Throughput optimization of multi-hop and multi-path cooperation in WPSNs with hardware noises

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Abstract
This paper proposes a novel multi-path and multi-hop wireless powered sensor network in case of hardware impairment, constituting an energy node, one source node, single sink node, and a series of distributed relay sensor nodes, where the energy node transmits wireless energy to all terminals in the first stage, and the relay sensor nodes relay the information of the source node to the sink node in the second stage. There exists $M$ available paths between the source node and sink node, one of which is chosen for serving source-sink communication. To enhance the minimum achievable data rate, we propose a multi-hop communication protocol based on time-division-multiple-access and an optimal throughput path algorithm. We formulate the time allocation optimization problem about energy and information transmission of the proposed multi-hop cooperation, and confirm through abundant simulation experiments that the proposed scheme can availably improve user unfairness and spectral efficiency, and thus enhance its throughput performance.

Keywords
Wireless powered communication network, energy imbalance, energy beamforming, throughput performance, user unfairness

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Introduction
With the rapid development of Internet of Things (IoT), the number of various terminals connected to the network has exploded exponentially. According to global system for mobile communication (GSM) association, the number of IoT devices (both cellular and non-cellular) will reach 25.2 billion in 2025.¹ Wireless sensor network (WSN) is one of the key core technologies of IoT, the research and development of which has been concerned by a wide range of scholars and researchers, and has a huge market potential in the future.²,³ WSN is a self-organizing network composed of low-cost and low-power micro-sensors distributed in the monitored area, which is composed of radio Communication.⁴,⁵ The purpose of WSN is to perceive, collect, process, and transmit information of perception and objects in the coverage area of the network. At present, WSN technology has been integrated into every aspect of human life, such as intelligent transportation, intelligent home, battlefield detection, target tracking, environmental monitoring, health monitoring, public safety and medical services, emergency positioning and navigation, and other fields.⁶–⁸ WSN technology has played

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an extremely important role in the outbreak control of COVID 19.9 As the basic technology and core component of epidemic data collection, the critical role of sensors is incomparable.

However, most sensors are powered by batteries so far, which exists many shortcomings. For instance, the batteries need to be powered manually or replaced manually. In many scenarios, the monitoring environment of the nodes is harsh and their batteries cannot be replaced in time, which will cause the operational disruptions of WSN. Besides, the nodes are high running cost, unportable, easy interruption, and even not used in some special applications, such as medical electronic sensors implanted in human body and sensors implanted in building concrete structure, so that the lifetime of the network is greatly limited. Therefore, in order to address this issue, many scholars proposed to power wireless devices with dedicated wireless power transfer (WPT) technology, and provide continuous and stable microwave energy for the wireless devices through air medium. The utilization of WPT technology can reduce the cost of battery replacement/recharging, and enhance the quality of communication service by reducing power outage.9–13

WPT technology has become one of the important research field both at home and abroad in more than one university research teams, such as: Shanghai Jiao Tong University, National University of Singapore, Hong Kong University, Princeton University, etc., as well as the focus of international industry development technical objects, for instance, the United States called Power cast company development of radio frequency (RF) charging suite and Intel’s wireless identification perceives RF energy transmission development platform, and so on.

Academically, many researchers have studied the application of WPT technology in wireless communication network,14–18 for example,14 investigated the performance of WSN based on average of information (AoI) which had the function of WPT, including the sensor nodes harvested energy from the RF signal (by the dedicated energy sources transfer) to transmit real-time status to update, concluded that the simple closed form expressions of AoT, and indicated that the size of the capacitor played a critical role in the system performance through one dimensional optimization.15 Studied the performance of wireless powered sensor network (WPSN) under various parameter settings through simulation, discussed the influence of wireless charging rate and battery capacity on the probability of packet delay and energy shortage on wireless sensor nodes, and by the simulation showed that the greater the battery capacity or wireless charging rate, the better the performance of WPSN. Under the condition of the eavesdropper and hardware noise,16 put forward the best path selection protocol to improve the consideration of energy harvesting system security performance and hardware damage through simulations in a multi-hop multi-path collaborative WSN,17 considered the WPSN with one base station and multiple energy receivers, studied the formulation of the optimal power allocation problem by the multi-antenna base station in the process of the energy beamforming and pilot transfer, and given the nonlinear energy harvesting node, proposed a solving method based on binary search and iteration feasibility test, which improved the rate of about 10% of the network awareness by simulations, compared with fixed power allocation method. In order to enhance channel utilization and prolong the network lifetime,18 studied the cooperation between multi-hop wireless rechargeable sensor network and continuous interference elimination technology.

However, almost all published references assume that hardware transceivers for wireless devices are perfect so far. While, the physical transceivers of low-cost sensor nodes are often affected by factors such as phase noise, nonlinear amplification amplitude and in-phase/orthogonal imbalance, which can significantly lower the performance of wireless networks.18,19 Therefore, the research on WPSN and the exploration of the key technology of resource optimal allocation are still in the initial stage under the condition of imperfect hardware.

This paper considers a novel multi-path and multi-hop WPSN consisting of an energy node (EN), a source node, a sink node, and a series of relay sensor nodes (RSNs), as shown in Figure 1, where first the EN broadcasts wireless energy to the source node and RSNs, then the source node utilizes energy harvested from the EN to transfer its own information to the RSNs, and finally the RSNs forward the received information to the sink node. The main contributions of this article can be summarized as follows. Input the material as simply as possible and do not embed special formatting in the text, such as field codes.

The main contributions of this article are shown below.

- To solve the problem of traditional WSN relying on manual battery replacement, we propose a novel model of wireless powered sensor network by introducing WPT into wireless sensor network, thus extending the network lifetime.
- In view of the imperfect hardware, we propose the optimal path algorithm according to the real-time location of the EN, source node, sink node, and RSNs, thus enhancing the throughput performance.
- To prove the proposed scheme can availably improve user unfairness and spectral efficiency, we derive the closed form expression of minimum reachable throughput in the case of wireless flat fading channel distribution. Simulation results validate our derivation.
Modeling system

Channel model

As shown in Figure 1, the source node and sink node communicate through a multi-hop mode. In addition, M available paths exist between the source node and sink node, one of which is chosen for serving source-sink communication. It is assumed that all transmitters, including sources and RSNs, are power-limited devices; as a result, they are equipped with built-in batteries to harvest wireless energy from the EN arranged in the WPSN. We also assume that all terminals installed with one antenna are low cost and low power, and operate in a half-duplex mode, namely running on the same frequency band, where the separation of energy and information transmission is adopted a time-division duplex circuit. Therefore, data transfer is achieved by time division multiple access (TDMA) over an orthogonal time slot.

In this paper, let $L_u$ denote the number of RSNs, which are indexed as $R_{u,1}, R_{u,2}, \ldots, R_{u,L_u-1}$ and $R_{u,L_u}$ on the $u$th path, where $u = 1, 2, \ldots, M$ and $L_u \geq 1$. Assuming that select the $u$th path to transmit data, which is divided into $L_u + 1$ orthogonal time slots. Specifically, the node $R_{u,j}$ transfers the source node’s data to the node $R_{u,j+1}$ within the $(j + 1)$th time slot, where $j = 0, 1, 2, \ldots, L_u$. Furthermore, notice that $R_{u,0} = \text{Source}$ and $R_{u,L_u+1} = \text{Sink}$ for all $u$. The impact of path-selection method to the system performance will be discussed in Section IV. All the channels are assumed to be independent and reciprocal, following quasi-static flat-fading, such that all the channels’ coefficients remain constant during each block transmission time, denoted by $T$, but can vary from different blocks. Make $c_{XY}$ denote the channel coefficient of the $X \rightarrow Y$ link, where $X, Y \in \{R_{u,j}, R_{u,j+1}\}$, $u = 1, 2, \ldots, M$, $j = 0, 1, 2, \ldots, L_u$. Here, we use $h_{XY} = |c_{XY}|^2$ to denote the corresponding channel gains, where $|\cdot|$ denotes the 2-norm operator.

Multi-hop communication protocol

In this subsection, we propose a multi-hop communication protocol, the operation of which in a transmission time block is depicted in Figure 2. At the beginning of a transmission block, channel estimation (CE) is performed within a fixed duration $\tau_0$. During the CE stage, the RSDs take turns to broadcast their pilot signals, so that the source node has the knowledge of $c_{R_{0,0}}$, and the $R_{u,j+1}$ knows $c_{R_{u,j+1}, R_{u,j+1}}$, $u = 1, 2, \ldots, M$ and...
the time allocations of node relays the message to the next hop for in the first stage. It is assumed that each selected RSN selected path, which relay the source node’s message to

Without loss of generality, transmission at the \((t)\) amount of time, the source node transmits its information to the RSNs \(R_{u,j} \rightarrow R_{u,j+1}\) In the selected path, which relay the source node’s message to the sink node using their individually harvested energy in the first stage. It is assumed that each selected RSN relays the message to the next hop for \(\tau_{j(i+1)}\) amount of time. Obviously, we have the following equation of the time allocations

\[
T = \tau_0 + \tau + \sum_{u=1}^{M} \sum_{j=0}^{L_u} \tau_{u,j(j+1)},
\]

which \(T\) denote the total block duration (or the end-to-end delay constraint). Without loss of generality, it is assumed that \(T = 1\) over all this full-text. The throughput performance of the multi-hop communication protocol will be derived in the next section.

### Analyze throughput performance

#### Energy transfer

We assume that \(\tau_u\) is the time duration of the data transmission at the \((j+1)th\) time slot on the \(u\)th path. Without loss of generality, \(\tau_u = T/(L_u + 1)\), and the time switching-based technique is adopted, that is, the node \(R_{u,j}\) harvests energy from the EN during the time of \(\alpha \tau_u\), where \(0 < \alpha < 1\) is a designed parameter. Like,\(^{15}\) the energy harvested by \(R_{u,j}\) can be given as

\[
E_{R_{u,j}} = \eta \alpha \tau_u P_{R_{u,j}} h_{R_{u,j}}
\]

where \(0 < \eta < 1\) is the efficiency of energy transfer, which is assumed the same for all the nodes, and \(h_{R_{u,j}}\) is the channel gain of \(R_{u,0} \rightarrow R_{u,j}\).

The rest of time \((1 - \alpha)\tau_u\) is utilized to transmit data. Therefore, \(R_{u,j}\)’s transmitting power from the energy collecting can be computed by

\[
P_{\text{max}}^{R_{u,j}} = \frac{E_{R_{u,j}}}{(1 - \alpha)\tau_u} \frac{\Delta}{\eta \alpha} P h_{R_{u,j}}
\]

In this paper, we use the same assumption of,\(^{15}\) that is, to prevent interference, various frequency bands are adopted for energy collection and data transmission. All the nodes (i.e., \(R_{u,j}\)) take the same amount of time \(\alpha \tau_u\) to collect energy at each time slot, and then adopt it to transfer data.

#### Multi-hop data transmission

Let \(s\) denote the data of the source transmitted from the RSN \(R_{u,j}\) to the RSN \(R_{u,j+1}\), where \(u = 1, 2, \ldots, M\) and \(j = 0, 1, 2, \ldots, L_u\). Considering hardware impairments, we can express the transmission \(R_{u,j} \rightarrow R_{u,j+1}\)’s received signal as

\[
y_{R_{u,j},R_{u,j+1}} = C_{R_{u,j},R_{u,j+1}} \sqrt{P_{R_{u,j}}} (s + \beta_{R_{u,j+1}}) + \mu_{R_{u,j+1}} + \nu_{R_{u,j+1}}
\]

where \(\beta_{XY}\) and \(\mu_{XY}\) represent the distortion, noises induced by the hardware impairments at the transmitter \(X\) and the receiver \(Y\), respectively. Like\(^{15,19,22}\) \(\beta_{XY}\) and \(\mu_{XY}\) can be modeled as cyclic symmetric complex Gaussian distribution, where \(\beta_{XY} \sim \mathcal{CN}(0, (\sigma_{\beta_{XY}}^2)P_{X})\) and \(\nu_{XY} \sim \mathcal{CN}(0, (\sigma_{\nu_{XY}}^2)^2P_{X}h_{XY})\). Without loss of generality, we assume that the hardware impairment levels of all nodes are the same, that is, \((\sigma_{\beta_{XY}}^2) = \sigma_{\beta}^2\), \((\sigma_{\nu_{XY}}^2)^2 = \sigma_{\nu}^2\).

To account for the path loss, we can model the channel gain \(h_{XY}\), as:\(^{21}\) if the mean channel gain between any two points, either the EN/source/sink or an RSN, follows a path loss model. Make \(d_{XY}\) represent the distance between \(X\) and \(Y\), then

\[
h_{XY} = G_A \left( \frac{3 \times 10^8}{4 \pi d_{XY} f_c} \right)^\lambda
\]

where \(G_A\) represents the antenna gain, \(f_c\) denotes the carrier frequency, \(d_{XY}\) is the path loss factor during wireless energy and information transmission.\(^{23,24}\)

Consequently, we can express the \(R_{u,j} \rightarrow R_{u,j+1}\) link’s instantaneous signal-to-noise ratio (SNR) as

\[
\gamma_{R_{u,j},R_{u,j+1}} = \frac{P_{R_{u,j}} h_{R_{u,j},R_{u,j+1}}}{\theta P_{R_{u,j}} h_{R_{u,j},R_{u,j+1}}^2 + N_0}
\]

where \(\theta = \sigma_{\beta}^2 + \sigma_{\nu}^2\).

Then, the data rate of the \(R_{u,j} \rightarrow R_{u,j+1}\) link can be written as

![Figure 2. Multi-hop communication protocol.](image-url)
Therefore, the data rate of the \( u \)th path is calculated by
\[
Rate_u = \min_{j = 1, 2, \ldots, L_u + 1} (Rate_{R_u, R_{u,j+1}})
\] 
(8)

**Max-min throughput optimization**

**Problem formulation**

In this paper, we assume that the source will randomly select one of the paths to transfer the data in cases where multi-path has the same number of shortest hops, and propose an optimal throughput path protocol (OTP) to optimize the performance of the WPSN, where the selected path provides the maximum data rate. Mathematically, we denote
\[
Rate_b = \max_{u = 1, 2, \ldots, M} Rate_u
\] 
(9)

where \( b \in \{1, 2, \ldots, M\} \).

Therefore, the problem can be expressed as
\[
\begin{align*}
\text{(P1)} : \\
\max_{\alpha} \quad & \min_{j = 1, 2, \ldots, L_u + 1} (Rate_{R_u, R_{u,j+1}}) \\
\text{s.t.} \quad & (1) \text{ and (3)}.
\end{align*}
\] 
(10)

By introducing an auxiliary variable \( S \), the problem (P1) can be equivalently converted into its epigraphic form
\[
\begin{align*}
\text{(P2)} : \\
\max_{\alpha} \quad & S \\
\text{s.t.} \quad & (1) \text{ and (3)}, \\
& \frac{(1 - \alpha)\tau_a}{T} \log_2 (1 + \gamma_{R_u, R_{u,j+1}}) \geq S, \\
& u = 1, \ldots, M, j = 1, \ldots, L_u + 1.
\end{align*}
\] 
(11)

Notice that the expressions of the transmit power \( P_{R_u} \) and the data rate \( Rate_{R_u, R_{u,j+1}} \) are not concave functions. Thus, the current form of the problem (P2) is non-convex, which has no effective optimization algorithms. In the next section, the above non-convex problem will be transformed into a convex one, which can be resolved to adopt some known convex optimization techniques, such as interior point method\(^{24}\).

**Numerical results**

This section assesses the throughput performance of the proposed novel system model of the WPCN. All the following figures present the optimal sum throughput or minimum data rate performance of various methods. All simulations adopt the Power cast TX91501-3 W transmitter and P2110 Power harvester, respectively, as the energy transmitter at the EN with transmit power \( P = 3 \) watts \((W)\) and the energy receiver at each WD with \( \eta = 1 \) energy harvesting efficiency.\(^2\) Unless otherwise stated, assuming that the antennas-number of the HAP is \( M = 5 \), and the noise power \( N_0 \) equals \( 10^{-7}W \) in the bandwidth under consideration for all receivers.\(^{20}\) The average channel gain between any two points, either HAP or a WD, keeps to a path loss model.\(^{21}\) For example, make \( d_{i,j} \) represent the distance between the EN and the \( i \)th WD, then \( \delta_i^a = G_{d} (\frac{1}{4\pi d_{i,j}})^{a_0} \), where \( d_{i,j} \) is the path loss factor during WET DL and WIT UL, which is set as \( 3, 23 \) \( G_{d} = 4 \) and \( f_c = 915MHz \).\(^{24}\) Unless otherwise stated, it is assumed that 40 WDs are uniformly distributed in a circle cell of radius \( r = 3 \), and \( d = 9 \) denotes the distance from the circle center to the HAP. Every point in the following figures is as a mean of 1000 for independent WD positions.\(^5\) In Figure 3, we survey the influence of time impact factor \( \alpha \) on average minimum data rate (max-min throughput-user fairness) and sum throughput (spectrum efficiency). It is observed that the max-min and sum throughput is zero when \( \alpha = 0 \), that is, no time is assigned for wireless energy transmit (WET) to the nodes in the downlink (DL) and thus no energy is available for wireless information transmit (WIT) in the uplink (UL), as well as when \( \alpha = 1 \) or \( 1 - \alpha = 0 \), that is, no time is assigned to the nodes for WIT in the UL. It is also observed that the throughput first increases with \( \alpha \) when \( \alpha < \alpha^* = 0.1 \), but decreases with increasing \( \alpha \) when \( \alpha > \alpha^* \), where \( \alpha^* \) is the optimal time allocation to maximize the max-min and sum throughput. This can be explained as follows. With small \( \alpha \), the amount of energy harvested by relay nodes in the DL is small. In this regime, as relay nodes harvests more energy with increasing \( \alpha \), that is, more energy is available for the information transmission in the UL, the max-min and sum throughput increases with \( \alpha \). However, as \( \alpha \) becomes larger than \( \alpha^* \), the max-min and sum throughput is decreased more significantly due to the reduction in the allocated UL transmission time, \( (1 - \alpha)\tau_a \); as a result, the max-min and sum throughput starts to decrease with increasing \( \alpha \). Therefore, there exists a unique optimal \( \alpha^* \) to maximize the max-min and sum throughput.
In Figure 4, the average minimum data rate (max-min throughput-user fairness) and sum throughput (spectrum efficiency) are depicted as a function of energy harvesting ratio $\eta$.

Herein, the energy harvesting ratio $\eta$ plays a key role in the energy harvesting process since it affects not only the received power at the shortest relay path but also the transmit power of the source and the relay nodes, which agree with the results in equation (3). It can be seen from these figures that the higher value of $\eta$ is, the greater the max-min and sum throughput are. The reason is that more energy can be harvested by the relay nodes from the HAP, and thus the higher energy that the relay nodes can be used for forwarding the information from the source to the destination.

In Figure 5, we investigate the impact of the transmit power of the HAP (dB) on the value of the throughput. As expected, all the three schemes’ data rates increase as $P_{\text{HAP}}$ increases. However, both Figure 5(a) and (b) show that the max-min and sum throughput of the random path selection protocol is always lower than that of the shortest path selection protocol. In other words, the performance of both max-min throughput and sum throughput for our proposed scheme (shortest path selection with fixing two hops) is the best among the three schemes.
Finally, Figure 6 demonstrates the max-min and sum throughput as a function of the level of impairments $u$. It can be investigated from Figure 6(a) that the max-min throughput of all the schemes degrades as $u$ increases. The reason is that the higher the value of $u$ is, the less SNR is as shown in (6), and thus the relay nodes’ data rate and sum throughput decrease. Specifically, the decline in max-min and sum throughput is relatively small as $u$ increases from 0.2 to 0.5, whereas our proposed scheme is still obviously superior to the other methods. This suggests that the proposed shortest path selection with fixing two hops protocol is more robust to hardware impairment compared with the other two schemes, thus it can operate better with device has poor hardware quality.

**Conclusion**

This paper studied a novel system model of WPCN constituting two multi-antenna HAPs and a distributed of single-antenna $N$ WDs, where a novel multi-antenna enabled clustering-cooperation interactive communication protocol method was exploited to enhance the throughput fairness. We applied energy beamforming technology at the two HAPs with multiple antennas to reach directional energy transmission to equilibrate the WDs’ various energy consumption levels, particularly the two CHs’ high-power consumption. We formulated the problem of optimal maximum-minimization throughput among WDs through joint optimization of EB design, and the allocation of transmission time.
between HAPs and WDs, and transmission power of the two CHs. Many simulation results demonstrated that, compared with the representative benchmark method, the proposed system model and multi-antenna clustering-cooperation interactive communication based on time-division-multiple-access can significantly enhance user fairness and spectrum efficiency in various scenarios.

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Notes
1. In practical work, in the case of a certain understanding of the levels of impairment transceiver, the transceiver should be selected with impairment levels, so that the system performance is optimized.15
2. Please see the detailed product specifications on the website of Powercast Co. (http://www.powercastco.com).

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