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An OFDM based interference reducing scheme with trajectory and resource optimization for UAV-powered IoT Networks

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Abstract

The massive and pervasive deployment of sensors for information collecting in IoT networks result to the scarcity of energy. Unmanned aerial vehicle (UAV) enabled wireless power transfer (WPT) is a feasible solution to provide energy for pervasively deployed sensors. In this paper, we propose an orthogonal frequency division multiplexing (OFDM) based interference reducing scheme with trajectory and resource optimization for UAV-powered IoT networks. The simulation results show that our proposed scheme outperforms two benchmark schemes in sum transmission rate.

1 Introduction

With the commercialization of 5G, Internet of Things (IoT) has been integrated into our everyday life. Sensors are fundamental components of IoT networks due to their function of environmental information collecting for data processing and analyzing, which requires for tremendous energy. [1]. Thus, how to provide adequate energy for sensors nodes becomes a practical challenge.

Energy harvesting (EH) has been proposed to extend the life time of sensors nodes by harvesting energy from the environment, e.g., solar, wind and thermal [2]. However, a critical problem of EH is that the harvested energy is unstable due to the uncertainty of the weather and other environmental factors [3]. Wireless power transfer provides IoT sensors with more reliable energy supply by harvesting energy from radio frequency (RF) signal, in which the channel power gain depends on the distance between energy transmitter and receiver. UAV-enabled WPT is able to improve the channel power gain by flexible trajectory optimization, which has attracted significant attention [4]-[5]. Another challenge of IoT networks is that interference exists at the receiver when multiple sensor nodes transmit their collected information. Orthogonal frequency division multiplexing (OFDM) enables efficient signal transmission by flexibly allocating the transmission power over orthogonal subcarriers to avoid interference, which has been adopted by the 5G network standards [6].

In this paper, we propose an OFDM based interference reducing scheme with resource and UAV trajectory optimization for UAV-powered IoT networks. In the proposed scheme, two UAV-powered ground sensors nodes GN 1 and GN 2 transmit their collected information with the harvested energy to the corresponding UAV in the uplink. Two UAVs fly from given start points to end points at a fixed altitude H. The UAVs' trajectories and resource allocation are optimized to achieve larger sum transmission rate of two GNs. The advantage of our proposed scheme over two benchmark schemes is verified in the simulation.

2 System Model

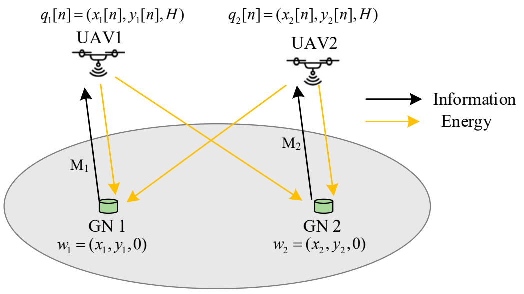

Figure 1. Proposed system model.

As shown in Figure 1, the proposed system model includes two UAVs denoted as UAV 1 and UAV 2, and two wireless powered ground sensor nodes GN 1 and GN 2, which are deployed at w_1 and w_2, respectively. We assume that two UAVs fly from start point $q_i[0]$ to end point $q_i[N]$, $i \in \{1,2\}$, at a fixed altitude H in limited time T. The trajectories of UAVs are equally discretized into N time slots with length of δ. In each time slot $n \in N$, UAV i is assumed to hover at $q_i[n]$. Each time slot n is divided into a information transmission phase $\delta_I[n]$ and an energy transferring phase $\delta_E[n]$. In the $\delta_E[n]$, GN 1 and GN 2 harvest energy from both two UAVs. Then, in the $\delta_I[n]$, two GNs transmit the collected information to the corresponding UAV over orthogonal subcarriers with the harvested energy. The total number of subcarriers is denoted as W.

3 Problem Formulation

In this paper, we aim to maximized the sum transmission rate of GN 1 and GN 2 while ensuring the minimum transmission rate R_{th} of each sensor node by optimizing UAVs' trajectories, time allocation and information transmission power. The distance between UAV j and GN i is given by

$$d_{q_j,w_i}[n] = \sqrt{||q_j[n] - w_i||^2 + H^2} \tag{1}$$

The channel power gain of the link UAV $j \to$ GN i in time slot n over subcarrier k is given by

$$\begin{aligned} h_{q_j,w_i}[n][k] &= \left|\sqrt{\beta_{q_j,w_i}[n]} g_{q_j,w_i}[k]\right|^2 \\ &= \beta_0 \left|g_{q_j,w_i}[k]\right|^2 d_{q_j,w_i}^{-\alpha}[n], \end{aligned} \tag{2}$$

where

$$\beta_{q_j,w_i}[n] = \beta_0 d_{q_j,w_i}^{-\alpha}[n], \tag{3}$$

$$g_{q_j,w_i}[k] = \sqrt{\frac{K}{K+1}}\tilde{g} + \sqrt{\frac{1}{K+1}}\hat{g}[k], \tag{4}$$

where $\alpha = 2$ denotes the path loss exponent, $\beta_0 = 10^{-3}$ denotes the average channel power gain at the reference distance of $d_0 = 1m$, K denotes the Rician factor of the uplink channel between UAVs and GNs, $\tilde{g}$ and $\hat{g}$ denote the deterministic LoS channel component and Rayleigh fading factor, respectively. The total energy consumed by GN i is given by

$$Q_i^{total} = \sum_{k \in M_i} \sum_{n=1}^{N} Q_i[n][k], \tag{5}$$

where $Q_i[n][k]$ denotes the transmission power of GN i in the time slot n over subcarrier k. The total harvested energy at GN i is given by

$$E_i^{total} = \sum_{n=1}^{N} \sum_{k=1}^{W} E_i[n][k], \tag{6}$$

where

$$E_i[n][k] = \eta p_k \delta_E[n] (h_{q_i,w_i}[n][k] + h_{q_j,w_i}[n][k]), \tag{7}$$

where $i \in \{1,2\}, j \in \{1,2\}, i \neq j$, $p_k = \dfrac{P}{W}$ denotes the power transferred by UAV over subcarrier k, η denote the energy conversion efficiency, and P denotes the total energy transfer power. The information transmission rate in time slot n over subcarrier k of GN i is given by

$$r_i[n][k] = \frac{\delta_I[n]}{\delta} \log_2\left(1 + \frac{Q_i[n][k] h_{q_i,w_i}[n][k]}{\sigma^2}\right) \tag{8}$$

where $k \in M_i, n \in N, i \in \{1,2\}$, and σ denotes the noise power. The subcarriers in M are allocated as follows. First, allocate the subcarriers in M to M_1 one by one in descending order of $h_{q_1,w_1}[n][k]$ until R_1 reaches the minimum transmission rate R_{th}. Then, allocate the remaining subcarriers in M to M_2 in similar way until R_2 reaches R_{th}. Finally, the remaining subcarriers in M is allocated to M_1 if $h_{q_1,w_1}[n][k] > h_{q_2,w_2}[n][k]$, which is otherwise allocated to M_2. The optimization problem is given by

$$(P1): \max_{\{A,B,C\}} \frac{1}{N} \sum_{n=1}^{N} \left(\sum_{k \in M_1} r_1[n][k] + \sum_{k \in M_2} r_2[n][k] \right) \tag{9}$$

subject to

$$\begin{aligned} &C1: Q_i^{total} \leq E_i^{total}, \forall i \in \{1,2\} \\ &C2: \delta_E[n] + \delta_I[n] \leq \delta, \forall n \in N \\ &C3: 0 \leq \delta_I[n] \leq \delta, 0 \leq \delta_E[n] \leq \delta, \forall n \in N \\ &C4: ||q_i[n] - q_i[n-1]||^2 \leq S_{\max}^2, \forall n \in N \\ &C5: ||q_1[n] - q_2[n]||^2 \geq d_{\min}^2, \forall n \in N \\ &C6: \frac{1}{N} \sum_{n=1}^{N} \sum_{k \in M_i} r_i[n][k] \geq R_{th}, i \in \{1,2\} \end{aligned}$$

where $A = \{Q_1[n][k], Q_2[n][k]\}$ denotes the transmission power allocation, $B = \{q_1[n], q_2[n]\}$ denotes the UAVs' trajectories and $C = \{\delta_E[n], \delta_I[n]\}$ denotes the time allocation.

4 Problem Solution

It is easy to find that problem (P1) is non-convex. Thus, we decompose (P1) into the following three subproblems which are solved iteratively by utilizing the successive convex programming (SCP) technique [7].

4.1 Power Allocation

Due to the independency of the energy harvested by GN 1 and GN 2, the power allocation of them can be optimized respectively. With given time allocation and UAVs' trajectory, the power allocation optimization problems are given by

$$(P2.1): \max_{\{Q_1\}} \frac{\delta_I[n]}{N\delta} \sum_{n=1}^{N} \sum_{k \in M_1} \log_2\left(1 + \frac{Q_1[n][k] h_{q_1,w_1}[n][k]}{\sigma^2}\right) \tag{10}$$

subject to

$$C7: Q_1^{total} \leq E_1^{total}$$

$$(P2.2): \max_{\{Q_2\}} \frac{\delta_I[n]}{N\delta} \sum_{n=1}^{N} \sum_{k \in M_2} \log_2\left(1 + \frac{Q_2[n][k] h_{q_2,w_2}[n][k]}{\sigma^2}\right) \tag{11}$$

subject to

$$C8: Q_2^{total} \leq E_2^{total}$$

Problem (P2.1) and (P2.2) are convex, which can be solved by Lagrange dual method. The Lagrange function is given by

$$\begin{aligned} L(\lambda_i, Q_i) &= \frac{\delta_I[n]}{N\delta}\sum_{n=1}^{N}\sum_{k\in M_i}\log_2\left(1+\frac{Q_i[n][k]h_{q_i,w_i}[n][k]}{\sigma^2}\right) \\ &+ \lambda_i\left(E_i^{total}-\sum_{n=1}^{N}\sum_{k=1}^{K}\delta_I[n]Q_i[n][k]\right). \end{aligned} \tag{12}$$

According to the Karush-Kuhn-Tucker (KKT) conditions, the optimal solution is achieved when $\frac{\partial L}{\partial Q_1[n][k]}=0$, we can obtain

$$Q_i[n][k] = \frac{\sigma^2}{h_{q_i,w_i}[n][k]}\left(\frac{1}{\lambda_i N\delta\ln 2}-1\right). \tag{13}$$

Obviously, the transmission power is non-negative, i.e., $Q_i[n][k], i\in\{1,2\}\geq 0$. Consequently, the feasible region of dual variable is $\lambda_i\in\left(0,\frac{1}{N\delta\ln 2}\right]$, and the optimal dual variable λ_i^* can be obtained by gradient descent algorithm. The dual variable at $t-th$ iteration is updated according to

$$\Delta\lambda_i = E_i^{total}-\sum_{n=1}^{N}\sum_{k=1}^{K}\delta_I[n]Q_i[n][k], \tag{14}$$

$$\lambda_i^{(t+1)} = \lambda_i^{(t)}+step(t)\cdot\Delta\lambda_i^{(t)}. \tag{15}$$

4.2 Time Allocation

With given power allocation and UAVs' trajectories, the time allocation optimization problem is given by

$$(P3): \max_{\{C\}} \frac{1}{N}\sum_{n=1}^{N}\left(\sum_{k\in M_1} r_1[n][k]+\sum_{k\in M_2} r_2[n][k]\right) \tag{16}$$

subject to

$$C1-C3, C6$$

Problem (P3) is a linear programming problem, which can be solved by standard optimization techniques.

4.3 UAVs' Trajectories Optimization

We introduce a auxiliary variable R, and substitute (1), (2), (5), (6) and (7) into (P1) to formulate the UAVs' trajectories optimization problem with power allocation and time allocation, which is given by

$$(P4): \max_{\{B\}} R \tag{17}$$

subject to

$$C9: \frac{\delta_I[n]}{N\delta}\sum_{n=1}^{N}\sum_{i=1}^{2}\sum_{k\in M_i}\log_2\left(1+\frac{Q_i[n][k]\beta_0\left|g_{q_i,w_i}[k]\right|^2}{(||q_i-w_i||^2+H^2)\sigma^2}\right)\geq R$$

$$\begin{aligned} C10: &\sum_{n=1}^{N}\sum_{k=1}^{W}\eta p_k\delta_E[n]\left(\frac{\beta_0\left|g_{q_i,w_i}[k]\right|^2}{||q_{ij}-w_i||^2+H^2}+\frac{\beta_0\left|g_{q_j,w_i}[k]\right|^2}{||q_j-w_i||^2+H^2}\right) \\ &-\sum_{n=1}^{N}\sum_{k=1}^{W}\delta_I[n]Q_i[n][k]\geq 0, i\neq j \end{aligned}$$

$$C11: ||q_{ij}[n]-q_i[n-1]||^2\leq S_{\max}^2, \forall n\in N$$

$$C12: ||q_1[n]-q_2[n]||^2\geq d_{\min}^2, \forall n\in N$$

$$C13: \frac{\delta_I[n]}{N\delta}\sum_{n=1}^{N}\sum_{k\in M_i}\log_2\left(1+\frac{Q_i[n][k]\beta_0\left|g_{q_i,w_i}[k]\right|^2}{(||q_i-w_i||^2+H^2)\sigma^2}\right)\geq R_{th}$$

It is easy to find that the constraints of $C9$, $C10$, $C12$ and $C13$ are non-convex. Thus, problem (P4) is non-convex, which is difficult to obtain the optimal solution. We utilize SCP technique to solve (P4), in which the non-convex constraints are approximated to their lower bounds at each iteration. Thus, with any given UAV trajectory $q_j^{(t)}[n]$ at $t-th$ iteration, we can obtain

$$\begin{aligned} r_i^{lb}[n][k] &\leq \log_2\left(1+\frac{Q_i[n][k]\beta_0\left|g_{q_i,w_i}[k]\right|^2}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right) \\ &\triangleq \log_2\left((||q_i[n]-w_i||^2+H^2)\sigma^2+Q_i[n][k]g_{q_i,w_i}[k]\right) \\ &- \log_2\left((||q_i^{(t)}[n]-w_i||^2+H^2)\sigma^2\right) \\ &+ \frac{\hat{q}_i^{(t)}[n]\log_2(e)}{(||q_i^{(t)}[n]-w_i||^2+H^2)}, \end{aligned} \tag{18}$$

where $\hat{q}_i^{(t)}[n]=|q_i[n]-w_i||^2-|q_i^{(t)}[n]-w_i||^2$.

$$\begin{aligned} E_i[n][k] &= \eta p_k\delta_E[n]\left(\frac{\beta_0\left|g_{q_i,w_i}[k]\right|^2}{||q_i-w_i||^2+H^2}+\frac{\beta_0\left|g_{q_j,w_i}[k]\right|^2}{||q_j-w_i||^2+H^2}\right) \\ &\geq \frac{2C_{n,k}\left|g_{q_i,w_i}[k]\right|^2}{\left\|q_i^{(t)}[n]-w_i\right\|^2+H^2}+\frac{2C_{n,k}\left|g_{q_j,w_i}[k]\right|^2}{\left\|q_j^{(t)}[n]-w_i\right\|^2+H^2} \\ &- \frac{C_{n,k}\left|g_{q_i,w_i}[k]\right|^2(H^2+\|q_i[n]-w_i\|^2)}{(\left\|q_i^{(t)}[n]-w_i\right\|^2+H^2)^2} \\ &- \frac{C_{n,k}\left|g_{q_j,w_i}[k]\right|^2(H^2+\|q_j[n]-w_i\|^2)}{(\left\|q_j^{(t)}[n]-w_i\right\|^2+H^2)^2}) \\ &\triangleq E_i^{lb}[n][k], \end{aligned} \tag{19}$$

where $C_{n,k}=\eta p_k\beta_0\delta_E[n]$, $i\in\{1,2\}, j\in\{1,2\}, i\neq j$.

$$\begin{aligned} ||q_1[n]-q_2[n]||^2 &\geq -||q_1^k[n]-q_2^k[n]||^2 \\ &+ 2(q_1^k[n]-q_2^k[n])^T(q_1[n]-q_2[n]). \end{aligned} \tag{20}$$

With the lower bounds in (18), (19), (20) and any given $q_i^{(t)}[n]$, problem (P4) can be approximated to

$$(P4.1): \max_{\{B\}} R \tag{21}$$

subject to

$$
\begin{aligned}
&C14{:}\frac{\delta_I[n]}{N\delta}\left(\sum_{n=1}^{N}\sum_{k\in M_1} r_1^{lb}[n][k]+\sum_{n=1}^{N}\sum_{k\in M_2} r_2^{lb}[n][k]\right)\geq R\\
&C15{:}\sum_{n=1}^{N}\sum_{k=1}^{K}\left(E_i^{lb}[n][k]-\delta_I[n]Q_i[n][k]\right)\geq 0, i\in\{1,2\}\\
&C16{:}||q_i[n]-q_i[n-1]||^2\leq S_{\max}^2, \forall n\in N, i\in\{1,2\}\\
&C17{:}-||q_1^k[n]-q_2^k[n]||^2+2(q_1^k[n]-q_2^k[n])^T(q_1[n]-q_2[n])\geq d_{\min}^2\\
&C18{:}\frac{\delta_I[n]}{N\delta}\sum_{n=1}^{N}\sum_{k\in M_i} r_i^{lb}[n][k]\geq R_{th}, i\in\{1,2\}
\end{aligned}
$$

Problem (4.1) is convex, which can be solved by standard optimization techniques. In summary, subproblems (P2.1), (P2.2), (P3) and (P4) and are solved in an alternating manner by SCP technique to a feasible solution to (P1).

5 Simulation Results

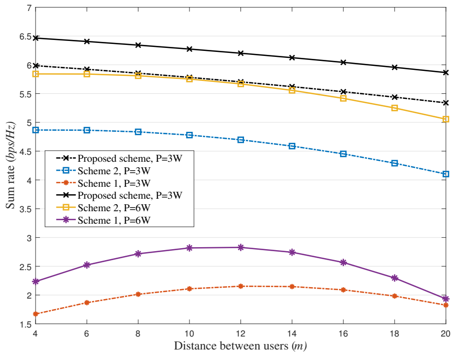

Figure 2. Sum transmission rate versus the distance between two GNs

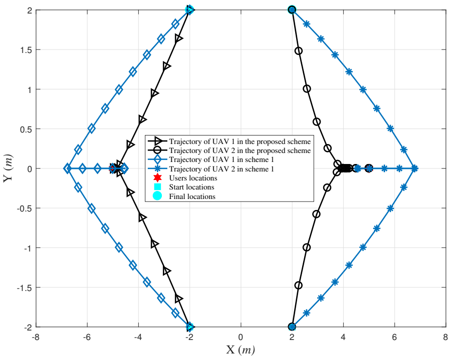

Figure 3. UAVs' trajectories of the proposed scheme and benchmark scheme 1

In this section, numerical results are presented to verify the advantage of the proposed scheme. In the simulation, we set $\eta = 0.6$, UAVs' flying altitude $H = 5$m, $d_{min} = 1$m, $K = 3$, $\sigma^2 = 10^{-5}$W, $|\tilde{g}|^2 = -40$dB, $\hat{g}[k] \sim CN(0,\text{-}40\text{dB})$, and $W = 32$. We compare the proposed scheme with the following two benchmark schemes: in scheme 1 two GNs transmit their collected information to UAVs simultaneously, and caused serious interference, which is reduce by time division method in scheme 2.

Figure 2 shows the sum transmission rate versus the distance between two GNs. We can observe from Figure 2 that our proposed scheme outperforms two benchmark schemes. We can find that the sum transmission rate of scheme 1 increases when distance between two GNs is smaller than 12m due to the reduction of interference, but decreases when distance become larger due to worse channel conditions. Figure 3 shows the UAVs' trajectories of the proposed scheme and scheme 1. We can observe from Figure 3 that the UAVs of scheme 1 tends to keep away from the interference source for smaller interference. However, the interference is avoided in our proposed scheme, which mean UAVs can fly directly to the corresponding GN for better channel condition.

6 Conclusion

In this paper, we propose an OFDM based interference reducing scheme for UAV-powered IoT sensors, and maximize the sum transmission rate under by optimizing UAV trajectory and resource allocation. Simulation results indicate that our proposed scheme outperforms two benchmark schemes.

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