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Multi-antenna Enabled Cluster-based Cooperation in Wireless Powered Communication Networks

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Abstract. In this paper, we consider a wireless powered communication network (WPCN) consisting of a multi-antenna hybrid access point (HAP) that transfers wireless energy in the downlink to wireless devices (WDs), and receives the information transmissions from the WDs in the uplink. To enhance the throughput performance of some far-away WDs, we allow one of the WDs acting as the cluster head that helps relay the information transmitted by the other cluster members. This cluster-based cooperation can effectively enhance the throughput performance of some far-away WDs. However, its performance is also limited by the high energy consumption of the cluster head. To tackle this energy imbalance issue, we propose in this paper to exploit the capability of multi-antenna energy beamforming technique at the HAP, which focuses more transferred power to the cluster head to balance the energy consumption of all the WDs. Specifically, we derive the throughput performance of the proposed scheme and demonstrate through simulations that the proposed multi-antenna enabled cluster-based cooperation can effectively improve the throughput fairness performance of the WPCNs.

Introduction

Battery-powered wireless devices (WDs) limit the performance of the modern mobile wireless communication system due to the limitations of battery life. Once the energy is depleted, a WD needs manual replacement/recharging of the battery. Frequent manual replacement/recharging will interrupt the operation of WDs and reduce the quality of service. Alternatively, dedicated wireless power transfer (WPT) technology can provide continuous and sustainable microwave energy over air to the WDs. The use of WPT can reduce the battery replacement/recharging cost, and also improve the communication quality by reducing their energy outages [1-8].

Wireless powered communications (WPC) is an important application of WPT, where the information transmissions of WDs, such as sensor, are powered by WPT. Despite of its extensive application, WPCN suffers from severe throughput issue. For example, [9] proposes a harvest-then-transmit protocol, where a hybrid access point (HAP) equipped with single antenna first broadcasts radio frequency (RF) energy to all WDs in the downlink, and then the WDs transmit their individual information with time-division-multiple-access (TDMA) to HAP using their harvested energy in the uplink. However, such design may lead to a doubly near-far unfairness problem that WDs far-away from HAP achieve low throughput because they harvest less energy and consume more to transmit information. To improve throughput fairness, different user cooperation methods are proposed [7,8,10,11]. For instance, [10] proposes a two-user cooperation, where the nearby user acts as a relay to forward the transmission of far-away user to the HAP. [7] and [8] allow the two users to exchange their information and form a distributed antenna system to transmit their information jointly. [11] further considers a general multiple user scenario, where a far-away user's transmission is assisted by multiple WDs.

In this paper, we propose a novel user cooperation method among a cluster of WDs, where one of the WDs acts as the cluster head (CH) to relay the information transmission of the other cluster members (CMs), as shown in Fig.1. The throughput performance of some far-away WDs can be greatly improved because of the reduced transmit power consumption. However, the disadvantage is that the CH may suffer from high energy consumption that can eventually restrict the network performance. To solve this energy imbalance problem, in this article we propose to exploit the capability of multi-antenna energy beamforming (EB) technique at the HAP, where the HAP can focus more transferred power to the CH to balance the energy consumption of all the WDs.

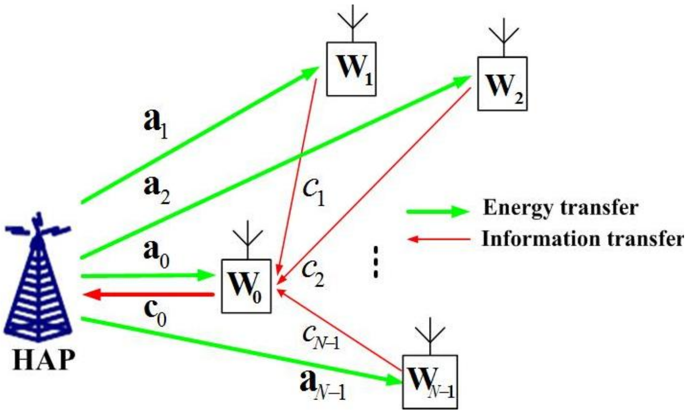

Fig. 1. A WPCN with WET in the downlink(DL) and WIT in the uplink(UL)

The main contributions of this paper are as follows.

Firstly, we propose a novel cluster-based cooperation protocol for improving the throughput performance in WPCNs. Our proposed method selects one of the WDs as the CH that helps relay the information transmitted by the other CMs to resolve the doubly-near-far problem for the far-away users.

Secondly, to address the high energy consumption issue of the CH, we propose to use multi-antenna EB technique at the HAP, which focuses more transferred power to the CH to balance the energy consumption of all the WDs.

Lastly, we derive the expression of throughput performance for the proposed scheme, and demonstrate through simulations that the proposed multi-antenna enabled cluster-based cooperation can effectively improve the throughput fairness performance of the WPCN.

System Model

Channel Model

As shown in Fig.1, this paper considers a WPCN consisting of one HAP and N WDs. Specifically, the HAP broadcasts wireless energy in the downlink (DL) and receives wireless information transmission (WIT) in the uplink (UL). The HAP has stable power supply to coordinate the WET/WIT to/from the N WDs. Each WD is equipped with a rechargeable battery to store the harvested wireless energy from the HAP. The HAP and all the WDs operate over the same frequency band, where a time division duplexing (TDD) circuit [12] is implemented at both the HAP and the WDs that separates the energy and information transmissions. In particular, the HAP is equipped with $M > 1$ antennas, while each WD is equipped with one single antenna.

In this paper, one of the WDs is selected as the CH that helps relay the UL WIT of the other cluster members (CMs). The method to select the CH will be discussed in Section IV. Without loss of generality, the CH is indexed as W_0 , and the CMs are indexed as $W_1, \cdots; W_{N-1}$. All the channels are assumed to be independent and reciprocal and follow quasi-static flat-fading, such that all the channel coefficients remain constant during each block transmission time, denoted by T, but can vary from block to block. The channel vectors between the HAP to W_i are denoted by $\mathbf{a}_i \in \mathbf{C}^{M\times 1}$ where $\mathbf{a}_i \sim CN(0,\delta_i^2\mathbf{I}),\ i = 0,\cdots,N-1.$ Besides, the channel coefficient from the j-th CM to the CH is denoted by $c_j \sim CN(0,\delta_j^2),\ j = 1,\cdots,N-1.$ The corresponding channel gains are denoted by $h_i \triangleq |\mathbf{a}_i|^2$ and $g_i \triangleq |c_i|^2$.

At the beginning of a transmission block channel estimation (CE) is performed within a fixed duration t_0. During the CE stage, the WDs take turns to broadcast their pilot signals, so that HAP has the knowledge of $\mathbf{a}_i$, $i = 0,\cdots,N-1$, and the CH knows c_i, $i = 1,\cdots,N-1.$ respectively. Then, the CH sends its estimation of c_i's to the HAP, such that the HAP has the full knowledge of CSI in the network.

Cluster-based Cooperation Protocol

As shown in Fig.2 after the CE stage, the cluster-based cooperative WPCN operates in three phases in each time block of duration T. In the first phase with time duration βT, $\beta \in (0,1)$ the HAP broadcasts wireless energy in the downlink with fixed transmit power P. In the next two phases with $(1-\beta)T - t_0$ amount of time, the N WDs transmit their independent information to the HAP using their individually harvested energy. Specifically, in the second phase, we assume that each of the $(N-1)$ CM transmits the individual message to the CH for δ amount of time. Notice that each CM's transmission can also be overheard by the HAP. In the third phase, the CH relays the decoded messages of the (N-1) CMs and transmits its own message to the HAP. The time taken to transmit a CM's message is assumed to be $\alpha\delta$, and the time taken to transmit its own message is $(1+\alpha)\delta$. This is to make sure that each WD's message is transmitted for $(1+\alpha)\delta$ amount of time across the second and the third phases.

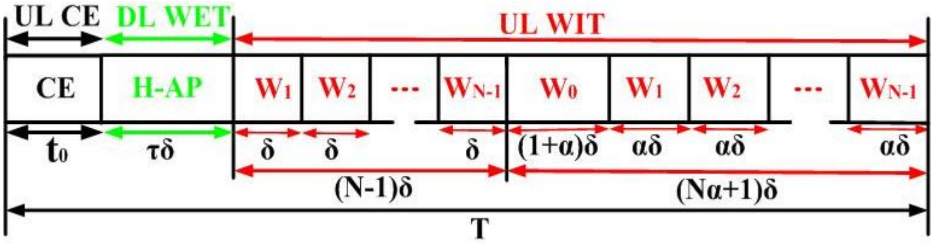

Fig. 2. The Cluster-Based Cooperation Protocol

For the simplicity of illustration, we let $\tau\delta \triangleq \beta T$, to denote the duration of the first phase. Then, we have

$$\mathrm{T} = \mathrm{t}_0 + \tau\delta + \mathrm{N}(1+\alpha)\delta \tag{1}$$

where τ and α are system parameters, and δ can be uniquely determined from the above equation. Without loss of generality, we assume $T = 1$ throughout this paper. We assume that the HAP calculates the optimal τ^* and α^* that leads to the maximum throughput performance, and then broadcasts to all the WDs the values of τ^* and α^*, such that all the WDs can keep their time-switching circuit synchronized for either energy and information transmissions. Notice that, besides the transmission in the third phase, the HAP can also overhear each WD's message in the second phase, although not dedicated to it, which can be used to improve the overall transmission rate compared to decoding the message in the third phase alone. In the next section, we derive the throughput performance of the proposed cooperation protocol.

Throughput Performance Analysis

Phase I: Energy Transfer Design

We notice that the CH needs to transmit *N* messages in total, which would consume significantly more energy than the other CMs. Therefore, the received energy of the CH is the performance bottleneck of the network. To balance the energy consumed and received, we consider in this paper an energy beamforming [13,14] technology to focus the transmitted energy to the CH. Specifically, in the first phase of time $\tau\delta$, the HAP transmits $\mathbf{w}(t) \in \mathbf{C}^{M\times 1}$ random energy signals on the *M* antennas. Specifically, the transmit power of HAP is constrained by

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

where $tr(\cdot)$ denotes the trace of a matrix and $(\cdot)^H$ denotes the complex conjugate operator. Then, the received energy signal by the *i*-th WD is

$$\mathrm{y}_{\mathrm{i}}^{(1)}(\mathrm{t}) = \mathbf{a}_{\mathrm{i}}^{\mathrm{T}}\mathbf{w}(\mathrm{t}) + \mathrm{n}_{\mathrm{i}}^{(1)}(\mathrm{t}),\ \mathrm{t} \in [\mathrm{t}_0, \mathrm{t}_0 + \tau\delta],\ \mathrm{i} = 0, \cdots, \mathrm{N}-1 \tag{3}$$

where $n_i^{(1)}(t)$ denotes the receiver noise power in the first phase. With the noise power neglected, the amount of energy harvested by the WDs can be expressed as [9]

$$\mathrm{E}_{\mathrm{i}} = \eta\tau\delta \cdot \mathrm{E}\left[\left|\mathrm{y}_{\mathrm{i}}^{(1)}(\mathrm{t})\right|^2\right] = \eta\tau\delta \cdot \mathrm{tr}(\mathbf{A}_{\mathrm{i}}\mathbf{Q}),\ \mathrm{i} = 0, \cdots, \mathrm{N}-1. \tag{4}$$

Here, $\mathbf{A}_{\mathrm{i}} \triangleq \mathbf{a}_i\mathbf{a}_i^H$ and $0 < \eta < 1$ denotes the energy harvesting efficiency, which is assumed equal for all the WDs.

In this paper, the energy beamforming matrix $\mathbf{Q}$ in (4) is designed by solving the following optimization problem,

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

The objective is to maximize the minimum receive power among the *N* WDs. Specifically, $\mathbf{Q} \succ= 0$ indicates that $\mathbf{Q}$ is a positive semidefinite matrix. The two constraints indicate that the received power of the CH is at least $(\alpha N+1)$ times of the minimum receive power among the (*N*-1) CMs. This matches our intuition that the transmission duration of a CH is $(\alpha N+1)$ times of a CM.

Phase II: Intra-cluster Transmissions

Let $\mathbf{Q}^*$ denote the optimal solution to (5), then the received energy by the *i*-th WD is $E_i=\eta\tau\delta\cdot tr(\mathbf{A}_i\mathbf{Q}^*)$, $i=1,\cdots,N-1$. In the second phase, the CMs take turns to transmit their messages to the CH, where each CM's transmission takes δ amount of time. We assume that the CMs exhaust the harvested energy, and each transmits with a constant power during the second stage. Then, the transmit power of the *i*-th CM is $P_i=E_i/\delta=\eta\tau\cdot tr(\mathbf{A}_i\mathbf{Q}^*)$, $i=1,\cdots,N-1$. Let $s_i^{(2)}(t)$ denote the baseband signal of the *i*-th WD transmitted in the second phase with $E[|s_i^{(2)}(t)|^2]=1$, the received signals at CH are then expressed as

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

where $i=1,\cdots,N-1$, and $n_i^{(2)}(t)$ denotes the receiver noise at the CH with noise power $E[|n_i^{(2)}(t)|^2]=N_0$. Then, the CH can decode the CMs' messages at rates given by

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

Meanwhile, the HAP can also overhear the transmission of the CMs, such that it receives

$$y_{H,i}^{(2)}(t)=\mathbf{a}_i\sqrt{P_i}s_i^{(2)}(t)+n_{H,i}^{(2)}(t)\ . \tag{8}$$

during $t\in(t_0+(\tau+i-1)\delta,\ t_0+(\tau+i)\delta]$, where $i=1,\cdots,N-1$ and $n_{H,i}^{(2)}\sim CN(0,N_0\mathbf{I})$.

Phase III: Cluster-to-HAP Transmission

After decoding the CMs' messages, the CH transmits the (*N*-1) CMs' messages along with its own message one by one to the HAP, where each message transmission takes $\alpha\delta$ amount of time. The transmit power of the CH is

$$P_0=\frac{E_0}{(\alpha N+1)\delta}=\frac{\eta\tau}{\alpha N+1}tr(\mathbf{A}_0\mathbf{Q}^*). \tag{9}$$

Let $s_i^{(3)}(t)$ denote the baseband signal of the *i*-th WD transmitted in the third phase. Then, the HAP receives the *i*-th WD's message as

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

Specifically, as shown in Fig.2 the CH first transmits its own message using $(1+\alpha)\delta$ amount of time, and then relays each WD's message in $\alpha\delta$ amount of time.

The HAP uses maximal ratio combining (MRC) method to maximize the receive signal-to-noise power ratio (SNR), where the combiner output SNR is

$$\gamma^{(3)}=\frac{|\mathbf{a}_i|^2P_0}{N_0}=\frac{\eta\tau\cdot h_0\cdot tr(\mathbf{A}_0\mathbf{Q}*)}{(\alpha N+1)N_0}. \tag{11}$$

Then, the data rate of the CH at the HAP is

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

For each CM's message, however, is received in both the second and third phases. In this case, the HAP can jointly decode each CM's message across two phases at a rate given by

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

Here, $R_i^{(2)}$ is given in (7). $V_i^{(2)}$ denotes the information that can be extracted by the HAP from the received signal in (6) (in the second phase) using an optimal MRC receiver, which is given by

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

With the WDs' data rates given in (12) and (13), we can evaluate both the spectral efficiency and fairness of the proposed protocol. Specifically, the spectral efficiency can be reflected from the sum throughput performance, i.e.,

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

Besides, the fairness of the proposed protocol can be reflected by considering the minimum data rate among the WDs [9], i.e.,

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

We can see that the throughput performance is determined by the time allocation parameter τ and α. Therefore, the optimal performance in (15) or (16) can be easily obtained through a two-dimension search over feasible values of τ and α.

Benchmark Method

For performance comparison, we consider three benchmark methods. For fair comparisons, we assume that all the WDs exhaust their harvested energy and transmit with constant power in the WIT stage, and the HAP uses MRC method to maximize the receive SNR.

Cooperation without EB. The only difference from the proposed cooperation in this paper is that the HAP transmits wireless energy isotropically to the WDs during the WET phase, i.e., the transmit beamforming matrix satisfies $\mathbf{Q} = \mathbf{I}P/M$ where $\mathbf{I}P/M$ is an identity matrix.

Non-cooperation with EB. For this method, the first time slot $\tau\delta$ is assigned for WET and the WDs transmit their independent information to the HAP directly in the remaining time using TDMA. The energy beamforming matrix $\mathbf{Q}$ during the WET stage is calculated by maximizing the minimum received power among the WDs as follows:

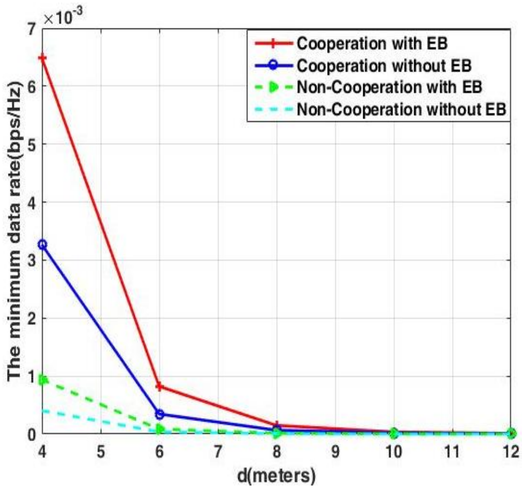

Fig. 3. The impact of the distance to the minimum throughput.

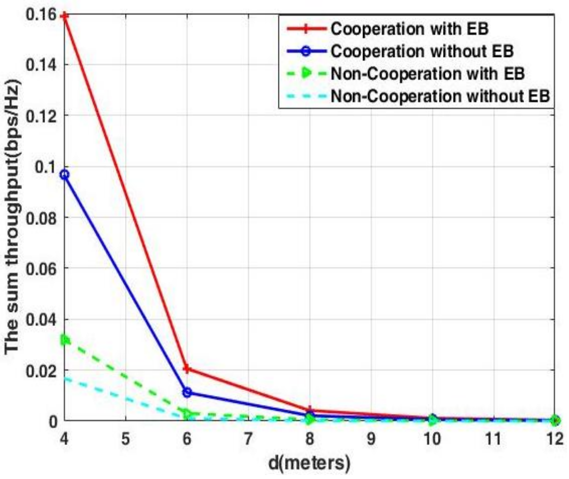

Fig. 4. The impact of the distance to the sum throughput.

$$\begin{aligned} &\max_{\mathbf{Q}_1 \succ= 0} \ \lambda_1 \\ &\text{s.t.} \ \ \mathrm{tr}(\mathbf{Q}_1 \mathbf{A}_i) \le \mathrm{P}, \\ &\qquad \mathrm{tr}(\mathbf{Q}_1 \mathbf{A}_i) \ge \lambda_1, \ \ i = 0, \cdots, N-1. \end{aligned} \tag{17}$$

Let $\mathbf{Q}_1^*$ denote the optimal solution to (17). The amount of energy harvested by the WDs can be expressed as

$$\mathrm{E}_{\mathrm{i}_{\mathrm{HTT}}}^{\mathrm{EB}} = \eta\tau\delta \cdot \mathrm{tr}(\mathbf{A}_i \mathbf{Q}_1), \ \ i = 0, \cdots, N-1. \tag{18}$$

Then the WDs take turns to transmit their messages to the HAP, where each WD's transmission takes $\theta = (T - \tau\delta - t_0)/N$ amount of time. The combiner's output SNR for the *i*-th WD is

$$\gamma_i^{(4)} = \frac{|\mathbf{a}_i|^2 \mathrm{P}_{\mathrm{i}_{\mathrm{HTT}}}^{\mathrm{EB}}}{\mathrm{N}_0} = \frac{\eta\tau\delta \cdot h_i \cdot \mathrm{tr}(\mathbf{A}_i \mathbf{Q}_1^*)}{\mathrm{N}_0 \theta}, \ \ i = 0, \cdots, N-1. \tag{19}$$

Therefore, the data rates of the WDs at the HAP are

$$\mathrm{R}_{\mathrm{i}_{\mathrm{HTT}}}^{\mathrm{EB}} = \theta \log_2 \left(1 + \gamma_i^{(4)}\right), \ \ i = 0, \cdots, N-1. \tag{20}$$

Non-cooperation without EB. In this case, the HAP transmits isotropically with $\mathbf{Q} = \mathbf{I} P/M$ during the WET stage, and then the WDs transmit independently to the HAP after harvesting energy in a TDMA manner with equal transmit time. The data rate can be similarly expressed as in (20) and (19), but with $\mathbf{Q}_1^* = \mathbf{I} P/M$.

Numeral Results

In this section, we evaluate the performance of the proposed cooperation method. In all figures, the optimal sum throughput or minimum data rate performance of different schemes is presented. Unless otherwise stated, it is assumed that the number of antennas at HAP is $M = 5$ the energy receiver harvesting efficiency is 1, the transmit

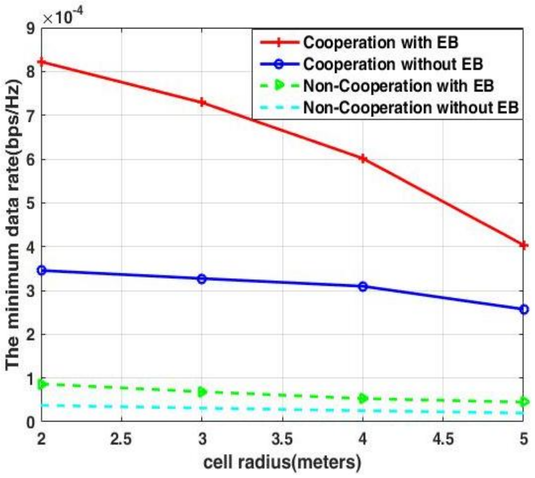

Fig. 5. The impact of the cell radius to the minimum throughput.

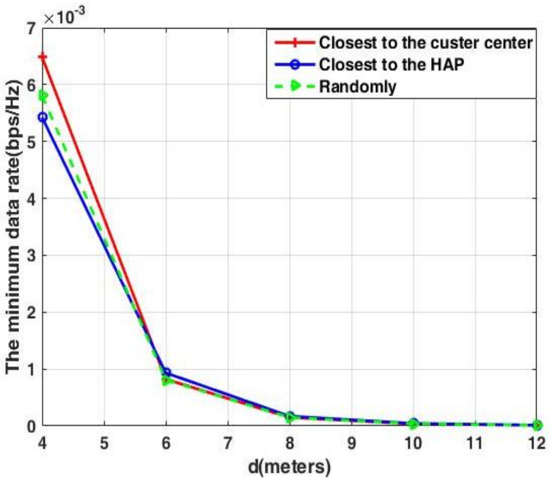

Fig. 6. The impact of cluster head selection to the minimum throughput.

power of HAP is $P = 3$W, and the noise power $N_0 = 10^{-10}$W in the considered bandwidth for all receivers. The mean channel gain between any two nodes, either the HAP or a WD, follows a path loss model. For instance, let $d_{H,i}$ denote the distance between the HAP and the *i*-th WD, then $\delta_i^2 = \left((3\times10^8)/(4\pi d_{H,i}\, f_c)\right)^{d_D}$, where d_D is the path loss factor during downlink WET and uplink WIT, which is set as 3 [6], and $f_c = 915$MHz [10].

Unless otherwise stated, we assume that 15 WDs are uniformly distributed within a circle cell with radius r, and the circle's center is d away from the HAP. Besides, the WD closest to the center is chosen as the cluster head. Each point in the following figures is an average of 20 independent WD placements.

In Fig.3, we fix the cell radius as 2 m (meters) and compare the average minimum data rate among all the WDs achieved by the proposed method with the benchmark schemes when the distance d changes. As expected, the data rates of all the schemes decrease as the distance increases. However, it is also observed from Fig.3 that the performance of our proposed scheme (Cooperation with EB) is the best among the four schemes. For example, when $d = 4$ m, the proposed method is over 2 times larger than that of the Cooperation without EB, when d increases to 8 m, the throughput of the three benchmark schemes is close to 0, while the proposed method can still keep fairly high throughput. This shows that the performance advantage of the proposed cluster-based cooperation is especially evident when the cluster is relatively far away from the HAP. This is partly because the doubly-near-far problem severely degrades the data rate of some far-away users, while our proposed method can effectively help relay those far-away users' messages.

In Fig.4, we use the same setup as in Fig.3 but compare the sum throughput performance of the above four schemes. Still, the performance of our proposed method significantly outperforms the other three schemes. However, the performance advantage is not that evident as in Fig.3 mainly because our major design objective is to enhance fairness, while spectrum efficiency is the secondary concern.

In Fig.5, we evaluate the minimum data rate performance by fixing $d = 6$ m and change the cell radius r. We can infer that the minimum data rate decreases as the radius increases, because the maximum distance from the HAP to the WDs increases as well. It can be seen from Fig.6 that the performance of our proposed method is the best among all the four schemes as r increases, for instance, when $r = 2$m, the proposed method is over 2 times greater than that of the Cooperation without EB. Moreover, with the increase of r, the throughput of the other three schemes is in close proximity to 0, but ours can still hold relatively high throughput. This suggests that using EB technology at the HAP and cooperative transmission is necessary and helps in improving the minimum throughput of the system when r is large.

At last, we use the same setup as in Fig.3 and investigate the impact of the cluster head selection method on the minimum throughput of the WPCNs. Specifically, we consider three cluster head selection methods: the WD closest to the cluster center, closest to the HAP, or randomly select a WD as the CH. As expected, the data rates of the three methods decrease as the distance increases. However, it is observed from Fig.6 that when d is small ($d \leq 6$ m), selecting the WD closest to the cluster center has the best performance among the three different cluster head selection methods. However, the performance advantage becomes marginal when d is large. This is because the intra-cluster communication quality dominates the overall performance when d is small, such that selecting the WD closest to the cell center achieves the maximum average intra-cluster communication performance. Meanwhile, the inter-cluster link dominates when d is large, such that the performance disparity among different CH selection methods becomes marginal. Overall, selecting a WD closest to the cell center achieve good performance under different network setups.

Conclusion

This paper studied a WPCN consisting of a multi-antenna HAP and N WDs, where a novel multi-antenna enabled cluster-based cooperation method is exploited to improve the throughput fairness. We applied energy beamforming technique at the HAP to focus more transferred power to the cluster head to balance the energy consumption of all the WDs. We derived the throughput performance of the proposed scheme, and by comparing with three representative benchmark methods and three ways of cluster head selection, we demonstrated through simulations that the proposed multi-antenna enabled cluster-based cooperation can effectively improve the throughput fairness performance of the WPCNs under different setups.

Acknowledgements

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