Interactive communication with clustering collaboration for wireless powered communication networks

Lina Yuan¹, Huajun Chen² and Jing Gong¹

Abstract
In this article, we propose a novel wireless powered communication network, which is composed of two multiple antennas hybrid access points and a series of distributed wireless devices. The two hybrid access points transmit downlink wireless energy to the wireless devices and receive uplink wireless messages from the wireless devices; meanwhile, the information of wireless devices nearer to their corresponding hybrid access point should be transmitted to the faraway hybrid access point. To improve the throughput performance of some wireless devices away from their corresponding hybrid access point, we propose a clustering-collaboration interactive communication protocol with multiple antennas by Time Division Multiple Access, where two of the distributed wireless devices are selected as cluster heads to help relay information of other cluster members, which can efficiently improve some faraway wireless devices' throughput performance. However, its performance is also constrained by cluster heads' high-energy consumption. To solve this energy imbalance problem, multi-antenna energy beamforming technology is exploited for the hybrid access points, which distributes more transmission power to the cluster heads to balance all the wireless devices' energy consumption. In particular, we obtain the proposed system's throughput performance through the multi-antenna cluster-based collaboration, and verify through simulations that this scheme can effectively enhance user unfairness and improve the throughput performance.

Keywords
Wireless powered communication network, interactive communication, clustering collaboration, user unfairness, throughput performance

Date received: 25 August 2021; accepted: 10 November 2021

Handling Editor: Yanjiao Chen

Introduction
The finite battery life cycle of wireless devices (WDs) powered by battery is the bottleneck of modern wireless communication network (WCN) performance.¹ When its energy is exhausted, a WD requires to replace/recharge the battery manually, which can lead to interruption of normal operation of WDs and serious degradation of communication performance. Moreover, the state-of-the-art development of wireless energy transmission/wireless power transmission (WET/WPT) technology makes a new network paradigm possible, called wireless powered communication network (WPCN),²–⁴ in which WDs' information transfer, such as sensors, is powered by dedicated WET to supply sustainable and

¹School of Data Science, Tongren University, Tongren, China
²School of Automation, Guangdong University of Technology, Guangzhou, China

Corresponding author:
Lina Yuan, School of Data Science, Tongren University, Chuandong Moxiang Garden, Bijiang District, Tongren 554300, Guizhou, China. Email: dsyltn@gztrc.edu.cn

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
continuous microwave energy through the air. The utility of WET can effectively lower the cost of batteries replaced or recharged, reduce power interruption, and improve the quality of communication. Because WET has the potential to address the key energy confinement, WET is expected to be a significant component of the future WCNs.

WPCN has drawn much attention from domestic and foreign scholars,5–7 and has been widely applied in various fields to prolong network life cycle effectively or enhance network’s data rate, especially in the application of lower power consumption, for instance, radio frequency identification (RFID) networks,8 unmanned aerial vehicle (UAV),9 Mobile Edge Computing (MEC),10 Big Data,11 5G Communication,12,13 Blockchain,14 and wireless sensor networks (WSNs).15–17 At present, there are a large number of literatures regarding WPCN. For example, Ju and Zhang18 studied a WPCN’s throughput performance with multi-user and one single-antenna hybrid access point (HAP), which first put forward a classical harvest-then-transmit (HTT) protocol, where in the downlink (DL) the HAP broadcasts radio frequency (RF) energy to all users, and in the uplink (UL) all users use the energy harvested DL to transfer their respective information to the HAP via Time Division Multiple Access (TDMA). However, there is a phenomenon that these users far away from their associated HAP harvest less energy but require more energy to transmit their information, and vice versa, which is so-called “doubly-near-far” unfairness problem in WPCN due to the distance-dependent power loss. This will result in lower throughput of users far away from the associated HAP, which makes user unfairness exist in the networks, and thus affects the performance of the whole networks. Therefore, Che et al.19 also revealed that this design would lead to great unfairness in the throughput among users, especially that the data rate of these users was two orders of magnitude smaller than that of other users, and this unfairness problem was more obvious, which directly reduced the sensing accuracy of WPCN.

Subsequently, many researchers proposed different methods of user cooperation to improve user fairness of WPCN, that is, users close to the associated HAP forwarded the information of users far away from the associated HAP.20–28 For example, Zhong et al.20 presented those two users interact with each other’s information to form a distributed system of antennas that jointly transfer their messages Chen et al.21 thought of a simple reference module for three nodes in a WPCN, where a harvest-then-cooperate (HTC) protocol was first put forward, and then extended it to common multi-user collaboration scenarios. Ju and Zhang22 proposed a two-user collaboration method, in which the closer user acted as a relay to assist in transmitting the farther user’s message to HAP. Zhong et al.23 further considered a general multi-user scenario: multiple users are used to assist users far from the associated HAP to transmit their formation. Besides, Yuan et al.29–31 proposed a multi-antenna cluster-based cooperation protocol, in which a WD acted as a cluster head (CH) and relayed the other cluster members’ (CMs) messages to the HAP. While considering interactive transmission between multi-HAP and multi-user, the clustering collaboration’s throughput performance is unknown.

This article focuses on a novel WPCN system consisting of two HAPs (HAP1 and HAP2) and N WDs, as shown in Figure 1, where HAP1 and HAP2 first broadcast wireless energy to the N WDs, and the N WDs then use the collected energy from HAP1 and HAP2 to transmit their independent messages to the corresponding HAP. The distance between each WD and the two HAPs is compared, and the one nearer to HAPi belonged to the user of HAPi, i = 1, 2. Assume that there is (k + 1) and (N – k – 1) WDs nearer to HAP1 and HAP2. The purpose of this article adopts the cluster-based cooperation protocol in Yuan et al.29–31 in which the (k + 1) WDs’ information transmitted to HAP1 and HAP2, respectively. Because direct transmission leads to user unfairness, the article adopts the cluster-based cooperation protocol in Yuan et al.29–31 in which one of the (k + 1) WDs is designated as CH to help relaying the other CMs’ information transmission as shown in Figure 2(a), and so it is the (N – k – 1) WDs as shown in Figure 2(b). Some farther WDs’ throughput performance can be significantly enhanced due to the reduction of transmission power consumption. However, the shortcoming is that the two CHs can be affected by high-energy consumption, ultimately limiting the network performance. In order to address the problem of energy imbalance, this article adopts the technology of multi-antenna energy beamforming (EB) at the two HAPs to enable HAPs to
transfer more energy to the two CHs to achieve a balance of the energy expenditure of all the WDs.

The main contributions of this article are shown as follows:

- A novel WPCN system model is proposed for interactive information between two HAPs and a clustering-collaboration interactive communication with multiple antennas by TDMA to improve its data rate.

- To deal with the issue of the two CHs' high-energy consumption, multi-antenna EB technique at the HAPs is exploited, where more transmission power is concentrated into the two CHs to achieve a balance of energy consumption for all WDs. The application of multi-antenna EB technique at HAPs not only improves the efficiency of WET DL but also enhances the spectral efficiency of wireless information transmission (WIT) UL.

- We develop the issue of maximizing the minimum power received among the WDs and demonstrate through simulations that this scheme can efficiently enhance the proposed system's throughput unfairness performance.

**Modeling system**

**Channel model**

As shown in Figure 1, a novel WPCN system model is proposed constituting two HAPs (i.e. HAP1 and HAP2) and N WDs, where HAP1 and HAP2 include \((N - k - 1)\) and \((k + 1)\) WDs, respectively. Specially, the two HAPs perform WET DL and receive WIT UL. The two HAPs have steady power requirement to coordinate WET and WIT from the N WDs. Each WD is furnished with an internal battery for reserving wireless energy collected from its closer HAP. All the WDs and the two HAPs run on the same frequency band, and apply a time-division-duplexing circuit for separating energy and message transmissions. In particular, both the two HAPs and each WD are fitted with \(M > 1\) antennas and single antenna, respectively. Our purpose is to make their respective messages transmit to each other’s HAP. In other words, the messages of \((k + 1)\) WDs within HAP1 should be transmitted to HAP2, while the messages of \((N - k - 1)\) WDs within HAP2 should be transmitted to HAP1.

In this article, two of the WDs are selected to act as the CHs that assist in relaying the other CMs' WIT UL. The means of choosing the CHs will be covered in the “Numerical results” section. In general, the two CHs are labeled as \(W_0\) (i.e. CH1) and \(W_{k+1}\) (i.e. CH2), respectively. The CMs associated with the \(W_0\) are indexed as \(W_1, \ldots, W_k\), and the CMs associated with the \(W_{k+1}\) are denoted as \(W_{k+2}, \ldots, W_{N-1}\). It is assumed that all the channels are independent and reciprocity, and go by quasi-static flat-fading, so that all the channel coefficients stay the same within transmission time per block, expressed as \(T\), but it can change between blocks. The channel coefficient vectors between the HAPj (\(j = 1, 2\)) and \(W_i\) are, respectively, denoted by \(a_i \in \mathbb{C}^{M \times 1}\) and \(b_i \in \mathbb{C}^{M \times 1}\), where \(a_i \sim \mathcal{CN}(0, \sigma_i^2 I)\) and \(b_i \sim \mathcal{CN}(0, \sigma_i^2 I), i = 0, \ldots, N-1\). In addition, the channel coefficient from the \(j\)th CM to its corresponding CH is represented as \(c_j \sim \mathcal{CN}(0, \delta_i^2), j = 1, \ldots, N-1\). The corresponding channel gains are denoted by \(a_i \| b_i \| = |a_i|^2\) and \(g_i \| b_i \| = |c_i|^2\).

At the start of a transport block, there is over a fixed time period of \(t_0\) for performing channel estimation (CE). During the stage of the CE, the WDs take turns broadcasting their pilot signals, such that the two HAPs have the knowledge of \(a_i, i = 0, \ldots, N-1\), CH1 knows \(c_i, i = 1, \ldots, k\), and CH2 also knows \(c_i, i = k + 2, \ldots, N-1\), respectively. Then, CH1 and
CH$_2$ send their estimation of $c_i$’s to their corresponding HAP, so that channel state information in the WPCN is fully understood the knowledge by the two HAPs.

**Clustering-cooperation Interactive communication protocol**

As seen in Figure 3 after the CE phase, the multi-antenna clustering-cooperation interactive WPCN runs in three stages in each duration block $T$ by TDMA. During the first phase with time duration $\tau$, the two HAPs separately broadcast wireless radio energy DL with a fixed transmitted power $P_1$ and $P_2$.

During the second phase with $(N-2)\delta$ amount of time, the $k$ and $(N-k-2)$ CMs transfer their independent information to CH$_1$ and CH$_2$ in turn, using the energy they each harvested during the first stage. In particular, assume that each CM transfers its individual information to the corresponding CH in a certain amount of time $\delta$. During the third phase with $(Na-2)\delta$ amount of time, CH$_1$ first transfers its own message to HAP$_1$ for $(1+\alpha)\delta$ amount of time, and then takes turns to relay the $k$ CM’s messages to HAP$_1$ that it spends $k\alpha\delta$ amount of time on transmitting each CM’s message. So, it is the process of CH$_2$’s transmitting information. Clearly, we have the following time allocation equation

$$T = t_0 + \tau + N(1+\alpha)\delta$$  \hspace{1cm} (1)

where $\alpha$ is a system parameter, and $\delta$ can be only confirmed by the above equation through fixing $\tau$. To ensure generality, we assume $T = 1$ for the entire text. We assume that the two HAPs calculate the optimal $\alpha^*$ by knowing global channel state information, which results in maximum throughput performance, and then broadcast the value of $\alpha^*$ to all the WDs, so that the time-switching circuits of all the WDs can be synchronized in the transmission of energy and information.\(^{29}\)

Note that, in addition to the third stage of the transmission, each CM’s information can also be overheard by the two HAPs that do not dedicate them in the second stage, which can be utilized to achieve higher overall transfer rate than that of decoding the information in the third stage alone.\(^{29}\) The difference with the Yuan et al.\(^{29}\) is that although HAP$_2$ and HAP$_1$ can, respectively, overhear their own $k$ and $(N-k-2)$ WDs’ messages in the second stage, we assume that HAP$_2$ and HAP$_1$ can successfully cancel their overheated information in the third phase. The next section will derive the clustering-cooperation interactive communication protocol’s throughput performance.

**Analyzing throughput performance**

**Stage I: design energy transfer**

Note that CH$_1$ and CH$_2$ need to, respectively, transmit $(k + 1)$ and $(N-k-1)$ messages in total, whose consumed energy would be considerably more than that of the other CMs. Therefore, the energy received by the two CHs is a bottleneck in network performance. In order to balance energy consumption and reception, this article considers the technology of EB\(^{32,33}\) to concentrate the transferred energy into the two CHs.

Within time $\tau$, HAP$_1$ and HAP$_2$ separately transmit $w_1(t) \in C^{M \times 1}$ and $w_2(t) \in C^{M \times 1}$ random energy signals on the $M$ antennas for their corresponding CHs and CMs. Specifically, the transmission power of the two HAPs is

$$E[|w_i(t)|^2] = \text{tr}(E\{w_i(t)w_i(t)^H\})$$

$$\varpi = \text{tr}(Q_i) \leq P_i, \quad i = 1, 2$$  \hspace{1cm} (2)

where $\text{tr}(\cdot)$ and $(\cdot)^H$ express trace of a matrix and complex conjugate operator, respectively. Then, the received energy signal by the $i$th WD within HAP$_1$ is

$$y_i^{(1)}(t) = a_i^T w_1(t) + n_i^{(1)}(t), \quad t \in [t_0, t_0 + \tau], \quad i = 0, \ldots, k$$  \hspace{1cm} (3)

where $n_i^{(1)}(t)$ represents noise power of the receiver in the first stage. Similarly, the received energy signal by the $i$th WD within HAP$_2$ is

![Figure 3. The clustering-cooperation interactive communication protocol.](image-url)
\[ y^{(12)}_i(t) = b_i^T w_2(t) + n_i^{(1)}(t), \quad t \in [t_0, t_0 + \tau] \]
\[ i = k + 1, \ldots, N - 1 \]  

In particular, all WDs can harvest the energy broadcast by HAP\(_1\) and HAP\(_2\) within \( \tau \) time duration owing to the broadcast nature of wireless energy.

Ignoring noise power, we can represent the amount of energy collected by the WDs as

\[ E_i = \eta \tau \left \{ E \left [ \left | y^{(1)}_i(t) \right |^2 \right ] + E \left [ \left | y^{(12)}_i(t) \right |^2 \right ] \right \} \]
\[ = \eta \tau [\text{tr}(A_iQ_1) + \text{tr}(B_iQ_2)], \quad i = 0, \ldots, N - 1 \]  

Here, \( A_i = a_i a_i^H \), \( B_i = b_i b_i^H \), and \( 0 < \eta < 1 \) express the efficiency of energy collection, which assumes that all the WDs are the same.

This article designs the EB matrix \( Q_1 \) and \( Q_2 \) in equation (2) through addressing the following optimization problem

\[
(P1): \quad \max_{Q_1, Q_2 > 0} \quad \lambda_1 + \lambda_2 \\
\text{s.t.} \quad \text{tr}(Q_iA_i) \leq P_1, \quad i = 0, \ldots, N - 1 \\
\quad \text{tr}(Q_iA_0) \geq [\alpha(k + 1) + 1] \lambda_1 \\
\quad \text{tr}(Q_iB_i) \leq P_2, \quad i = 0, \ldots, N - 1 \\
\quad \text{tr}(Q_iB_{k + 1}) \geq [\alpha(N - k - 1) + 1] \lambda_2 
\]

The objective is to maximize the minimum received power among the \( N \) WDs. More specifically, \( Q_1, Q_2 \geq 0 \) makes clear that both \( Q_1 \) and \( Q_2 \) are positive semidefinite matrices, \( \lambda_1 \) and \( \lambda_2 \) in equation (6) express the minimum received power among the \( k \) CMs and \((N - k - 2)\) CMs, respectively. The first and second constraints in equation (6) demonstrate that CH\(_1\)’s received power is at least \( \alpha(k + 1) + 1 \) times the minimum received power among the \( k \) CMs. This is consistent with our intuition: the transmission time of CH\(_1\) is \( \alpha(k + 1) + 1 \) times a CM associated with CH\(_1\). The third and fourth constraints in equation (6) show that CH\(_2\)’s received power is at least \( \alpha(N - k - 1) + 1 \) times the minimum received power among the \((N - k - 2)\) CMs. This is consistent with our intuition: the transmission time of CH\(_2\) is \( \alpha(N - k - 1) + 1 \) times a CM associated with CH\(_2\).

**Stage II: intra-cluster transfer**

Let \( Q_1^* \) and \( Q_2^* \) express the problem’s (P1) optimal solution, and subsequently the received energy by the \( i \)th WD can be written as \( E_i = \eta \tau \delta \left [ \text{tr}(A_iQ_1^*) + \text{tr}(B_iQ_2^*) \right ], \quad i = 1, \ldots, k, k + 2, \ldots, N - 1 \). During the second stage, the CMs transfer their information to their corresponding CHs in turn, where every CM’s transmission occupies \( \delta \) amount of time. Assume that the CMs deplete the collected energy, and the transmitted power of each CM is constant in the second phase. Then, the \( i \)th CM’s transmission power is \( P_i = E_i/\delta = \eta \tau \delta [\text{tr}(A_iQ_1^*) + \text{tr}(B_iQ_2^*)], \quad i = 1, \ldots, k, k + 2, \ldots, N - 1 \). Make \( s^{(2)}_i(t) \) represent the baseband signal transmitted by the \( i \)th WD during the second stage with \( E[|s^{(2)}_i(t)|^2] = 1 \); CH\(_1\)’s and CH\(_2\)’s received signals are then expressed as

\[
\begin{align*}
y^{(2)}_{0,i}(t) &= c_i \sqrt{P_i} s^{(2)}_i(t) + n^{(2)}_{0,i}(t) \\
&\quad t \in [t_0 + (\tau + i - 1), t_0 + (\tau + i)], \quad i = 1, \ldots, k \\
y^{(2)}_{k + 1,i}(t) &= c_i \sqrt{P_i} s^{(2)}_i(t) + n^{(2)}_{k + 1,i}(t) \\
&\quad t \in [t_0 + (\tau + i - k - 1), t_0 + (\tau + i - k)], \quad i = k + 2, \ldots, N - 1
\end{align*}
\]

where \( E[|n^{(2)}_{i,t}(t)|^2] = N_0 \) denotes noise power of the two CHs and \( n^{(2)}_i(t) \) expresses the receiver noise, respectively. Then, the two CHs can decode their corresponding CMs’ messages at rates given by

\[
R^{(2)}_i = \delta \log_2 \left ( 1 + \eta \tau g_i \frac{[\text{tr}(A_iQ_1^*) + \text{tr}(B_iQ_2^*)]}{N_0} \right ) \quad i = 1, \ldots, k, k + 2, \ldots, N - 1
\]

Meanwhile, the CMs’ transmission can also be overheard by HAP\(_1\) and HAP\(_2\), such that HAP\(_1\) and HAP\(_2\) can, respectively, receive

\[
y^{(2)}_{CH_1,i}(t) = b_i \sqrt{P_i} s^{(2)}_i(t) + n^{(2)}_{CH_1,i}(t) \\
&\quad t \in [t_0 + (\tau + i - 1), t_0 + (\tau + i)], \quad i = 1, \ldots, k
\]

and

\[
y^{(2)}_{CH_2,i}(t) = a_i \sqrt{P_i} s^{(2)}_i(t) + n^{(2)}_{CH_2,i}(t) \\
&\quad t \in [t_0 + (\tau + i - k - 2), t_0 + (\tau + i - k)], \quad i = k + 2, \ldots, N - 1
\]

where \( n^{(2)}_{CH_1,i}(t), n^{(2)}_{CH_2,i}(t) \sim \text{CN}(0, N_0 I) \).

**Stage III: cluster-to-HAP transfer**

After decoding their corresponding CMs’ information, the two CHs successively send their corresponding CMs’ information along with their own information to their relevant HAP, where each information takes \( \alpha \delta \) amount of time to transfer. CH\(_1\)’s and CH\(_2\)’s transmission power, respectively, are

\[
P_0 = \frac{E_0}{(k + 1)\alpha + 1} = \eta \tau \cdot \frac{[\text{tr}(A_0Q_1^*) + \text{tr}(B_0Q_2^*)]}{(k + 1)\alpha + 1}
\]
respectively, is

\[ P_{k+1} = \frac{E_k + 1}{(N - k - 1)\alpha + 1}\]

(13)

\[ = \eta\tau: \text{tr} \left( A_k + iQ_i \right) + \text{tr} \left( B_k + iQ_2 \right) \]

(14)

Let \( s_i^{(3)}(t) \) expresses the baseband signal transmitted by the \( i \)th WD during the third stage. Then, the \( i \)th WD's information received by HAP2 and HAP1, respectively, is

\[ y_i^{(31)}(t) = \text{a}_i\sqrt{P_0}s_i^{(3)}(t) + \text{n}_i^{(31)}(t), \quad i = 0, \ldots, k \]

(14)

and

\[ y_i^{(32)}(t) = \text{b}_i\sqrt{P_0 + \text{a}_i^2}s_i^{(3)}(t) + \text{n}_i^{(32)}(t), \quad i = k + 2, \ldots, N - 1 \]

(15)

More specifically, Figure 3 shows the CHs first take \((1 + \alpha)\delta\) amount of time to transmit their own messages, and then relay each corresponding WD's message within \(\alpha\delta\) amount of time.

To maximize the received signal to noise ratio (SNR), HAP2 and HAP1 adopt the method of maximal ratio combining (MRC), in which their combined output SNR are

\[ \gamma^{(31)} = \frac{|a_i|^2P_0}{N_0} = \eta\tau h_0 \left[ \text{tr} \left( A_0Q_1^i \right) + \text{tr} \left( B_0Q_2^i \right) \right] \]

(16)

\[ = (k + 1)\alpha + 1\] \[ i = 0, \ldots, k \]

\[ \gamma^{(32)} = \frac{|a_i + 1|^2P_{k+1}}{N_0} = \eta\tau h_{k+1} \left[ \text{tr} \left( A_k + iQ_i \right) + \text{tr} \left( B_k + iQ_2 \right) \right] \]

(17)

\[ = (N - k - 1)\alpha + 1\] \[ i = k + 1, \ldots, N - 1 \]

Then, the data rates of CH1 at HAP2 and CH2 at HAP1, respectively, are

\[ R_0 = (1 + \alpha)\delta\log_2 \left( 1 + \gamma^{(31)} \right) \]

(18)

and

\[ R_{k+1} = (1 + \alpha)\delta\log_2 \left( 1 + \gamma^{(32)} \right) \]

(19)

However, HAP2 and HAP1 receive each CM's information in both the second and third stages, in which of the situation, the message for each CM can be decoded by HAP2 and HAP1 across two stages at a rate, respectively, given by

\[ R_{i}^{CH_1} = \min \{ R_{i}^{(2)}, V_i^{(21)} + \alpha\delta\log_2 \left( 1 + \gamma^{(31)} \right) \} \]

(20)

and

\[ R_{i}^{CH_2} = \min \{ R_{i}^{(2)}, V_i^{(22)} + \alpha\delta\log_2 \left( 1 + \gamma^{(32)} \right) \} \]

(21)

where \( R_{i}^{(2)} \) is given in equation (9), and \( V_i^{(21)} \) and \( V_i^{(22)} \) denote the messages separately extracted by HAP2 and HAP1 from their received signals in equations (7) and (8) (during the second stage) employing a best and optimal MRC receiver, which are, respectively, shown as

\[ V_i^{(21)} = \delta\log_2 \left( 1 + \frac{\eta\tau h_i \left[ \text{tr} \left( A_iQ_1^i \right) + \text{tr} \left( B_iQ_2^i \right) \right]}{N_0} \right), \]

(22)

\[ i = 1, \ldots, k \]

and

\[ V_i^{(22)} = \delta\log_2 \left( 1 + \frac{\eta\tau h_i \left[ \text{tr} \left( A_iQ_1^i \right) + \text{tr} \left( B_iQ_2^i \right) \right]}{N_0} \right), \]

(23)

\[ i = k + 2, \ldots, N - 1 \]

According to the data rates of WDs given in equations (20), (21), (22), and (23), both the spectral efficiency and fairness of our proposed protocol can be evaluated. More specifically, sum throughput performance can reflect spectral efficiency, that is

\[ R_{\text{sum}} = R_0 + \sum_{i=1}^{k} R_{i}^{CH_1} + R_{k+1} + \sum_{i=k+2}^{N-1} R_{i}^{CH_2} \]

(24)

Furthermore, considering the minimum data rate among the WDs can reflect the fairness of our proposed protocol, that is

\[ R_{\text{min}} = \min \{ R_0, R_1^{CH_1}, \ldots, R_k^{CH_1}, R_{k+1}, R_{k+2}^{CH_2}, \ldots, R_{N-1}^{CH_2} \} \]

(25)

It can be seen that the time allocation parameters \( \tau \) and \( \alpha \) determine the throughput performance. Consequently, the optimal performance in equation (24) or (25) can be more easily accessible by simply searching the feasible values of \( \tau \) and \( \alpha \) in two dimensions.

Benchmark method

The classical benchmark method Independent Transmission (IT)—with two multi-antenna HAPs adopting EB (IT with two HAPs)—has been compared
in this article. For a relatively fair comparison, all the WDs are assumed to use up their energy collected during the WIT stage and transfer at a fixed power, and the two HAPs use MRC scheme to maximize the received SNR.

For this approach, the first duration \( \tau \) is allocated as WET and the WDs use TDMA to pass their separate messages directly to their respective HAP for the rest of the time. The EB matrices \( Q_1' \) and \( Q_2' \) in the stage of WET are computed by maximizing the minimum received power among the WDs as shown below:

\[
\max_{Q>0} \quad \lambda'_1 + \lambda'_2 \\
\text{s.t.} \quad \text{tr}(Q_1'A_i) \leq P_1 \\
\text{tr}(Q_2'B_i) \leq P_2 \\
\text{tr}(Q_1'A_i) \geq \lambda'_i, \quad i = 0, \ldots, N - 1 \\
\text{tr}(Q_2'B_i) \geq \lambda'_i, \quad i = 0, \ldots, N - 1
\]  

(26)

Let \( Q_1'^* \) and \( Q_2'^* \) represent the problem’s (equation (26)) optimal solution. The WDs’ collected energy can be represented as

\[
E_{\text{intr}}^{\text{EB}} = \eta \text{tr}(A,Q_1') + \text{tr}(B,Q_2'), \quad i = 0, \ldots, N - 1
\]  

(27)

Then the WDs transfer their information to their corresponding HAP one by one, where the transmission of each WD spends \( \theta = (T - \tau \delta - t_0)/N \) amount of time. The \( i \)th WD’s combiner output SNR is

\[
\gamma_i^{(4)} = \frac{|a_i|^2 P_{\text{intr}}^{EB} N_0}{\theta N_0} = \frac{\eta \text{tr}(A,Q_1'^*) + \text{tr}(B,Q_2'^*)}{\theta N_0} \\
i = 0, \ldots, N - 1
\]  

(28)

In consequence, the WDs’ data rates at the two HAPs are

\[
K_{\text{intr}}^{EB} = \theta \log_2(1 + \gamma_i^{(4)}), \quad i = 0, \ldots, N - 1
\]  

(29)

**Numerical results**

This section evaluates our proposed novel system model’s throughput performance for WPCN by simulation software MATLAB to simulate. All figures below show various approaches of the performance for the minimum data rate or optimal sum throughput. The Powercast TX91501-3W transmitter and P2110 Power harvester are, respectively, adopted as energy transmitter at HAP1 and HAP2 with transmitting power \( P_1 = P_2 = 3 \text{ watts(W)} \) and energy receiver at each WD with energy harvesting efficiency \( \eta = 0.51 \) in all simulations (please see the detailed product specifications on the website of Powercast Co. http://www.powercastco.com). Except as otherwise noted, it is assumed that the number of antennas for both HAP1 and HAP2 and noise power in the bandwidth under consideration for all receivers are \( M = 5 \) and \( N_0 = 10^{-10} W/1 \) respectively.\(^{29–31,35}\) A path loss model is kept for the average channel gain between any two points, either HAP1 (HAP2) or a WD. \(^{29–31,35}\) A path loss model is kept for the average communication links on the throughput performance benchmark scheme IT with two HAPs in Section Benchmark method by fixing the cell radius \( r = 6 \) m when the distance \( d \) varies. Specifically, sum throughput (spectral efficiency) is also compared.

Unsurprisingly, the data rates for all three schemes go down as \( d \) goes up. However, as shown in Figure 4(a) and (b), our proposed scheme (CCCH with two CHs) for the maximum–minimum and sum throughput performance is the best of the three schemes. For instance, in Figure 4(a), when \( d = 5 \) m, CCCH with two CHs and CCHAP with two CHs are, respectively, over 2 and 1 times more than the benchmark scheme, when \( d \) adds up to 12 m, the throughput for the IT with two HAPs is approximated to 0, while the proposed method CCCH with two CHs can still keep a fairly high optimal throughput. This indicates that our proposed system model and clustering-collaboration interactive communication have obvious performance advantages when the distance from the cluster to HAP1 is reversely far away. This is in part due to the doubly-near-far problem, which reduces some far-off WDs’ data rate severely; however, our proposed scheme can efficiently help to relay the information of those far-off WDs.

Figure 5 demonstrates the influence of intra-cluster communication links on the throughput performance...
by setting $d = 9$ m and changing the cell radius $r$. As seen from Figure 5, with the increase of $r$, the proposed scheme’s performance is performed the best among the other two schemes; for example, in Figure 5(a) and (b), when $r = 3$ m, our proposed scheme’s maximum–minimum and sum throughput performance are, respectively, over 3 and 2 times larger than those of the benchmark method. Moreover, as $r$ increases, the other two methods’ throughput has a little change, but ours can remain reversely a high throughput. This means adopting EB technology at multi-antenna HAPs and clustering-collaboration interactive communication are necessary and helpful to enhance the system’s minimum throughput when $r$ is relatively big.

Finally, Figure 6 demonstrates the stability of throughput performance as the number of $N$ WDs ranges from 50 to 100 with an increase. In general, we fix $d = 9$ m and $r = 6$ m. As can be observed from Figure 6(a) that all schemes’ maximum and minimum throughput decreases with the increase of $N$. The reason is that the average transmission time assigned per WD is shorter, and thus the worst-performing WD’s data rate decreases. More specifically, as the number of $N$ WDs increases from 50 to 100, the decrease in

![Figure 4. Performance comparison of the various transmission methods when $r = 3$ m and the cluster-to-HAP, $d$ changes: (a) maximum–minimum throughput and (b) sum throughput.](image)

![Figure 5. Performance comparison of the various transmission methods when $d = 9$ m and the radius of the cluster $r$ changes: (a) maximum–minimum throughput and (b) sum throughput.](image)
maximum–minimum throughput is steady, whereas the maximum–minimum throughput decreases significantly when $N$ increases further. However, Figure 6(b) shows the sum throughput rises as $N$ goes up in spite of the probable decrease of the data rate per individual. This suggests that there exists a trade-off for the throughput of between each individual WD and aggregate network. In practice, even so, it can be still observed that our proposed method has a fairly high-performance gain compared to the benchmark method, in which in the case of relatively large networks (such as $N = 100$), the worst-performing WD can still keep an extremely high data rate.

**Conclusion**

In this article, a novel WPCN system model consisting of two HAPs with multiple antennas and a single antenna with $N$ WDs is studied. A new interactive communication protocol for clustering collaboration with multiple antennas is used to improve throughput fairness. EB technology at the multi-antenna two HAPs is adopted for achieving directional energy transfer to equilibrate the WDs’ diversified energy consumption levels, especially the high-power consumption of both CHs. Through the joint optimization of EB design, the allocation of transfer time between HAPs and WDs, the transmitting power of two CHs, and the problem of optimal maximum–minimum throughput among WDs are formulated. Extensive simulation results demonstrate that the proposed system model and multi-antenna clustering-collaboration interactive communication with TDMA can significantly improve user fairness and spectrum efficiency in various scenarios compared with representative benchmark methods.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was financially supported by Doctoral research project of Tongren University (trxyDH2003), Doctoral talent project of Tongren Science and Technology Bureau (No.[2020]124), and Basic Research Program of Guizhou Province-ZK[2021] General 299.

**ORCID iD**

Lina Yuan https://orcid.org/0000-0002-8060-9689

**References**

1. Ling M and Xiao X. Outage performance of double-relay cooperative transmission network with energy harvesting. *Phys Commun* 2018; 29: 261–267.
2. Bi S, Ho CK and Zhang R. Wireless powered communication: opportunities and challenges. *IEEE Commun Mag* 2015; 53(4): 117–125.
3. Bi S, Zeng Y and Zhang R. Wireless powered communication networks: an overview. *IEEE Commun Mag* 2016; 23(2): 1536–1284.
4. Bi S and Zhang R. Placement optimization of energy and information access points in wireless powered...
5. Aboelwafa N, Abd-Elmagid A and Biason A. Towards optimal resource allocation in wireless powered communication networks with non-orthogonal multiple access. Ad Hoc Netw 2019; 85: 1–10.

6. Abd-Elmagid A, ElBatt T and Seddik G. Optimization of energy-constrained wireless powered communication networks with heterogeneous nodes. Wireless Netw 2019; 25(2): 713–730.

7. Onalan G, Salik D and Coleri S. Relay selection, scheduling and power control in wireless powered cooperative communication networks. IEEE Trans Wireless Commun 2020; 19(11): 7181–7195.

8. Lu X, Wang P, Niyato D, et al. Wireless networks with RF energy harvesting: a contemporary survey. IEEE Commun Surv Tut 2015; 17(2): 757–789.

9. Xie L, Xu J and Zhang R. Throughput maximization for UAV-enabled wireless powered communication networks. IEEE Int Things J 2018; 6(2): 1690–1703.

10. Bi S and Zhang YJ. Computation rate maximization for wireless powered mobile-edge computing with binary computation offloading. IEEE Trans Wireless Commun 2018; 17(6): 4177–4190.

11. Wang J, Yang Y, Wang T, et al. Big data service architecture: a survey. J Internet Technol 2020; 21(2): 393–405.

12. Khan J, Sehrai DA, Khan MA, et al. Design and performance comparison of rotated y-shaped antenna using different metamaterial surfaces for 5G mobile devices. Comput Mater Con 2019; 60(2): 409–420.

13. Sehrai DA, Muhammad F, Kiani SH, et al. Gain-enhanced metamaterial-based antenna for 5G communication standards. Comput Mater Con 2020; 64(3): 1587–1599.

14. Zhang J, Zhong S, Wang T, et al. Blockchain-based systems and applications: a survey. J Internet Technol 2020; 21(1): 1–14.

15. Song M and Zheng M. Energy efficiency optimization for wireless powered sensor networks with nonorthogonal multiple access. IEEE Sensors Letters 2018; 2(1): 7500304.

16. Choi K, Rosyady P and Ginting L. Theory and experiment for wireless-powered sensor networks: how to keep sensors alive. IEEE Trans Wireless Commun 2018; 17(1): 430–444.

17. Tang Q, Yang K, Li P, et al. An energy efficient MCDS construction algorithm for wireless sensor networks. EURASIP J Wirel Commun Netw 2012; 2012: 83.

18. Ju H and Zhang R. Throughput maximization in wireless powered communication networks. IEEE Trans Wireless Commun 2014; 13(1): 418–428.

19. Che Y, Duan L and Zhang R. Spatial throughput maximization of wireless powered communication networks. IEEE J Select Areas Commun 2015; 33(8): 1534–1548.

20. Zhong M, Bi S and Lin X. User cooperation for enhanced throughput fairness in wireless powered communication networks. In: 23rd international conference on telecommunications, Thessaloniki, 16–18 May 2016, pp.1–6. New York: IEEE.

21. Chen H, Li Y, Rebelatto JL, et al. Harvest-then-cooperate: wireless-powered cooperative communications. IEEE Trans Signal Process 2015; 63(7): 1700–1711.

22. Ju H and Zhang R. User cooperation in wireless powered communication networks. In: IEEE global communications conference, Austin, TX, 8–12 December 2014, pp.1430–1435. New York: IEEE.

23. Zhong M, Bi S and Lin X. User cooperation for enhancement throughput fairness in wireless powered communication networks. Wireless Netw 2017; 23(4): 1315–1330.

24. Zhou Z, Peng M, Zhao Z, et al. Wireless-powered cooperative communications: power-splitting relaying with energy accumulation. IEEE J Select Areas Commun 2016; 34(4): 969–982.

25. Xiong K, Chen C, Qu G, et al. Group cooperation with optimal resource allocation in wireless powered communication networks. IEEE Trans Wireless Commun 2017; 16(6): 3840–3853.

26. Chen Z, Cai L, Cheng Y, et al. Sustainable cooperative communication in wireless powered networks with energy harvesting relay. IEEE Trans Wireless Commun 2017; 16(12): 8175–8189.

27. Zhai C, Zheng L, Lan P, et al. Wireless powered cooperative communication using two relays: protocol design and performance analysis. IEEE Trans Veh Technol 2018; 67(4): 3598–3611.

28. Chen H, Zhai C, Li Y, et al. Cooperative strategies for wireless-powered communications: an overview. IEEE Wireless Commun 2018; 25(4): 112–119.

29. Yuan L, Bi S, Zhang S, et al. Multi-antenna enabled cluster-based cooperation in wireless powered communication networks. IEEE Access 2017; 5: 13941–13950.

30. Yuan L, Bi S, Lin X, et al. Throughput maximization of cluster-based cooperation in underlay cognitive WPCNs. Computer Netw 2020; 166: 106853.

31. Yuan L, Chen H and Gong J. Throughput optimization of multi-hop and multi-path cooperation in WPSNs with hardware noises. Int J Distrib Sens N 2021; 17(6): 1–8.

32. Zhou X, Zhang R and Ho CK. Wireless information and power transfer: architecture design and rate-energy tradeoff. IEEE Trans Commun 2013; 61(11): 4754–4764.

33. Liu L, Zhang R and Chu KC. Multi-antenna wireless powered communication with energy beamforming. IEEE Trans Wireless Commun 2014; 62(12): 4349–4361.

34. Xu J and Zhang R. Energy beamforming with one-bit feedback. IEEE Trans Signal Process 2014; 62(20): 5370–5381.

35. Boyd S and Vandenberghe L. Convex optimization. Cambridge: Cambridge University Press, 2004.