r_i^{2\alpha}}+\frac{a_{(j)}(m+\kappa)a_0}{r_j^{2\alpha}}\Big)dr_i dr_j, \end{aligned} \tag{21}$$

Case II: The ith ordered device ($i > 2N-2m$) is paired with the $(4N+1-2m-i)$th ordered device in the $\mathcal{N}_0$ group, and the ith ordered device ($i \leq 2N-2m$) is paired with the $(2N+1-2m-i)$ ordered device is paired. Then, the achievable sum rate of all paired devices can be obtained:

$$\begin{aligned} r_{\text{sum}}(m)=&\sum_{i=1}^{N-m}\frac{(1-t_0)(N-1)!}{(i-1)!(2N-2m-2i)!(2m-1+i)!}\int_{r_i}^{r_e}\int_0^{r_e}\frac{4r_i^{2i-1}r_j(r_j^2-r_i^2)^{2N-2m-2i}(r_e^2-r_j^2)^{2m-1+i}}{r_e^{4N}} \\ &\cdot\log_2\Big(1+\frac{a_{(i)}(m+\kappa)a_0}{r_i^{2\alpha}}+\frac{a_{(j)}(m+\kappa)a_0}{r_j^{2\alpha}}\Big)dr_i dr_j \\ &+\sum_{i=2N-2m+1}^{2N-m}\frac{(1-t_0)(N-1)!}{(i-1)!(4N-2m-2i)!(2m+i-1-2N)!}\int_{r_i}^{r_e}\int_0^{r_e}\frac{4r_i^{2i-1}r_j(r_j^2-r_i^2)^{4N-2m-2i}(r_e^2-r_j^2)^{2m+i-1-2N}}{r_e^{4N}} \\ &\cdot\log_2\Big(1+\frac{a_{(i)}(m-1+\kappa)a_0}{br_i^{2\alpha}}+\frac{a_{(j)}(m-1+\kappa)a_0}{br_j^{2\alpha}}\Big)dr_i dr_j, \end{aligned} \tag{22}$$

To this end, the problem is to determine the number of devices in the interference group, namely $2m$.

FAIRNESS ANALYSIS OF THE HYBRID NOMA TRANSMISSION SCHEME

In WPCNs, devices far away from the HAP harvest less energy compared to devices close to the HAP, but they need to transmit at higher power in order to achieve a specific rate, which can lead to a double near–far effect. The double near–far effect causes serious fairness issues in wireless-powered IoT networks. Therefore, in this section, we analyze the fairness of the hybrid NOMA transmission scheme by determining the device grouping and pairing policies. Here, we focus on the max–min fairness to unveil the effect of the double near–far problem in wireless-powered IoT networks.

In the WIT phase, device i and device j send their information to the HAP at the same time, and the received signal at the HAP is given in Equation (7).

At the HAP, the messages of two users are decoded using successive interference cancellation (SIC). To achieve max–min fairness, the decoding order of the HAP for users i, j is critical. Assuming that device i has better channel conditions than device j, and in order to achieve a greater rate for device j with worse channel conditions, the minimum achievable rate (denoted as $r_{min}^{i,j}$) of evices i, j can be divided into the following two cases.

In the first case, the HAP first decodes the signal sent by device i and subtracts its components from the received signal, and can then subsequently decode the signal sent by device j without signal interference from device i. In this case, the achievable rates for i and j are $r_i = \frac{1-t_0}{N}\mathbf{E}[1 + \frac{\gamma_i}{1+\gamma_j}]$ and $r_j = \frac{1-t_0}{N}\mathbf{E}[\log_2(1+\gamma_j)]$, respectively. The minimum rate is $r_{min}^{i,j} = log_2(1+\gamma_i)$, which must satisfy

$$log_2(1+\gamma_i) \leq log_2(1+\frac{\gamma_j}{\gamma_i+1}) \tag{23}$$

In the second case, HAP decodes the signals sent by i, j simultaneously, in which case the achievable rates for i and j are $r_i = r_j = \frac{1-t_0}{N}\mathbf{E}[\frac{1}{2}\log_2(1+\gamma_i+\gamma_j)]$. The minimum rate id $r_{min}^{i,j} = \frac{1}{2}log_2(1+\gamma_i+\gamma_j)$, which must satisfy

$$\begin{aligned} log_2(1+\gamma_i) > log_2(1+\frac{\gamma_j}{\gamma_i+1}) \\ log_2(1+\gamma_j) > log_2(1+\frac{\gamma_i}{\gamma_j+1}) \end{aligned} \tag{24}$$

After calculation, the minimum rate achievable for each pair of devices i, j (denoted as $r_{min}^{i,j}$) can be expressed as

$$r_{min}^{i,j}(m) = \begin{cases} \frac{1-t_0}{N}\mathbf{E}[\log_2(1+\gamma_j)], & if\ \gamma_i \geq \gamma_j^2+\gamma_j, \\ \frac{1-t_0}{N}\mathbf{E}[\frac{1}{2}\log_2(1+\gamma_i+\gamma_j)], & if\ \gamma_i < \gamma_j^2+\gamma_j, \end{cases} \tag{25}$$

Thus, we can express this max–min fairness problem as

$$\begin{aligned}
\max_{\mu,\nu,m} \max_{\forall i\in\mathcal{N}, j\in\mathcal{N}} \quad & min\{\nu_i\mu_{i,j}r^{i,j}_{min}(m), (1-\nu_i)\mu_{i,j}r^{i,j}_{min}(m)\} && (26a)\\
s.t. \quad & C1: r_i \le log_2(1+\gamma_i), && (26b)\\
& C2: r_j \le log_2(1+\gamma_j), && (26c)\\
& C3: r_i + r_j \le log_2(1+\gamma_i+\gamma_j), && (26d)\\
& C4: \mu_{i,i} = 0, \forall i \in \mathcal{N}, && (26e)\\
& C5: \mu_{i,j} = \mu_{j,i}, \forall i, j \in \mathcal{N}, && (26f)\\
& C6: \mu_{i,j}(\nu_i - \nu_j) = 0, \forall i, j \in \mathcal{N}, && (26g)\\
& C7: \mu_{i,j} \in \{0,1\}, \forall i, j \in \mathcal{N}, && (26h)\\
& C8: \nu_i \in \{0,1\}, \forall n \in \mathcal{N}. && (26i)
\end{aligned}$$

As in the problem in Equation (10), to solve the problem in Equation (26), we investigate the fairness performance under two specific hybrid NOMA transmission schemes, namely FPTG and FGTP.

First-pairing-then-grouping scheme

In this subsection, the FPTG policy is considered. Firstly, all devices are required to be sorted according to their channel gains from highest to lowest, and the sorted devices are paired according to the max–min pairing policy, *i.e.,* the ith device is paired with the $2N+1-i$th device. After pairing, m pairs of devices are grouped into the interference group and the remaining $N-m$ pairs are grouped into the non-interference group. The basic idea is to allow m pairs of devices grouped into the interference group $\mathcal{N}_0$ to transmit energy and data at the same time, by sacrificing the rate of devices in the interference group and increasing the rate of devices in the non-interference group. Therefore, the key in the FPTG policy is to decide the pair of devices to be classified in the interference group as well as the optimal m so that the device with the lowest rate in both groups can reach the maximum.

The first step is to decide the devices to be divided in the interference group. Based on the basic idea of improving network fairness, the device with the higher minimum rate should be assigned to the interference group to suffer from WET interference, and the rate of the worse performing device in the non-interference group is improved at the expense of the rate of the better device. Therefore it is important to determine which device pairs have higher minimum rates. Figure 3 compares the minimum rates of devices performing non-orthogonal transmission in descending order according to channel conditions and performing max–min pairing for different numbers of device pairs N. Figure 3 shows that the trend of the minimum rate curves of the devices under various N increases first and then decreases slowly as the sequence number of ordered devices increases, with the peak always occurring at the backward device pair. Subsequently, according to this conclusion, under the FPTG strategy, the latter m pairs of ordered devices should be put into the interference group and the former $N-m$ pairs of ordered devices should be placed into the non-interference group. Finally, the optimal m should be determined so that the minimum rates of the two groups of devices are maximized.

To determine the optimal m, first it is necessary to analyze the minimum achievable rate $r^{(i),(j)}_{min}$ for each pair of ordered devices. Assuming that the HAP uses the maximum power $\bar{P}_s$ to charge the devices, the minimum achievable rate for the ordered devices (i,j) paired in the $\mathcal{N}_0$ group can be expressed as

$$r^{(i),(j)}_{min} = \begin{cases} \frac{1-t_0}{N}\mathbf{E}[\log_2(1+\frac{a_{(j)}(m-1+\kappa)a_0}{bR^{2\alpha}_{(j)}})], & if\ R_{(i)} \le \sqrt[2\alpha]{\frac{ba_{(i)}R^{4\alpha}_{(j)}}{a_j(bR^{2\alpha}_{(j)}+a_{(j)}(m-1+\kappa)a_0)}} \\ \frac{1-t_0}{N}\mathbf{E}[\frac{1}{2}\log_2(1+\frac{a_{(i)}(m-1+\kappa)a_0}{bR^{2\alpha}_{(i)}}+\frac{a_j(m-1+\kappa)a_0}{bR^{2\alpha}_{(j)}})], & if\ R_{(i)} > \sqrt[2\alpha]{\frac{ba_{(i)}R^{4\alpha}_{(j)}}{a_j(bR^{2\alpha}_{(j)}+a_{(j)}(m-1+\kappa)a_0)}} \end{cases} \quad (27)$$

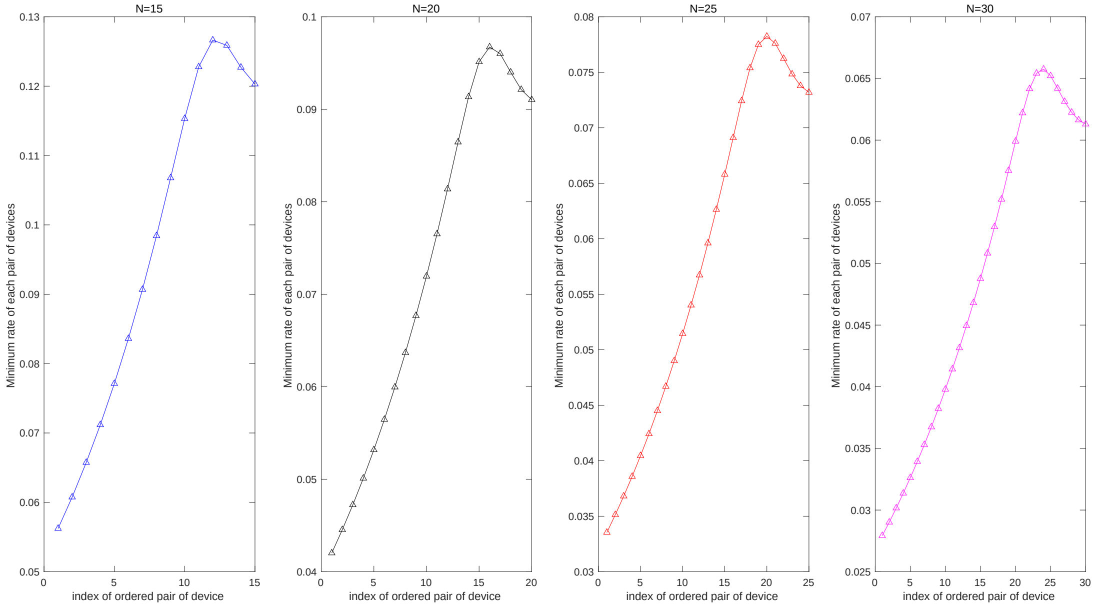

Figure 3. The minimum rate of non-orthogonal transmission for each pair of devices at different N.

The minimum achievable rate for the paired ordered devices (i, j) in the $\mathcal{N}_1$ group is

$$r_{min}^{(i),(j)} = \begin{cases} \frac{1-t_0}{N}\mathbf{E}[\log_2(1+\frac{a_{(j)}(m+\kappa)a_0}{R_{(j)}^{2\alpha}})], & if\ R_{(i)} \leq \sqrt[2\alpha]{\frac{ba_{(i)}R_{(j)}^{4\alpha}}{a_j(bR_{(j)}^{2\alpha}+a_{(j)}(m-1+\kappa)a_0)}}, \\ \frac{1-t_0}{N}\mathbf{E}[\frac{1}{2}\log_2(1+\frac{a_{(i)}(m+\kappa)a_0}{R_{(i)}^{2\alpha}}+\frac{a_j(m1+\kappa)a_0}{R_{(j)}^{2\alpha}})], & if\ R_{(i)} > \sqrt[2\alpha]{\frac{ba_{(i)}R_{(j)}^{4\alpha}}{a_j(bR_{(j)}^{2\alpha}+a_{(j)}(m-1+\kappa)a_0)}}, \end{cases} \tag{28}$$

According to proposition1, the achievable minimum rate of the pair of ith and jth ordered devices in the interference group $\mathcal{N}_0$ can be expressed as

$$\begin{aligned} r_{(i),(j)} = & \frac{(N-1)!(1-t_0)}{(i-1)!(j-i-1)!(2N-j)!}\Big[\iint\limits_{D_1}\frac{4r_i^{2i-1}r_j(r_j^2-r_i^2)^{j-i-1}(r_e^2-r_j^2)^{2N-j}}{r_e^{4N}}\log_2(1+\frac{a_{(j)}(m-1+\kappa)a_0}{br_{(j)}^{2\alpha}})dr_idr_j \\ & +\frac{1}{2}\iint\limits_{D_2}\frac{4r_i^{2i-1}r_j(r_j^2-r_i^2)^{j-i-1}(r_e^2-r_j^2)^{2N-j}}{r_e^{4N}}\log_2(1+\frac{a_{(i)}(m-1+\kappa)a_0}{br_{(i)}^{2\alpha}}+\frac{a_{(j)}(m-1+\kappa)a_0}{br_{(j)}^{2\alpha}})dr_idr_j\Big] \end{aligned} \tag{29}$$

The achievable minimum rate of the pair of ith and jth ordered devices in the non-interference group $\mathcal{N}_1$ can be expressed as

Table 2. Simulation parameters

Simulation parameter	Value
2N	40
r_e	20 m
L_0	0.1
d_0	1 m
α	3
σ^2	-79 dBm
$\bar{P}_s$	1
Interference channel	-63 dBm
t_0, t_n	1/N+1

$$r_{(i),(j)} = \frac{(N-1)!(1-t_0)}{(i-1)!(j-i-1)!(2N-j)!}\Big[\iint_{D_1} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{j-i-1}(r_e^2 - r_j^2)^{2N-j}}{r_e^{4N}} \log_2(1+\frac{a_{(j)}(m+\kappa)a_0}{r_{(j)}^{2\alpha}}) dr_i dr_j + \frac{1}{2}\iint_{D_2} \frac{4r_i^{2i-1} r_j (r_j^2 - r_i^2)^{j-i-1}(r_e^2 - r_j^2)^{2N-j}}{r_e^{4N}} \log_2(1+\frac{a_{(i)}(m+\kappa)a_0}{r_{(i)}^{2\alpha}} + \frac{a_{(j)}(m+\kappa)a_0}{r_{(j)}^{2\alpha}}) dr_i dr_j\Big] \tag{30}$$

where $a_0 = \frac{\eta \bar{P}_s L_0^2 d_0^{2\alpha}}{\sigma^2}$, $a_{(i)} = |g_{(i)}|^2 |h_{(i)}|^2$, $a_{(j)} = |g_{(j)}|^2 |h_{(j)}|^2$, $b = 1 + \frac{\bar{P}_s |h_I|^2}{\sigma^2}$, $\kappa = \frac{Nt_0}{1-t_0}$, $D_i : r_i \in \left[0, \sqrt[2\alpha]{\frac{ba_{(i)} r_j^{4\alpha}}{a_j (br_j^{2\alpha} + a_{(j)}(m-1+\kappa)a_0)}}\right]$, and $D_j : r_i \in \left(\sqrt[2\alpha]{\frac{ba_{(i)} r_j^{4\alpha}}{a_j (br_j^{2\alpha} + a_{(j)}(m-1+\kappa)a_0)}}, r_j\right)$.

First-grouping-then-pairing scheme

In this subsection, we consider the FGTP strategy. We first sort all devices in descending order based on channel gain. Then, the $2m$ devices with good channel conditions are assigned to the interference group and the remaining $2N - 2m$ devices are assigned to the non-interference group. Finally, the max–min pairing strategy is executed for each group. In this way, with a given FGTP policy, as the charging time increases, the non-interfering group of IoT devices with poor channel conditions all collect more energy to achieve higher data rates, but at the cost of lower rates for the devices in the $\mathcal{N}_0$ group with better channel conditions. This can significantly improve fairness. Therefore, we need to decide the number of devices to be grouped in the interference group to maximize the minimum rate of the two groups of devices.

PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed hybrid NOMA-based transmission scheme. We set the number of users as $2N = 40$ and the WET radius as r_e=20 m. The reference path loss L_0 is 0.1 at the reference distance d_0=1 m, the path loss exponent α is 3, the noise power σ^2 is −70 dBm, the energy conversion efficiency η is 0.5, and the maximum transmit power of P_s is 1, *i.e.*, $\bar{P}_s = 1$. The strength of the interference channel is about −63 dBm. For the time allocation, we set the dedicated WET time the same as the WIT time assigned to each user, *i.e.*, $t_0 = t_n = \frac{1}{N+1}$.

Throughput of the hybrid NOMA scheme

In Figure 4, we compare the throughput of the four policies using analytical and simulation methods, respectively. The simulation results follow the same trend as the computed results, and they fluctuate above and below the theoretical results. Notice that, when $m = 0$, the proposed schemes are degraded compared to the conventional NOMA scheme with non-orthogonal information transmission. As is shown, the proposed hybrid NOMA-based scheme performs better than the conventional NOMA scheme. The max–min pairing is always optimal in terms of achieving network throughput maximization. The FPGA policy is always the strongest and weakest pairing in terms of channel conditions, while the FGTP policy changes the pairing device according to

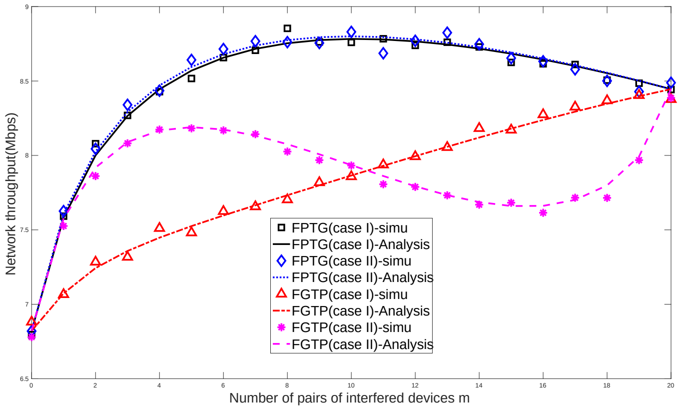

Figure 4. Network throughput comparison.

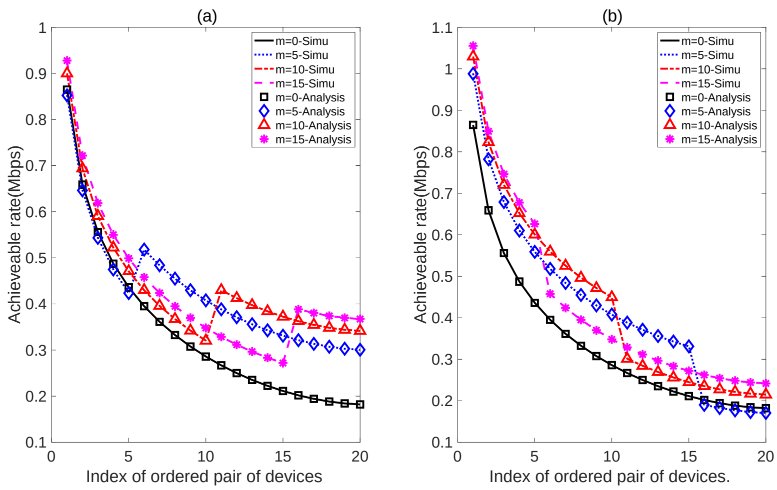

Figure 5. Rate of each pair devices under FPTG policy (a) Case I (b) Case II.

the m. Therefore, the FPTG policy is superior to FGTP in terms of achieving network throughput maximization. The simulation results verify this conclusion. It is observed that the network throughput of the FPTG scheme under both cases is close, and much better than those of the FGTP scheme. In addition, the network throughput of the FPTG scheme increases and then decreases with m, which is consistent with Equation (18) and Equation (19), and reaches the maximum throughput when $m = 10$.

Figure 5 and Figure 6 present the rate of each device for the FPTG and FGTP schemes under two cases, respectively. If $m = 0$, the scheme (noted as the black line) degrades to the conventional NOMA-based scheduling scheme. When we rank all devices in descending order of channel quality, the rate of the ranked devices decreases monotonically as well, where there exists a great difference between the rate of the highest device and lowest device. Devices with poorer channels have significantly lower rates.

Figure 5(a) and Figure 6(a) show the case where m pairs of devices with better channel conditions are assigned to the interference group, *i.e.*, devices with good channels are allowed to transmit energy concurrently with the data transmission. Thus, the achievable rates of the devices with poorer channels are improved by harvesting more energy at the cost of a reduced rate for the devices with good channel conditions. It can be seen that the

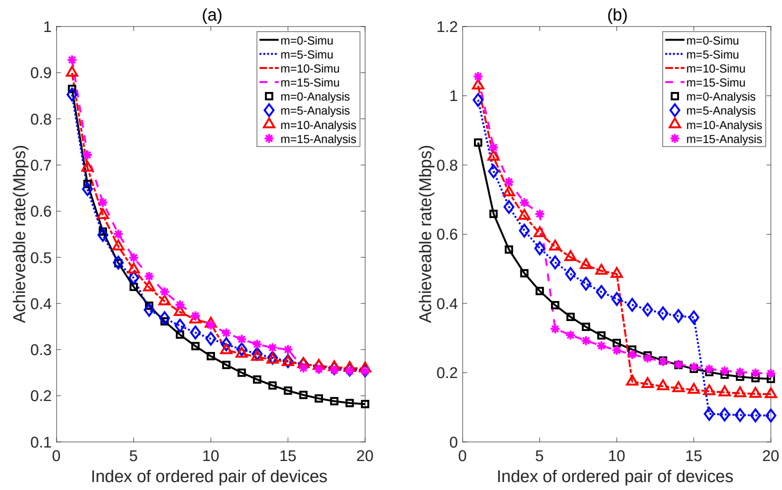

Figure 6. Rate of each pair devices under FGTP policy (a) Case I (b) Case II.

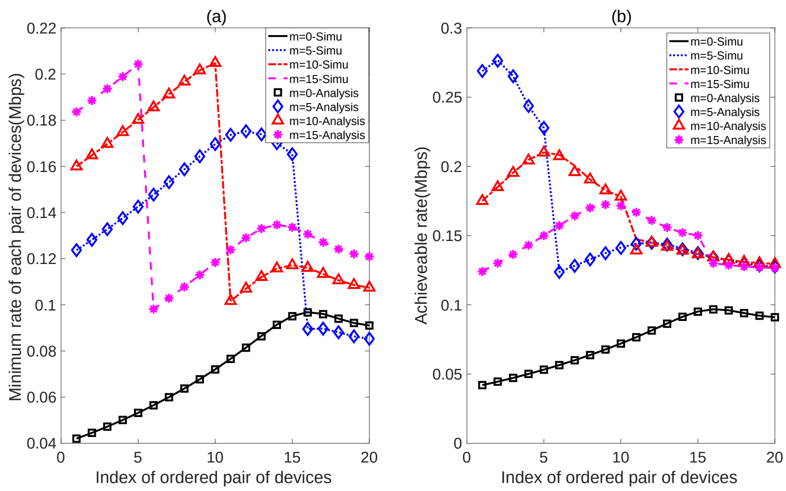

Figure 7. Minimum rate of each pair of devices (a) FPTG (b) FGTP.

gain in the interference group is significant under the FPTG scheme, as shown in Figure 5(a), while the gain in the interference group is not as significant under the FGTP policy, as shown in Figure 6(a), but the network throughput is improved under both policies.

Figure 5(b) and Figure 6(b) show the situation where the m pairs of devices with poor channel conditions are assigned to the interference group. The last m ordered pairs with poor channel conditions suffer a small rate loss due to interference, while the first $N-m$ ordered pairs with relatively good channel conditions gain a larger rate due to harvesting more energy. As a result, the throughput of the network is improved. Comparing the FPTG scheme represented in Figure 5(b) with the FGTP scheme in Figure 6(b), both have relatively significant gains in the non-interference group, while at the same time the latter has a larger rate loss for the devices in the interference group.

In Figure 6(a), the rate of the devices in the non-interference group remains basically the same at different m. The rate of the devices in the interference group increases slightly with the increase of m. Therefore, in the case of FGTP indicated by the purple line in Figure 4, the sum rate increases with the increase of m. In Figure 6(b), the rate loss of devices in the interference group is relatively obvious, and when m is small, the number of devices in the interference group and the impact on the sum rate are also small, so the sum rate first keeps increasing. As m increases, the devices in the interference group increase, the impact on the sum rate becomes larger, and the sum rate starts to show a decreasing trend. As m increases further, it can be seen that the devices in the interference group are not as affected due to the charging time also increasing significantly, while the gain of the non-interference group is significant, and so the sum rate subsequently increases. Thus, in the case of FGTP Case II indicated by the red line in Figure 4, the sum rate increases, decreases, and then increases again with increasing m.

Fairness of hybrid NOMA scheme

We then evaluate the max–min fairness of the proposed hybrid NOMA transmission scheme under two strategies. The achievable minimum rate of each pair of ordered devices under each strategy is shown in Figure 7. The simulation results are consistent with our analysis. When $m = 0$, the fairness-based NOMA scheme (indicated by the black line) is degraded to the traditional TDMA-based scheduling scheme. The minimum rate of each pair of devices indicated by the black line is relatively small, and the network fairness is poor. Under our proposed max–min fairness scheme, the minimum rate achievable by each group of devices is better than the minimum rate under TDMA, and the fairness of the network is improved. In particular, under the FGTP strategy, since devices with good channels are allowed to transmit energy at the same time as data transmission, the achievable rate for devices with poor channels is improved by harvesting more energy. Therefore, the minimum rate of the device is significantly increased.

In Figure 8, we show the minimum rate of all IoT devices under different number m of interfering devices. Figure 8(a) shows the variation of the minimum rate with m in the FPTG policy. It can be seen that the minimum rate of the devices in both groups increases due to longer charging time when m is small. As m increases, the minimum rate of the devices in the interference group $\mathcal{N}_0$ decreases due to suffering a larger interference rate.

For the FGTP strategy shown in Figure 8(b), the minimum rate of devices in the interference group $\mathcal{N}_0$ decreases monotonically with m due to interference, while the minimum rate of devices in the non-interference group $\mathcal{N}_1$ increases monotonically with m due to longer charging time.

Figure 9 compares the minimum rates of m for all devices under the two strategies. The minimum achievable rate of each pair of devices in the FGTP policy is always higher than that of the FPTG since the channel condition of the worse one $((2m + 1 - i)$th) in each pair of devices is stronger than that of the worse one $((2N + 1 - i)$th) in the FGTP policy for any m $(m < 2N)$ of the devices that are assigned to the interference group. The figure verifies this conclusion. Obviously, the performance under the FGTP strategy represented by the red line is stronger than that under FPTG represented by the blue line. The optimal scheme is $m = 9$ under the FGTP policy.

CONCLUSION

In this paper, we propose a hybrid NOMA-based transmission scheme to maximize the network throughput of a wireless-powered IoT network, in which the NOMA for both simultaneous WET and WIT and simultaneous WIT of devices are jointly explored. We apply the order statistics theory to analyze the optimal device pairing and grouping policies of the hybrid NOMA scheme in terms of network throughput and fairness, respectively. Simulation results are consistent with the analysis and verify the significant gain of the proposed hybrid NOMA-based transmission scheme. In the future, this work could be extended to multi-cell wireless-powered IoT networks with mobility.

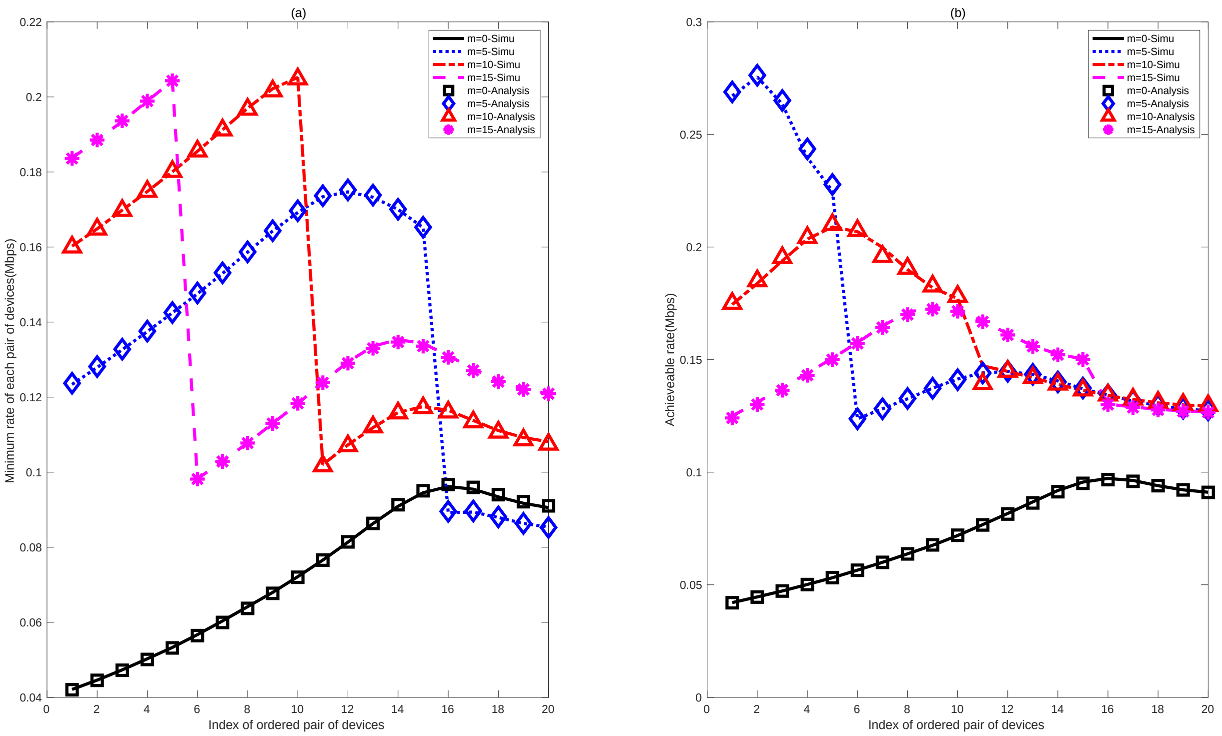

Figure 8. Minimum rates of devices in $\mathcal{N}_0$ and $\mathcal{N}_1$ (a) FPTG (b) FGTP.

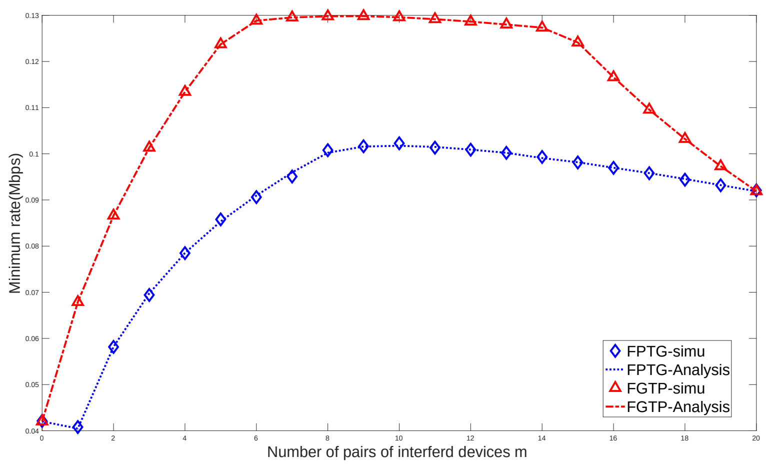

Figure 9. Minimum rate comparison

DECLARATION

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Authors' contributions
Made substantial contributions to conception and design of the study and performed data analysis and interpretation: Qi HW, Zhang H
Writing of the original draft preparation: Qi HW, revision of the manuscript: Peng YS, Zhang H
All authors have read and agreed to the published version of the manuscript.

Availability of data and materials
Not applicable.

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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