Nonlinear energy harvesting and clustering cooperation in WPCNs

Lina Yuan (dsjyln@gztrc.edu.cn)
Tongren University https://orcid.org/0000-0002-8060-9689
Wen Zhang
Tongren University
Jiajun Liang
Yulin Normal University https://orcid.org/0000-0002-1100-4731
Anran Zhou
Chengdu University

Research Article

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Nonlinear energy harvesting and clustering cooperation in WPCNs

Lina Yuan[a], Wen Zhang[a], Jiajun Liang[b,*], Anran Zhou[c]

[a] *School of Data Science, Tongren University, Tongren, China.*
[b] *Guangxi Colleges and Universities Key Lab of Complex System Optimization and Big Data Processing, Yulin Normal University, Yulin, Guangxi, China.*
[c] *College of Computer Science, Chengdu University, Chengdu, China.*

Abstract

The increasing demand for data and the rapid increase in the number of wireless connected devices make the shortage of energy and spectrum resources more serious. This paper considers a wireless powered communication network (WPCN) composed of N wireless devices (WDs) installed with single-antenna and a hybrid access point (HAP) equipped with multi-antenna, where HAP sends wireless energy to WDs in the downlink and receives information transmission from WDs in the uplink. To overcome "double near and far" problem, this paper adopts a clustering cooperative transmission method to enhance some WDs' throughput performance far from the HAP, i.e., one of N WDs is selected as a cluster head (CH) and the remaining $(N-1)$ WDs as cluster members (CMs), and the CH helps relay CMs' information to transmit. However, because the CH needs to transmit N WDs' information, its energy consumed during information transmission will be the bottleneck of the system performance. To achieve a tradeoff between energy and data rate, this paper adopts multi-antenna energy beamforming technology to concentrate more energy to transmit the CH, so as to balance the energy consumption among all WDs. Considering the influence of in-phase/orthogonal imbalance,nonlinear amplification amplitude and phase noise on those physical transceivers of low-cost sensor nodes, nonlinear energy harvesting technology is employed to improve throughput performance of the WPCN system. Particularly, the proposed scheme's throughput performance is derived, and simulation results demonstrate that this scheme can be effective to increase the WPCN system's throughput fairness and spectral efficiency.

Keywords: Nonlinear energy harvesting, clustering cooperative transmission, throughput fairness, wireless powered communication network, energy beamforming

1. Introduction

Statistically, the mean annual energy consumption (EC) of information and communication industry and carbon emission occupies 3% and more than 2% of the global EC total [1]. The technologies of relaying cooperation and energy harvesting (EH) can satisfy communication quality and reduce EC. In the post-5G era, due to the increasing complexity of wireless networks (WNs), it is an issue for how to design adequate the strategies of energy distribution to enhance systems' performance that requires more research and discussion.

In traditional energy-constrained WNs, wireless devices (WDs) usually use batteries as an energy source, requiring regular charging or battery replacement, which is difficult, even dangerous or impossible for a critical mass of WDs, thereby restricting the life cycle of WDs and WNs. EH, which allows WDs with limited energy to capture power from the surrounding environment, is an up-and-coming solution to extend the life cycle of energy-restricted WNs. For this purpose, EH has emerged two novel technologies: simultaneous wireless information and power transfer (SWIPT) and wireless powered communication

*Corresponding author
Email address: shuigpjd@163.com (Jiajun Liang)

network (WPCN). The former takes advantage of the ability of radio frequency (RF) signals to bring information and energy, capturing energy from RF signals and providing great convenience for charging energy-constrained WDs [2]. WPCN is a novel type of WN combining wireless information transmfer (WIT) and far-field RF charging of WDs batteries [3–6]. Charging is proceeded by RF energy transfer from base station (BS) to EH WDs, and RF-EH requires a novel WN resource allocation scheme [7].

Compared to other EH methods, such as sun, heat, wind, movement, etc., RF EH can be considered a novel solution because energy can be transmitted over the air without cables for using RF signals to carry energy and information [8]. In wireless communications, this technology is a comfortable solution for applications where batteries are limited, or where operating equipment is hazardous. WPCN technology can help energy-constrained nodes obtain energy from other nodes or the surrounding environment, and utilize this energy to transmit information to other nodes. WPCN has been widely used in wireless sensor networks (WSNs) [9], Internet of Things (IoT) systems [10], Unmanned Aerial Vehicle (UAV) communications [11], mobile edge computing (MEC)[12] and other fields. In recent years, WPCN technology has attracted extensive attention in academic circles. In order to enhance max-min throughput, various user collaboration schemes [13–17] were put forward. For instance, [13] and [14] allowed two WDs to exchange message with each other and formed a distributed antenna system to jointly transfer message. [15] proposed a two-user collaboration scheme, in which the user, who is near the HAP, serves as a relay and forwards the WD's information, who is far away from the HAP, to the HAP. [16] further considered a general multi-user scenario, where the transmission of a user distant from HAP is assisted by multiple WDs. [17] proposed a cluster-based collaboration method based on multiple antennas, in which a WD acts as a cluster head (CH) and transmits the other cluster members' (CMs') information to the HAP. The simulation results indicated that compared to other typical benchmark collaboration methods, the suggested cluster-based collaboration can availably increase the WPCN's user fairness and spectrum efficiency. However, the references published above suppose that WDs' hardware transceivers are complete. Actually the impact of in-phase/orthogonal imbalance, nonlinear amplification amplitude and phase noise on low-cost sensor nodes' physical transceivers, which can greatly reduce the WNs' performance.

Therefore, it is of great theoretical significance and application value to study WPCNs for nonlinear EH cooperative transmission. WPCN is an important application direction of IoT in the future, which has promising to settle the issue of low power IoT terminal life shortage. Research on efficient resource allocation method of WPCN can greatly enhance capacity and energy efficiency and expand the practical application range of WPCN. To achieve the goal of "self-sustainable", green and sustainable development of IoT in the future is of great significance [10].

This paper considers a point-to-multipoint WPCN system as seen in Fig. 1 consisting of a hybrid access point (HAP) equipped with M ($M > 1$) antennas and N WDs equip with one antenna, one of the WD labeled as W_0 is selected as a CH, and the remaining $(N-1)$ WDs as CMs. The specific contributions of this article are shown below.

- We propose a WPCN that adopts clustering cooperation approach with nonlinear EH technology. To be specific, one of the N WDs is selected as the CH, and the remaining $(N-1)$ WDs as CMs in the WPCN, where the CH help relaying the CMs' information to the HAP. In the meantime, energy beamforming (EB) technology is adopted at the multi-antenna HAP to enhance energy transfer efficiency in the downlink (DL) and spectral efficiency in the uplink (UL). The clustering cooperation approach with nonlinear EH technology can address the "double near far" problem and enhance the throughput fairness and spectrum efficiency.

- We develop a joint optimization problem to optimize the HAP' beamforming to maximize the minimum data rate (maximum-minimum throughput) in all the N WDs. The issue of the formulation is convex that can get an efficient solution by simple one-dimension search.

- We simulate the throughput fairness and spectrum efficiency of the WPCN under various scenarios. The simulation results demonstrate that the proposed approach can significantly enhance the

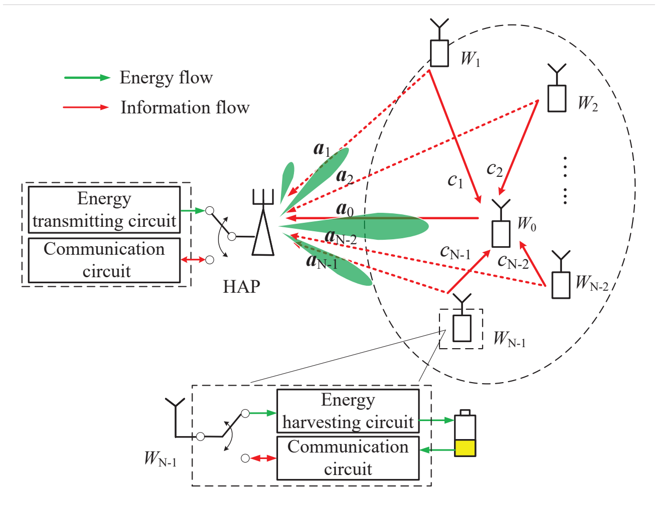


Figure 1: One point-to-multipoint WPCN system.

minimum data rate and sum throughput of the WPCN compared with three benchmark methods.

The rest of this article is structured as shown below. Section II and III respectively expound the system model and clustering cooperative transmission scheme. The throughput performance is analyzed in Section IV and three benchmark methods are briefly described in Section V. The numerical simulation results are provided to evaluate the clustering cooperation scheme's performance under nonlinear energy harvesting adopting the software MATLAB to simulate In Section VI. Finally, Section VII summarizes the whole paper.

2. System Model

Fig. 1 shows the considered point-to-multipoint WPCN system in this article, where firstly the HAP provides wireless energy for the N WDs through DL wireless energy transmission (WET) technology, and then the WDs employs the received power to transfer messages to the HAP UL. It is assumed that both the HAP and N WDs run in the same frequency band and realize a time division duplex (TDD) circuit to separate information and energy transmission [18]. The HAP has a steady supply of power to harmonize transmission between N WDs and WET/WIT. Each WD is set up a rechargeable battery to reserve the wireless energy harvested from the HAP. Assume the entire transmission process takes a fixed time of T seconds. It is worth noting that, before transmission, the HAP can obtain perfect channel side information (CSI) between the HAP and N WDs through the feedback of WDs and the existing channel estimation technology, and then calculate the optimal transmission strategy according to the obtained channel information by adopting the proposed optimization algorithm. For convenience, this section ignores the time taken by the feedback process, and uses the normalized unit time as the time of each transmission process, namely $T = 1$.

This article adopts the clustering cooperation method [17, 19–21], i.e., one of N WDs is chosen as a CH, represented by W_0, and the remaining $(N-1)$ WDs as CMs, represented by W_i $(i = 1, 2, \cdots, N-1)$. The CH is utilized to relay the CMs' WIT UL. It is assumed that all channels are independent of each other and subject to quasi-static flat fading, so that all channel coefficients remain unchanged within T, but it can be varied from one T to another T. The channel vector between the HAP and W_i $(i = 0, 1, \cdots, N-1)$ is expressed by $\mathbf{a}_i \in \mathcal{C}^{M\times 1}$, where $\mathbf{a}_i \sim \mathcal{CN}(\mathbf{0}, \sigma_i^2\mathbf{I})$ and σ_i^2 represents as the mean channel gain. The channel gain is $h_i \triangleq |\mathbf{a}_i|^2$. The channel coefficient from the the CH to the i-th CM is $c_i \sim \mathcal{CN}(0, \delta_i^2)$ $(i = 1, \cdots, N-1)$ and its corresponding channel gain is $g_i \triangleq |c_i|^2$, in which $|\cdot|$ represents the 2-norm operator.

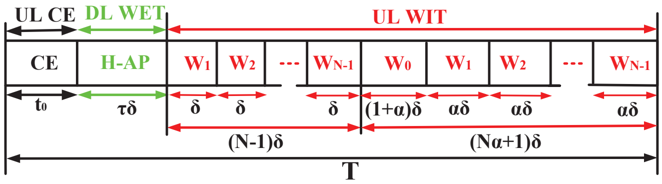


Figure 2: The clustering cooperation protocol with nonlinear EH.

Before T starts, CE is implemented within a settled time τ_0. In the CE stage, each WD broadcasts its own pilot signal in turn to equip the HAP and CH with knowledge of $\mathbf{a}_i$ $(i = 0, 1, \cdots, N-1)$ and c_i $(i = 1, \cdots, N-1)$, respectively. Afterwards, the CH transfers its correct estimate to the HAP so as to make it have an enough understanding of the CSI of the WPCN system.

3. Clustering Cooperation Protocol with Non-Linear EH

As seen in Fig. 2, after the stage of the CE, the WPCN system based on clustering cooperation can be divided into three stages within each T. In the first stage, the duration is βT, $\beta \in (0, 1)$ the HAP sends radio energy at transmitted power P DL. The duration of the second and third stages is $(1-\beta)T - \tau_0$, and each WD transmits its own message to the HAP employing the energy collected in the first stage. To ensure that the time required to transmit each WD message in the second and third stages is equivalent to $(1+\alpha)\delta$, suppose that each CM transmits its message to the CH in turn within δ in the second stage, and the HAP can also listen to the information transmission of each CM. During the third stage, the CH repeats $(N-1)$ CMs' decoded information within $\alpha\delta$ and transfers its own information to the HAP within $(1+\alpha)\delta$.

In order to simplify the description, the time required in the first stage is expressed by $\tau\delta \triangleq \beta T$, where τ and α represent the system parameters, thus the following expression holds

$$T = \tau_0 + \tau\delta + N(1+\alpha)\delta. \tag{1}$$

It can be seen from the above equation that the value of δ is unique. Assuming the HAP can calculate the optimal τ^* and α^* for obtaining the maximum throughput performance, the values of τ^* and α^* are then broadcasted to all WDs, so that all the N WDs hold time switch circuit in sync during power or message transmission. Although the CMs transfer messages to the CH during the second stage, which can be also listened by the HAP, so the HAP receives both the second and third stages of information transmissions, which can be utilized to enhance the overall data rate, compared with decoding messages during the third stage alone. The next section will derive throughput performance of the proposed clustering cooperation protocol with nonlinear EH.

3.1. Stage I: Design Energy Transfer

The CH consumes a more considerable amount of energy than the $(N-1)$ CMs because it requires to transfer N pieces of information in total. Therefore, the energy received by the CH is the choke point of network performance. To compromise between the consumed and received energy, this article adopts the technology of EB [22, 23] for centrally transmitting energy from the transmitting end to the CH. That is to say, within the time $\tau\delta$ of the first stage, the HAP transmits a random energy signal $\mathbf{w}(t) \in C^{M\times 1}$ to M antennas. Denote $\mathbf{Q}$, $\mathrm{tr}(\cdot)$, $()^H$ and $n_i^{(1)}(t)$ as EB matrix, the trace of a matrix, complex conjugate operator and noise power of the receiver in the first stage, respectively, then the transmitted power constraint conditions of the HAP and the received energy signal by the i-th WD are

$$E\left[|\mathbf{w}(t)|^2\right] = \mathrm{tr}\left(\left\{\mathbf{w}(t)\,\mathbf{w}(t)^H\right\}\right) \triangleq \mathrm{tr}(\mathbf{Q}) \leq P \tag{2}$$

and

$$y_i^{(1)}(t) = \mathbf{a}_i^T \mathbf{w}(t) + n_i^{(1)}(t), t \in [t_0, t_0 + \tau\delta], i = 0, 1, \cdots, N-1, \tag{3}$$

If noise power is ignored, the energy collected by the WDs can be expressed as

$$\begin{aligned} E_i^{CH_{NonLinear}} &= \frac{\frac{M}{1+\exp(-a(\tau\delta tr(\mathrm{tr}(\mathbf{A}_i\mathbf{Q}))-b))} - \frac{M}{1+\exp(ab)}}{1-\frac{1}{1+\exp(ab)}} \\ &\triangleq \psi\left(\tau\delta tr\left(\mathrm{tr}(\mathbf{A}_i\mathbf{Q})\right)\right), i = 0, \cdots, N-1, \end{aligned} \tag{4}$$

where $\mathbf{A}_i \triangleq \mathbf{a}_i\mathbf{a}_i^H$, $\psi(x_i) = \frac{\beta(x_i)-M\Omega}{1-\Omega}$, $\Omega = \frac{1}{1+\exp(ab)}$, $\beta(x_i) = \frac{M}{1+\exp(-a(x_i-b))}$, $E_i^{CH_{NonLinear}}$ is a typical S-shaped function of input power; Ω uses to assure that zero input and zero output for this model, and keeps unchanged number; M represents the circuit's maximum output power when the circuit is saturated, and is also a constant; Hold the values of a and b unchanged, which are associated with the impedance in the circuit, capacitance and the on-voltage of a diode.

This paper designs the EB matrix $\mathbf{Q}$ in (4) through addressing the following issue of optimization [25]

$$\begin{aligned} \max_{\mathbf{Q}\succ=0} \quad & \lambda \\ s.\,t. \quad & \mathrm{tr}\left(\mathbf{Q}\mathbf{A}_i\right) \le P, i = 0, \cdots, N-1, \\ & \mathrm{tr}\left(\mathbf{Q}\mathbf{A}_i\right) \ge \lambda, i = 1, \cdots, N-1, \\ & \mathrm{tr}\left(\mathbf{Q}\mathbf{A}_0\right) \ge (\alpha N + 1)\lambda. \end{aligned} \tag{5}$$

The goal is to maximize the minimum received power among the N WDs. To be specific, $\mathbf{Q} \succ= 0$ manifests $\mathbf{Q}$ is a positive semidefinite matrix. These two constraint conditions make clear that the CH's received power is at lowest $(\alpha N + 1)$ times as much as the minimum received power among the $(N-1)$ CMs.

3.2. Stage II: Intra-cluster Transfer

Suppose $\mathbf{Q}^*$ is the optimal solution of (5), and next the received energy by the i-th WD is $E_i^{CH_{NonLinear}} \triangleq \psi\left(\tau\delta\mathrm{tr}\left(\mathbf{A}_i\mathbf{Q}^*\right)\right), i = 1, \cdots, N-1$. During the second stage, the $(N-1)$ CMs transfer messages to the CH successively, and each CM's transmission time is δ. Assuming that the $(N-1)$ CMs work out all the collected energy in the first stage and each CM transfers information at a fixed power in phase two, the i-th CM's transmission power can be expressed as $P_i^{CH_{NonLinear}} = E_i^{CH_{NonLinear}}/\delta \triangleq \psi\left(\tau\delta\mathrm{tr}\left(\mathbf{A}_i\mathbf{Q}^*\right)\right)/\delta (i = 1, \cdots, N-1)$. Let $s_i^{(2)}(t)$ and $n_i^{(2)}(t)$ represent the baseband signal transmitted by the i-th WD in phase two and the noise of the receiver at the CH, respectively, and then the received signal at the CH is

$$\begin{gathered} y_{0,i}^{(2)}(t) = c_i\sqrt{P_i^{CH_{NonLinear}}}s_i^{(2)}(t) + n_i^{(2)}(t), \\ t \in (t_0 + (\tau + i - 1)\delta, t_0 + (\tau + i)\delta], \\ i = 1, \cdots, N-1. \end{gathered} \tag{6}$$

Afterwards, the CMs' information can be decoded by the CH at a prescribed rate, i.e

$$R_i^{(2)} = \delta\log_2\left(1 + \frac{\psi\left(\tau\delta\mathrm{tr}\left(\mathbf{A}_i\mathbf{Q}^*\right)\right)g_i}{\delta N_0}\right), i = 1, \cdots, N-1. \tag{7}$$

In the meantime, the CMs' transmission can also be listened by the HAP so that the received signal can be denoted as

$$\begin{gathered} y_{H,i}^{(2)}(t) = \mathbf{a}_i\sqrt{P_i^{CH_{NonLinear}}}s_i^{(2)}(t) + n_{H,i}^{(2)}(t), \\ t \in (t_0 + (\tau + i - 1)\delta, t_0 + (\tau + i)\delta], \\ i = 1, \cdots, N-1, \end{gathered} \tag{8}$$

where $n_{H,i}^{(2)}(t) \sim CN(0, N_0\mathbf{I})$.

3.3. Stage III: Cluster-to-HAP Transfer

After decoding the CMs' information, the CH transfers its own message and the $(N-1)$ CMs' messages together to the HAP successively, and the transmission time of each message is $\alpha\delta$. The transmitted power of the CH is

$$P_0^{CH_{NonLinear}} = \frac{E_0^{CH_{NonLinear}}}{(\alpha N+1)\,\delta} \triangleq \frac{\psi\left(\tau\delta \mathrm{tr}\left(\mathbf{A}_0\mathbf{Q}^*\right)\right)}{(\alpha N+1)\,\delta}. \tag{9}$$

Let $s_i^{(3)}(t)$ represent the transmitted baseband signal of the i-th WD in phase three. Afterwards, the message of the i-th WD is received by the HAP, which is shown below.

$$y_i^{(3)}(t) = \mathbf{a}_i\sqrt{P_0^{CH_{NonLinear}}}s_i^{(3)}(t) + n_i^{(3)}(t),\, i=0,1,\cdots,N-1. \tag{10}$$

To be specific, Fig. 2 indicates that the CH firstly takes $(1+\alpha)\,\delta$ time to transmit its own message, and then uses $\alpha\delta$ time to relay each WD's message.

The HAP utilizes Maximum Ratio Combination (MRC) approach to maximize the received signal-to-noise ratio (SNR), in which the synthesized output SNR is

$$\gamma^{(3)} = \frac{|\mathbf{a}_i|^2 P_0^{CH_{NonLinear}}}{N_0} \triangleq \frac{\psi\left(\tau\delta \mathrm{tr}\left(\mathbf{A}_0\mathbf{Q}^*\right)\right)h_0}{(\alpha N+1)\,\delta N_0}. \tag{11}$$

Afterwards, the CH's data rate at the HAP can be denoted as

$$R_0^{CH_{NonLinear}} = (1+\alpha)\,\delta\log_2\left(1+\gamma^{(3)}\right). \tag{12}$$

However, it is received for each CM's information in phase two and three. In this circumstance, the HAP can jointly decode each CM's messages together across two stages for a given rate

$$R_i^{CH_{NonLinear}} = \min\left\{R_i^{(2)}, V_i^{(2)} + \alpha\delta\log_2\left(1+\gamma^{(3)}\right)\right\},\, i=1,\cdots,N-1, \tag{13}$$

here, $R_i^{(2)}$ is given by (7), $V_i^{(2)}$ indicates the HAP adopts the optimal MRC receiver to extract information from the signal received by (6) (the second stage), and can be expressed as

$$V_i^{(2)} = \delta\log_2\left(1+\frac{\psi\left(\tau\delta \mathrm{tr}\left(\mathbf{A}_i\mathbf{Q}^*\right)\right)h_i}{\delta N_0}\right),\, i=1,\cdots,N-1. \tag{14}$$

According to the WDs' data rates given in (12) and (13), the spectral efficiency and fairness of the clustering cooperation protocol can be evaluated. In other words, the performance of sum throughput can reflect spectral efficiency, namely,

$$R_{sum}^{CH_{NonLinear}} = \sum_{i=0}^{N-1} R_i^{CH_{NonLinear}}. \tag{15}$$

Furthermore, considering the minimum data rate among WDs [3] can reflect the fairness of this protocol, i.e.,

$$R_{\min}^{CH_{NonLinear}} = \min\left\{R_0^{CH_{NonLinear}},\cdots,R_{N-1}^{CH_{NonLinear}}\right\}. \tag{16}$$

As can be seen above, the time allocation parameters τ and α can determine the system's throughput performance. Consequently, the optimal performance in (15) or (16) can be gotten through two-dimensional search of feasible values of τ and α.

4. Benchmark Approaches

Three benchmark approaches are considered for performance comparisons in this paper. To make it fair, it is assumed that all WDs use up all the energy collected in the first stage when transmitting information in the WIT stage and transmit at constant power, and the HAP also adopts the MRC method to maximize the received SNR.

4.1. Clustering Cooperative Approach for Linear EH

We have made a careful analysis of this approach and carried out a large number of simulation experiments before, please refer to the references [17] and [19] for details.

4.2. Independent Transmission with Non-Linear EH

The time required for the first stage of this approach, i.e., WET stage, is $\tau\delta$. In the remaining time, the N WDs uses TDD circuit to send their information directly to the HAP, that is, through maxi-min received power among the $(N-1)$ WDs, the EB matrix $\mathbf{Q}_1$ of WET stage is calculated, as shown below.

$$\begin{aligned} \max_{\mathbf{Q}_1 \succ = 0} \quad & \lambda_1 \\ s.\,t. \quad & \mathrm{tr}\left(\mathbf{Q}_1 \mathbf{A}_i\right) \leq P, \\ & \mathrm{tr}\left(\mathbf{Q}_1 \mathbf{A}_i\right) \geq \lambda_1, i = 0, \cdots, N-1. \end{aligned} \tag{17}$$

Make $\mathbf{Q}_1^*$ for (17)'s optimal solution. The harvested energy by the N WDs is the same as the Clustering Cooperation Approach with Non-Linear EH, as shown in (4), after that, the i-th WD's transmitted power is

$$P_i^{IT_{NonLinear}} = \frac{E_i^{IT_{NonLinear}}}{\delta} \triangleq \frac{\psi\left(\tau\delta \mathrm{tr}\left(\mathbf{A}_i \mathbf{Q}_1^*\right)\right)}{\delta}, i = 0, 1, \cdots, N-1. \tag{18}$$

Then, all the WDs transfer their own messages to the HAP successively, and each WD's transmission time is $\theta = (T - \tau\delta - t_0)/N$. The i-th WD's synthesized output SNR is

$$\gamma^{(4)} = \frac{|a_i|^2 P_i^{IT_{NonLinear}}}{N_0} = \frac{\eta\tau\delta h_i \mathrm{tr}\left(\mathbf{A}_i \mathbf{Q}_1^*\right)}{N_0 \theta}, i = 0, 1, \cdots, N-1. \tag{19}$$

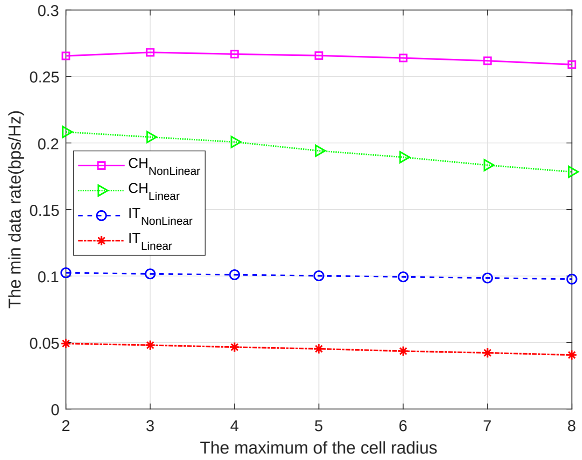
In consequence, the N WDs' data rates at the HAP can be expressed as

$$R_i^{IT_{NonLinear}} = \theta \log_2\left(1 + \gamma_i^{(4)}\right), i = 0, 1, \cdots, N-1. \tag{20}$$

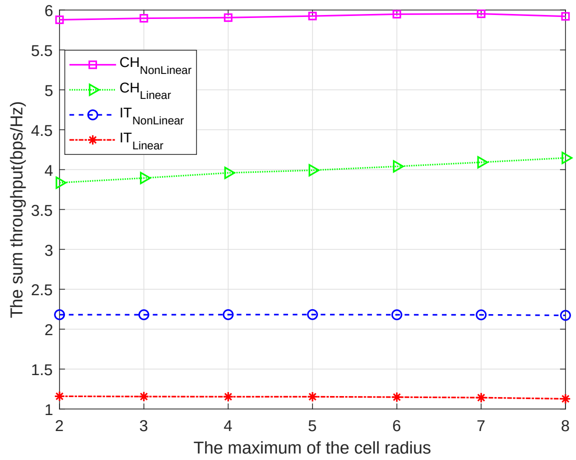
The optimal solution of the above-mentioned issue can be acquired as (5) as well, in which, for simplicity's sake, the algorithm in detail is omitted.

4.3. Independent Transmission with Linear EH

The transmission process is the same as the Independent Transmission Approach with Non-Linear EH, and the optimization problem is the same as well. The difference lies in the formula (18), (19) and (20), and let $\mathbf{Q}_2$, $\mathbf{Q}_2^*$ and $\gamma^{(5)}$ represent the EB matrix at the WET stage, the optimal solution of (17) and the i-th WD's synthesized output SNR, respectively, so the three equations are changed to



(a) Throughput fairness



(b) Spectrum efficiency

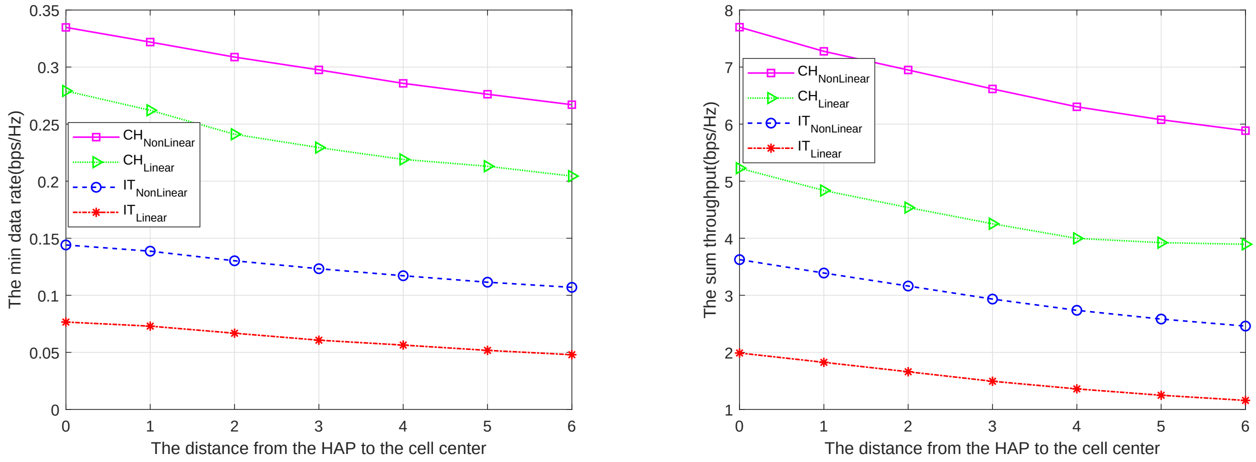
Figure 3: The impact on throughput fairness and spectrum efficiency by varying d with fixed $r = 3$ m and $N = 20$.

5. Numerical Simulation Results

This part will evaluate the throughput performance of Clustering Cooperative Approach with Non-Linear EH. In all of the following simulation figures, the results, obtained by simulation on the MATLAB R2021a software platform, draw the optimal performance of the minimum data rate or sum throughput of the four different schemes. In all simulation diagrams, suppose the HAP's number of antennas $M = 5$, the energy receiving efficiency $\eta = 0.4$, the HAP's transmitting power is $P = 0.1$ W, and the bandwidth noise power $N_0 = 10^{-12}$ W is considered for all receivers. The average channel gain among any two sensor nodes (the HAP or one of the N WDs) follows the path loss model. For example, let $d_{H,i}$ represent the distance between the i-th WD and the HAP, α, f_c and c are the path loss factor, the carrier frequency and the speed of light, respectively, then $\Delta_i^2 = \left(\frac{c}{4\pi d_{H,i} f_c}\right)^{\alpha}$. In this section, set α as 2 both DL WET and UL WIT [26], $c = 3 \times 10^8$ m/s and $f_c = 915$ MHz [15]. Unless otherwise stated, 20 WDs are assumed to be evenly distributed within a circle of radius r [27], and the distance from the center of the circle to the HAP is d. Besides, select the WD nearest the center as the CH. In the figures below, every point is the mean value of one WD for 20 times of independent arrangement. $CH_{NonLinear}$, CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear} represent the Clustering Cooperation Approach with Non-Linear EH, Clustering Cooperation Approach with Linear EH, Independent Transmission Approach with Non-Linear EH and Independent Transmission Approach with Linear EH, respectively.

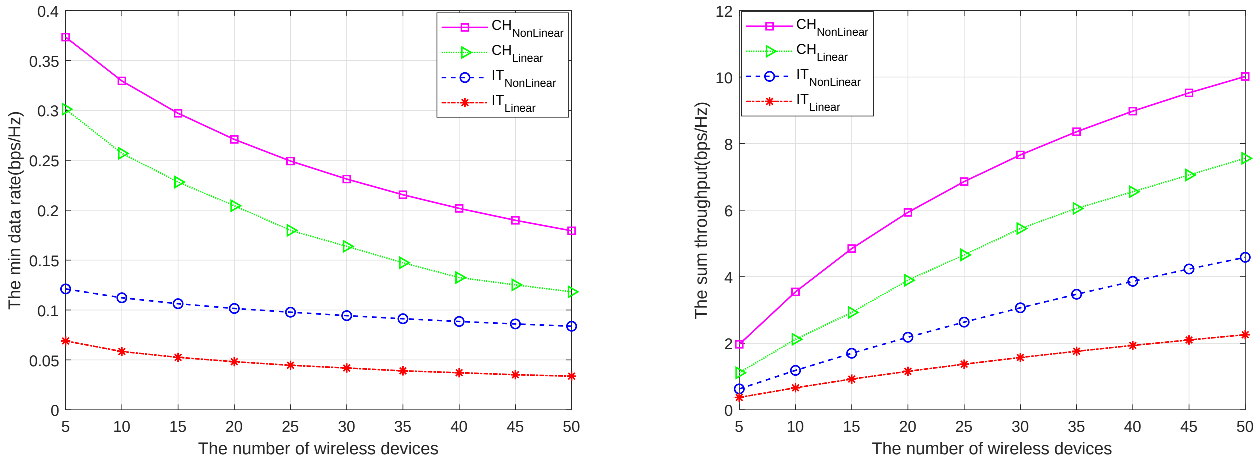
In Fig. 3, we compare the influences of our proposed $CH_{NonLinear}$ and the three benchmark methods (CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}) on fairness and spectral efficiency when the distance from the center of the circle to the HAP d varies from 0 m to 6 m with fixed the radius of the fixed cell $r = 3$ m. As expected, the minimum data rate and sum throughput of all schemes lessen with the increase of d. However, it can be observed from Fig. 3(a) that our proposed scheme's($CH_{NonLinear}'s$) performance in this paper is superior to that of the other three schemes. For example, when $d = 4$ m, $CH_{NonLinear}$ is 30%, 144% and 400% higher than CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}, respectively. When d increases to 6 m, $CH_{NonLinear}$ is 30%, 150% and 457% higher than CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}, respectively. This indicates that the proposed performance advantage is more obvious when the distance from the cluster to the HAP d are relatively far. As shown in Fig. 3(b), the performance of $CH_{NonLinear}$ is also the best in terms of sum throughput. Partly because the problem of "double near and far" seriously reduces some distant WDs' data rates, while our proposed $CH_{NonLinear}$ can availably help to forward the distant WDs' information.

As shown in Fig. 4, while the cell radius r changes with fixed $d = 6$ m, the influences of the proposed



(a) Throughput fairness (b) Spectrum efficiency

Figure 4: The impact on throughput fairness and spectrum efficiency by varying r with fixed $d = 6$ m and $N = 20$.



(a) Throughput fairness (b) Spectrum efficiency

Figure 5: The impact on throughput fairness and spectrum efficiency by varying N with fixed $r = 3$ m and $d = 6$ m

$CH_{NonLinear}$ and the three reference methods (CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}) on fairness and spectral efficiency are compared. Since the ultimate range from the HAP to the N WDs adds, we can infer that the minimum data rate lowers with the increase of r. It can be seen from Fig. 4(a) that with the augmentation of r, the throughput performance of our proposed approach $CH_{NonLinear}$ in this article is better than the other three methods. For instance, when $r = 2$ m, $CH_{NonLinear}$ is 27%, 159% and 439% higher than CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}, respectively. When r increases to 8 m, $CH_{NonLinear}$ is 45%, 165% and 538% higher than CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}, respectively. When r is relatively large, the performance advantages of our proposed $CH_{NonLinear}$ are more obvious. Fig. 4(b) demonstrates the performance of our proposed $CH_{NonLinear}$ is also the best in terms of sum throughput. This indicates that it is necessary to adopt the technologies of the Non-Linear EH, EB and cooperative transmission at the HAP to raise the minimum data rate and sum throughput of the system when r is larger.

Finally, Fig. 5 studies the influences of fairness and data rate for WPCN while the number of WDs N changes with fixing $d = 6$ m and $r = 3$ m. It can be inferred that the minimum data rate decreases with the increase of N. Fig. 5(a) demonstrates the throughput performance of $CH_{NonLinear}$ is the best with the increase of N. For example, when $N = 5$, $CH_{NonLinear}$ is 23%, 208% and 440% higher than

CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}, respectively. When N increases to 50, $CH_{NonLinear}$ is 51%, 114% and 431% higher than CH_{Linear}, $IT_{NonLinear}$ and IT_{Linear}, respectively. Fig. 5(b) indicates that the throughput performance of $CH_{NonLinear}$ is also the best in terms of sum throughput. This indicates that the technologies of EB and cooperative transmission at the HAP are necessary to help enhance the WPCN system's minimum data rate and sum throughput when N is larger.

6. Conclusions

In this article, we investigate a novel WPCN, where is composed of a multiple antenna HAP and N WDs, and propose a clustering cooperation approach with nonlinear energy harvesting technique to enhance the fairness and spectral efficiency of the system. Energy beamforming technology is applied to centralize more transmission energy to the CH to equilibrate all WDs' energy consumption. Compared the throughput performance of our proposed approach with that of three typical benchmark approaches. Simulation results demonstrate that our proposed method can availably enhance throughput fairness of WPCNs under different scenarios.

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8. Conflict of Interest Statement

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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