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The Efficient BackFi Transmission Design in Ambient Backscatter Communication Systems for IoT

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ABSTRACT According to the limited communication distance and the low transmission efficiency for massive electronic tags/sensors of traditional or bistatic backscatter technology, the BackFi transmission protocol design with energy harvesting of massive smart multi-hop electronic tags/sensors was investigated in the ambient backscatter communication systems. This paper proposed the large-scale tags/sensors multi-hop communication protocols with energy harvesting under Wi-Fi architecture, where the "CTS-to-self" frame can be used to set the traditional AP/STA to the sensing status without sending, and then, the new defined frame "Multi-RTS" may send the trigger signal to massive tags or sensors with its frame field as "M-RTS" strategy, compressed bitmap, tags/sensors number, and other messages. The tags/sensors shall respond to the sounding signal and give the backscatter signal to AP using energy harvesting. It can be mentioned that the Wi-Fi standard in this paper is based on the IEEE 802.11ah. Finally, AP can collect and modulate the backscatter signal after massive tags/sensors response to the reader. It was worth noting that the multi-hop relay adopts the power splitting way to implement the communication process, where the object function was energy efficiency maximization with the parameters optimization of transmitting power and relay scaling factor. In order to solve the non-convex problem, this paper derived the approximate expression in the high SNR case and achieved the optimal solution via the Lambert W function. The simulation and analysis verified the effectiveness of the proposed schemes and the correctness of the derivations.

INDEX TERMS Ambient backscatter communication, smart caching of tags/sensors, IoT, BackFi, multi-hop energy harvesting.

I. INTRODUCTION

Ambient backscatter communication systems (ABCS) enables radio frequency powered devices to harvest power from ambient RF signals (e.g., TV signal and WiFi signal), and to transmit information to nearby readers over the ambient RF carriers [1], [2]. As shown in Figure 1, compared with traditional backscatter communication systems, the ABCS is a promising technology for the future smart Internet of Things communication and can exempt the reader from generating RF sinusoidal carriers. The origin of radio backscatter dates back to World War II when the radio signal transmitted

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by some radar and backscattered from an on-coming airplane [3]. In the recent decades, a famous application of RFID system was Electronic Toll Collection(ETC) that can finish charge of vehicles without stopping, consequently, the rapidly development of integrated circuits decreased the cost of tags or sensors, which attracted extensive and intensive studies on radio backscatter methods [4], modeling [5], multi-antenna techniques [6] et.al.

However, no matter what the traditional backscatter or the ambient backscatter communication systems, which only support the single pair and single hop communication between the reader and the tag. This paper proposed the massive tags or sensors multi-hop communication protocols with energy harvesting under WiFi architecture. The multi-hop and massive tags/sensors communication has several advantages for the future smart IoT networks.

(1) The traditional backscatter communication using radio frequency source signals such as TV signal tower assumes that the tags can not cache data and only realize backscatter and non-scatter communication by modulation such as binary switching keying (OOK/2ASK), which is not suitable to long distance smart communications. Therefore, the multi-hop transmission of ambient backscatter communication based on BackFi is fully exploited in the paper. Not only the long distance transmission of ABCS can be realized, but also throughput and energy efficiency of large scale IoT are improved by exploiting the forwarding capability of tags or sensors under Wi-Fi data caching.

(2) Large scale multi-tag and multi-hop distributed communication with reader will interfere seriously to traditional networks in the same frequency band under current Wi-Fi architecture, especially considering forward compatibility with existing WLAN. Therefore, the carrier sensing multiple access with collision avoidance(CSMA/CA) brings serious challenges to implement the multi-tag and multi-hop cooperative communication. We will exploit multi-channel RTS/CTS polling, multi-layer network allocation vector(NAV) caching, adaptive switching, limited feedback with bit loading and other advanced technologies to implement the ABCS multi-hop transmission.

(3) The proposed ABCS protocol based on BackFi architecture can realize smart transmission of massive tags or sensors, such as smart cards can communicate directly with other smart cards without the distance restriction of readers-writers and realize the transfer between two credit cards and digital paper technology, etc.

A general ABCS architecture consists of three major components: (i) RF sources, (ii) ambient backscatter transmitters and (iii) receivers. The ambient RF sources can be divided into two types, i.e., static and dynamic ambient RF sources [7], [8], where the static ambient RF sources can transmit RF signals constantly, e.g., TV towers and FM base stations. The transmit powers of these RF sources are usually high, e.g., up to 1MW for TV towers. However, the dynamic ambient RF sources are the sources which operate periodically or randomly with typically lower transmit power, e.g., Wi-Fi AP.

The ABCS researches related with information transmission design and energy harvesting can be seen as follows. The ABCS technology has been investigated recently and was firstly proposed by Liu *et al.* [1] at University of Washington, who proposed a system model that used the TV signal in the environment to enable two passive devices to communicate with each other and the hardware implementation proves the correctness of the proposed model. Parks *et al.* [9] proposed a multiple antenna backscatter transmitter and a low power coding scheme with TV tower 539MHz, which increases the communication range and bit rate 1kbps at a distance of 80 feet. Wang *et al.* [10] deployed a backscatter transmitter consisting of low power analog devices with FM tower 91.5MHz and reduce the energy consumption of backscatter transmitters about 11.7μW at the backscatter transmitter. Bharadia *et al.* [11] designed a self-interference cancellation technique using Wi-Fi 2.4GHz to increase the communication range and bitrate and obtained the result of 5Mbps at a range of 1 meter. Qian *et al.* [12] designed a detector operates based on statistic variances of the received signals to improve BER performance and reduce the complexity of detectors. Zhang *et al.* [13] designed a frequency shifted backscatter technique to reduce self-interference and increase the communication range to 3.6 meters with bitrate 50kbps under Wi-Fi architecture. Liu *et al.* [14] deployed a full-duplex backscatter transmitter consisting of low power components with TV tower 920MHz to improve performance of ABCS in terms of BER, communication range, bitrate, reliability and energy consumption, which showed that the backscatter transmitter consumes 0.25μW for TX and 0.54μW for RX. Kellogg [15] deployed a backscatter transmitter consisting of low power analog devices using Wi-Fi AP to reduce the energy consumption of backscatter transmitters and achieved the results of 14.5μW at 1Mbps and 59.2μW at 11Mbps. Munir *et al.* [16] designed a relaying technique for full duplex backscatter devices with TV tower 539MHz to increase the bitrate, which gained 2kbps between the transmitter and a relay node and 1kbps between the relay and the receiver. Wang *et al.* [17] gave the detection and performance analysis of ambient backscatter communication systems. Ji *et al.* [18] then proposed the use of Wi-Fi signals in the environment for communication and further confirming the feasibility of ambient backscatter communication technology.

However, since the ambient backscatter technology is a new communication technology and can only work in short distance environments as elaborated above. Moreover, TV towers and base stations is unstable and the amount of acquisition is small. Therefore, the ABCS networks based on Wi-Fi architecture were proposed in this paper, which is especially suitable to the dense deployment of ultra-dense smart IoT networks. The paper designed multi-hop and massive tags/sensors backscatter transmission mechanism based on the existing Wi-Fi architecture (The so-called BackFi is defined by scholars from Stanford University [19]), which is expected to achieve long distance communication and high throughput transmission.

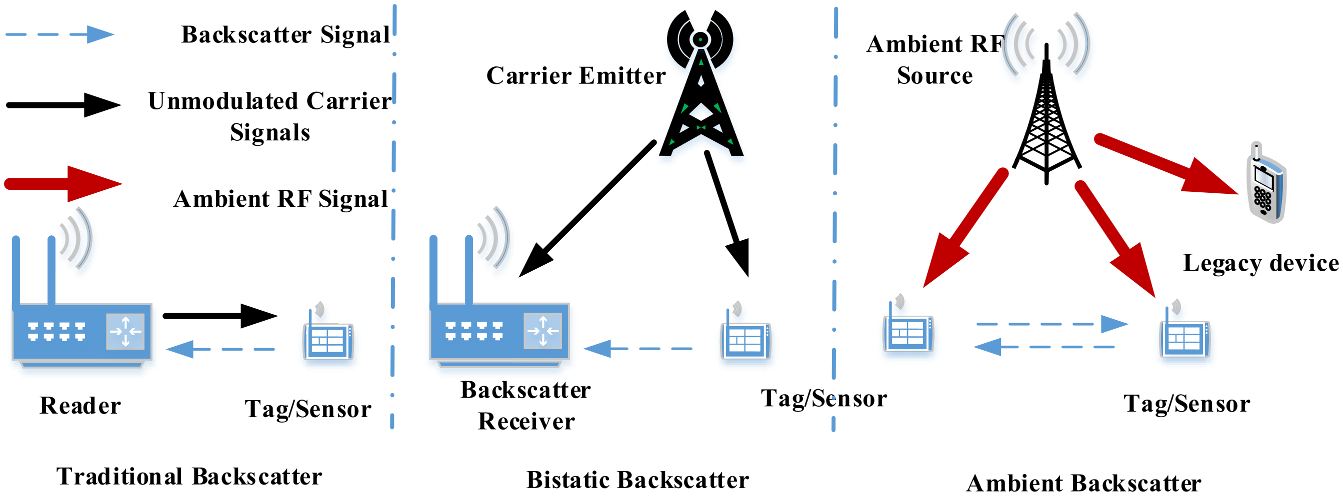


FIGURE 1. The different backscatter communication architecture comparison.

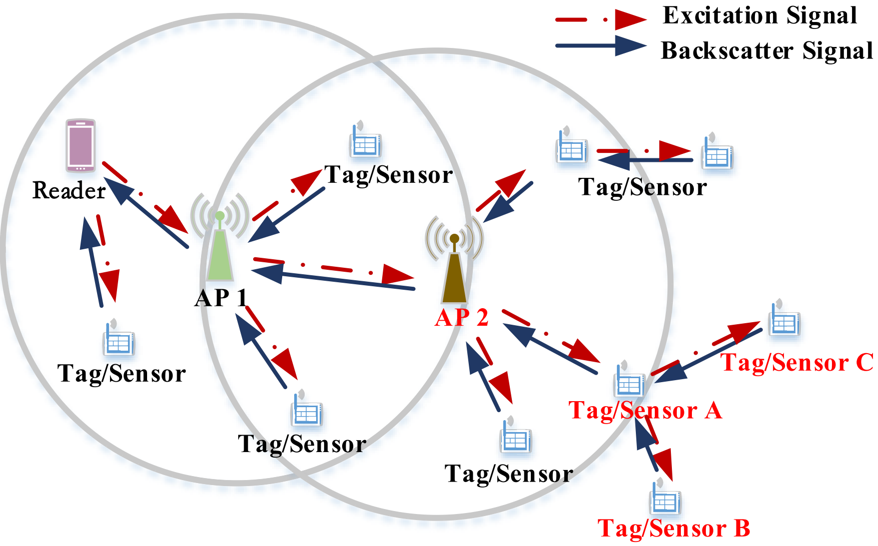


FIGURE 2. The System model of ABCS based on WiFi architecture.

Additionally, the multiple tags/sensors in ABCS networks are battery limitation without charging [21], [22], the rapid growth of the smart IoT devices have significantly increased energy consumption [23]–[25], this paper considers multi-hop transmission with half duplex rather than full duplex mode [26], [27] for wireless information communication with energy harvesting, where the ABCS multi-hop transmission protocols were designed according to IEEE 802.11 IoT architecture. Furthermore, in order to meet the requirements of energy harvesting at the destination node, the resource allocation of source node were jointly optimized for transmitting power, the relay scaling factor and other parameters.

The rest of this paper is organized as follows. Section II provides the system model; Section III designs the ABCS multi-hop transmission protocols based on BackFi. Moreover, the high signal-to-noise ratio approximation and Lagrangian multiplier method are used to optimize the transmitting power of source node and the relay scaling factor; The optimal resource allocation algorithm is proposed in Section IV; The derivation and optimization algorithm is verified by simulations in Section V; Finally, we summarize and conclude the paper in Section VI.

II. SYSTEM MODEL

The system model of large scale Tag/Sensor node of IoT based on Wi-Fi architecture can be seen as Fig.2, it can be mentioned that if there is no tag/sensor nodes in the coverage range of AP, then no backscatter feedback signal is needed; If the tag/sensor detects that it is in the range of a certain AP, then the backscatter signal is reflected to this AP firstly, if there is no associated AP, the backscatter signal can be directly responded to the reader or the relay

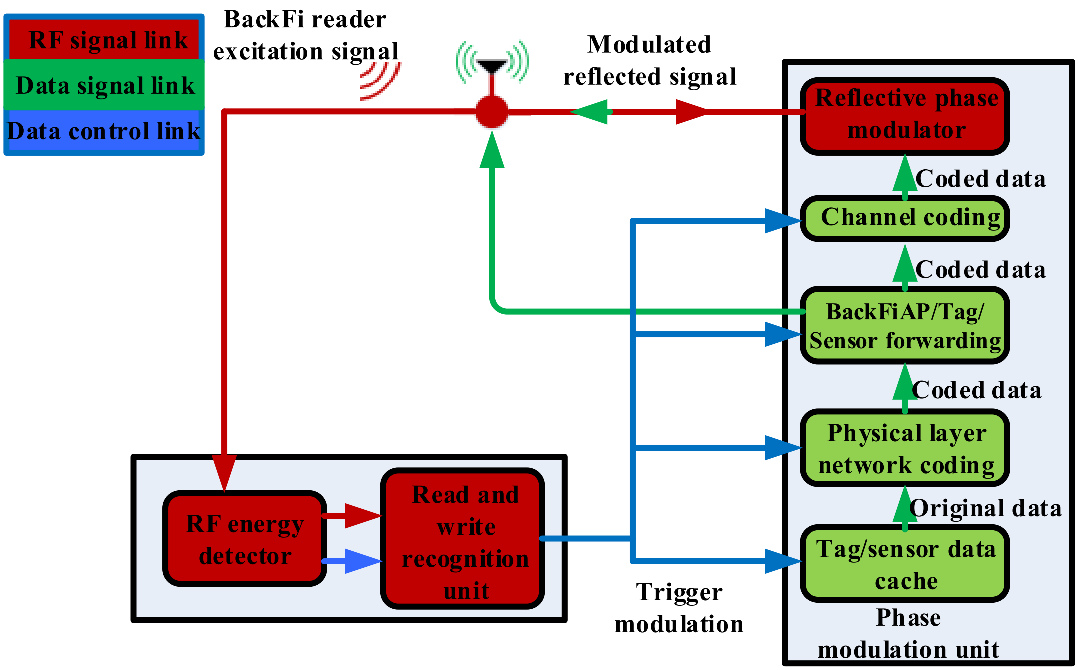


FIGURE 3. The link transmission architecture of BackFi.

tag/sensor node. If there are multiple tag/sensor nodes in the AP range and all of them shall carry out backscatter communication, then the AP can implement it through multi-user or grouping transmission, multiple tag/sensor nodes can reflect the backscatter signals orderly to the AP, which can encode the mixed signals and reflect them back to the reader. As shown in Fig.2, the interaction communication scenarios as AP2 and tag/sensor A, B and C may often encounter in large scale tag/sensor multi-hop transmission. It is worth noting that the optimization of power allocation and scaling factor with energy harvesting may focus on the interaction scenario as AP2 and tag/sensor A, B, C in the paper, where tag/sensor A may harvest energy from AP2 transmission and use it to implement energy and information transmission of tag/sensor B and C.

III. THE LARGE SCALE TAG/SENSOR TRANSMISSION PROTOCOLS DESIGN

This paper proposes the large scale smart tag/sensor multi-hop transmission protocols of ambient backscatter communications under Wi-Fi architecture, which can effectively improve the system throughput of the entire ABCS network. The basic architecture and principle can be seen as Fig.3. It can be shown that once the RF energy detector accepts the excitation signal of BackFi reader, then the identification units shall wake the modulation subsystem, the Tag/Sensors may read the original buffer data and modulate them to the excitation signals through backscatter phase modulator. It is mentioned that the BackFi AP or Tag/Sensor that acted as relay node needs to gather multiple signals and reflect them to the reader or upper node(It is noted that the traditional Tag/Sensors still not support data forwarding, which needs several protocol modifications). The proposed protocols can be elaborated as follows.

Firstly, the modified "CTS-to-Self" frame can be used to set traditional AP/STA to the sensing status without sending, then the new defined frame "Multi-RTS" may send trigger signal to massive tags or sensors with frame field as "M-RTS" strategy, compressed bitmap, tags/sensors number and other message, which can be shown as Fig.4. Where the "capability information" field of related frames for BackFi AP and Tag/Sensors can be acquired at association phase, moreover, the Tag/Sensor nodes can respond to the reader or upper node according to the order of sequence referenced as "M-RTS" field to avoid the collision. Moreover, the Multi-RTS frame can classified into several cases, firstly, the tags/sensors can be grouped according to limited number to implement the transmission in the massive tags/sensors communications. Secondly, the tags/sensors may be selected and grouped as a set or cluster to finish transmission, which can be used to energy harvesting for green networks [28], [29]. Thirdly, the tags/sensors could be achieved the high throughput transmission if the reader and tags/sensors have multiple antennas. It can be mentioned that the "CTS-to-Self" frame is a non response frame in current mechanism, which can be modified in this paper and named it as "Advanced CTS-to-Self" frame, where the "more data" field can be set as "1" to distinguished with traditional devices to trigger the BackFi AP or Tag/Sensor act as relay and forward data, on the contrast, the traditional devices do

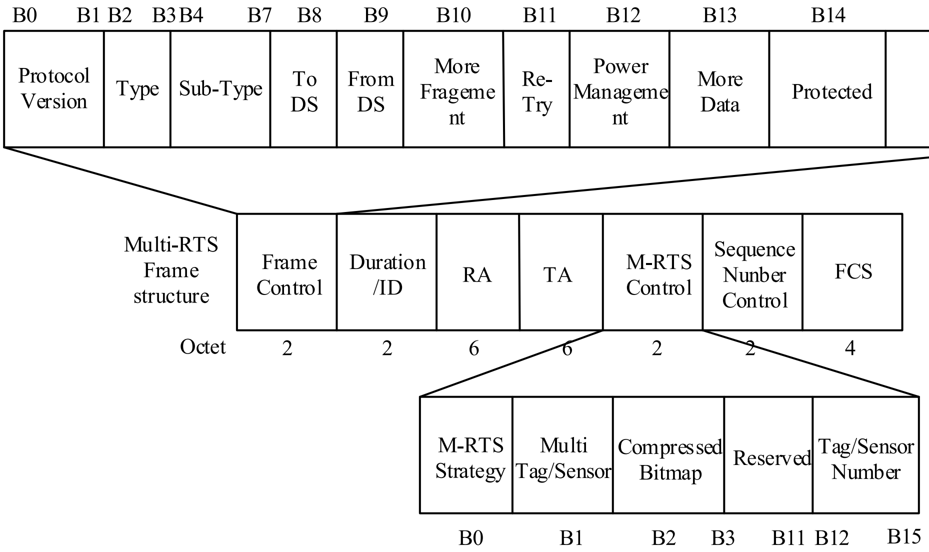


FIGURE 4. The new defined "Multi-RTS" frame architecture.

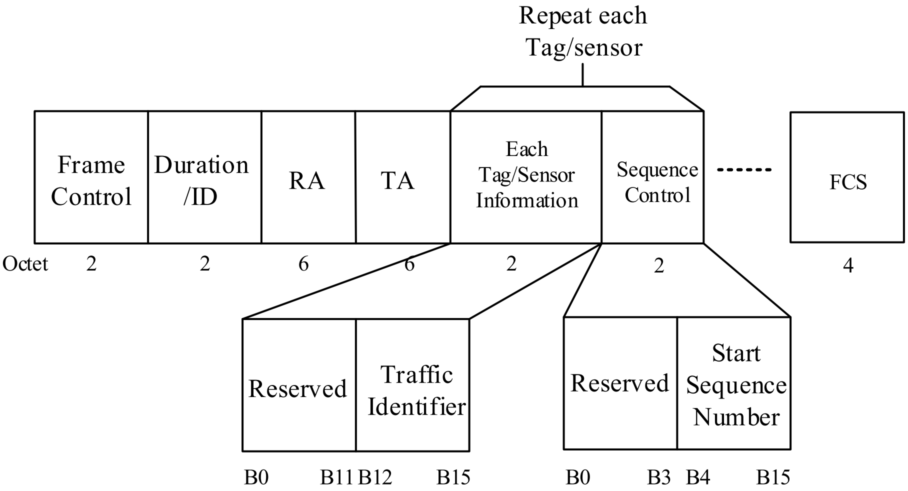


FIGURE 5. The defined multiple Tag/Sensor "Multi-TID" subtype control frame.

not detect the "more data" field in default and may go to "sleep/doze" state, the "Advanced CTS-to-Self" frame can be shown as Fig.5.

Secondly, the "CTS-to-Self" frame as the excitation signal may need all the Tag/Sensor node to implement backscatter communications. However, the "Multi-RTS" frame can select one or several Tag/Sensors to finish backscatter communications. If the Tag/Sensor signal is single reflection, then the "Multi Tag/Sensor" field can set "0"; If the Tag/Sensor signal is multiple reflection, then the "Multi Tag/Sensor " field can set "1" and the "Tag/Sensor" number shall set as the corresponding value, meanwhile, a subtype control frame shall be in the nick of "Multi-RTS" frame as shown as Fig.5.

The proposed protocol process of large scale Tag/Sensor nodes communications of ABCS networks can be referenced as Fig.6 as follows.

The tags/sensors shall respond the sounding signal and give the backscatter signal to AP through energy harvesting, finally, AP can collect and modulate the backscatter signal after massive tags/sensors response to the reader.

IV. THE OPTIMAL RESOURCE ALLOCATION ALGORITHMS

This section presents the optimal resource allocation algorithms for massive smart tags/sensors, as shown in Fig.7, which is a part of the system model depicted as Fig.2. Tag A is used to receive information and Tag B is used to collect energy. AP is the relay in this system model and the energy required is to transmit the signal comes from the reader, the AP acts as the two-way relay may be the next work in the future [30]. It is worth noting that the relay node adopt the power splitting way to implement communication process, where the object function was energy efficiency

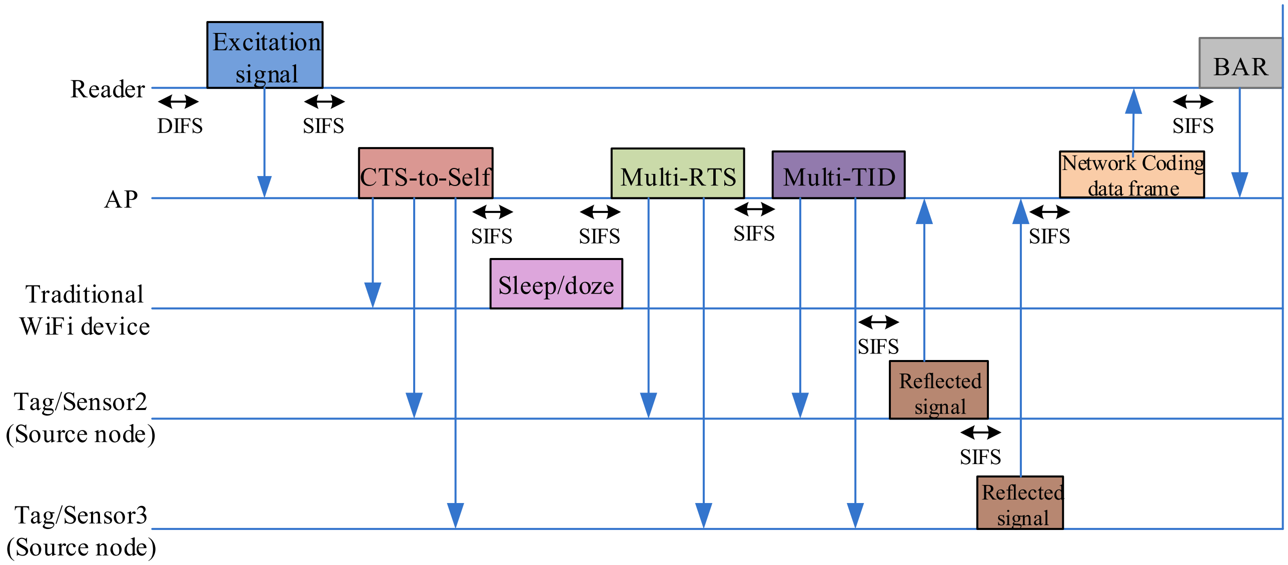


FIGURE 6. The signaling interaction process of the proposed multi-hop transmission protocol.

maximization with the parameters optimization of transmit power and power scaling factor. In order to solve the non-convex problem, the paper derived the approximate expression in high SNR case and achieved the optimal solutions via Lambert W function.

The communication process can be elaborated as follows. The signal received at the AP as the relay node can be given by:

$$y_R = \sqrt{P_S} hx + n_1 \tag{1}$$

where P_S is the transmit power of the source node as shown as reader in Fig.7, where the channel h from reader to AP follows zero mean unit variance Cyclic Symmetric Complex Gaussian distribution, namely $h\tilde{}\mathcal{CN}(0,1)$, and $n_1\tilde{}\mathcal{CN}(0,\sigma_1^2)$ is the additive white Gaussian noise (AWGN).

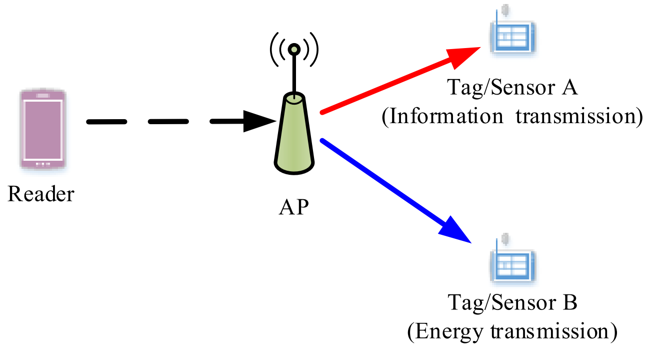


FIGURE 7. Communication model with multiple types of tags/sensors.

In order to communicate long distance with Tag/Sensor A and B, the AP can take advantage of the received signal from reader and use the power scaling factor ρ implement information and energy transmission to Tag/Sensor A and B, where the energy part for AP can be expressed as:

$$y_{R,E} = \sqrt{1-\rho}\, y_R \tag{2}$$

where $0<\rho<1$ is the power scaling factor for receiving the information part as:

$$y_{R,I} = \sqrt{\rho}\, y_R + z \tag{3}$$

where $z\tilde{}\mathcal{CN}(0,\sigma_z^2)$ is the conversion noise from RF to baseband. The signal sent from the relay node is expressed as follows:

$$\tilde{y}_R = \sqrt{\frac{||y_{R,E}||_F^2}{||y_{R,I}||_F^2}}\, y_R \tag{4}$$

The signal received for the wireless energy transmission as follows:

$$y_E = f\tilde{y}_R + n_E \tag{5}$$

It is mentioned that $h\tilde{}\mathcal{CN}(0,1)$ is the channel from the AP to Tag/Sensor B node that collects energy. n_E is the Gaussian white noise and $n_E\tilde{}\mathcal{CN}(0,\sigma_E^2)$.

The mathematical expression of wireless information transmission from the source (reader) to the Tag/Sensor A node via AP can be obtained as:

$$y_I = g\sqrt{\frac{(1-\rho)\left(p_s\|h\|^2+\sigma_1^2\right)}{\rho\left(p_s\|h\|^2+\sigma_1^2\right)+\sigma_z^2}}\left\{\sqrt{\rho}\left(\sqrt{p_s}hx+n_1\right)\right\}+n_I \tag{6}$$

where $n_I\tilde{}\mathcal{CN}(0,\sigma_I^2)$ is the additive white Gaussian noise. Based on equation (6), the SNR expression received by the Tag/Sensor A can be expressed as:

$$SNR_I = \frac{\|g\|^2\rho(1-\rho)p_s\|h\|^2 m}{\left(\rho m+\sigma_z^2\right)\sigma_I^2+\|g\|^2\left(\sigma_z^2+\rho\sigma_1^2\right)(1-\rho)\,m} \tag{7}$$

where $m=p_s\|h\|^2+\sigma_1^2$.

For the Tag/Sensor B node that harvests energy, the power received from the reader via AP through power splitting way can be elaborated as:

$$\|y_E\|^2 = \sigma_E^2 + \|f\|^2 (1-\rho)\left(p_s\|h\|^2 + \sigma_1^2\right) \tag{8}$$

Based on equations (7) and (8), the optimization problem of maximizing the energy efficiency of the ABCS networks can be written as:

$$\max_{p_s} \frac{\log_2(1+SNR_I)}{ap_s+b}$$
$$s.t.\ \sigma_E^2 + \|f\|^2(1-\rho)\left(p_s\|h\|^2+\sigma_1^2\right) \geq \gamma_0 \tag{9}$$

where $\gamma_0 > 0$ is the preset threshold and defines the minimum energy harvested at Tag/Sensor B in the ABCS networks. a > 1 and b > 0 are factors in the power consumption model considering power conversion efficiency and hardware circuit power consumption cost [17]. The aim for model (9) is to obtain the optimal transmit power and relay scaling factor. However, as shown in equation (7), the expression of SNR is very complicated and the variable p_s is still a quadratic term. To solve this problem, the high SNR approximation to achieve the exact SNR in equation (7). In the case of high SNR, the co-variance σ_z^2 of the RF conversion noise can be ignored. Therefore, equation (7) can be approximated as:

$$SNR_I^{/} = \frac{p_s\|h\|^2\rho(1-\rho)\|g\|^2}{\rho\sigma_I^2 + (1-\rho)\|g\|^2\rho\sigma_1^2} \tag{10}$$

then the asymptotically optimal solutions of p_s and ρ will be calculated iteratively.

A. OPTIMAL SOLUTION OF POWER SCALING FACTOR ρ AT THE TAG/SENSOR A NODE

Equation (10) can be simplified as:

$$SNR_I^{/} = \frac{p_s\|h\|^2\|g\|^2 - \rho p_s\|h\|^2\|g\|^2}{\sigma_I^2 + \|g\|^2\sigma_1^2 - \rho\|g\|^2\sigma_1^2} \tag{11}$$

Substituting equation (11) into (9), we can get:

$$\min_{p_s} \frac{ap_s+b}{\log_2\left(1+SNR_I^{/}\right)}$$
$$s.t.\ \rho \leq 1 - \frac{\gamma_0-\sigma_E^2}{\|f\|^2(p_s\|h\|^2+\sigma_1^2)} \triangleq \omega \tag{12}$$

Let $p_s||h||^2||g||^2 = A,\ ||g||^2\sigma_1^2 = B,\ \sigma_I^2 = C$ for simply expression.

Then the constraint can be written as:

$$\frac{1}{\log_2\left(1+SNR_I^{/}\right)} \leq \frac{1}{\log_2\left(1+\frac{A-A\omega}{C+B-\omega B}\right)} \tag{13}$$

Substituting equation (13) into equation (12):

$$\min_{p_s} \frac{ap_s+b}{\log_2\left(1+SNR_I^{/}\right)}$$
$$s.t.\ \frac{1}{\log_2\left(1+SNR_I^{/}\right)} \leq \frac{1}{\log_2\left(1+\frac{A-A\omega}{C+B-\omega B}\right)} \tag{14}$$

Equation (14) can be represented by Lagrangian function:

$$\Omega = \frac{ap_s+b}{\log_2\left(1+SNR_I^{/}\right)} + \lambda\left\{\frac{1}{\log_2\left(1+SNR_I^{/}\right)} - \frac{1}{\log_2\left(1+\frac{A-A\omega}{C+B-DB}\right)}\right\} \tag{15}$$

Therefore, we can achieve the expression of ρ as:

$$\rho = 1 - \frac{\gamma_0-\sigma_E^2}{\|f\|^2(p_s\|h\|^2+\sigma_1^2)} \tag{16}$$

B. ASYMPTOTICALLY OPTIMAL SOLUTION OF TRANSMIT POWER P_S

Equation (10) can be further written as:

$$SNR_I^{/} = p_s\frac{\|h\|^2(1-\rho)\|g\|^2}{\sigma_I^2 + (1-\rho)\|g\|^2\sigma_1^2} = \Phi p_s \tag{17}$$

Substituting equation (17) into equation (9), the formula can be transformed into:

$$\max_{p_s} \frac{\log_2(1+\Phi p_s)}{ap_s+b}$$
$$s.t.\ \sigma_E^2 + \|f\|^2(1-\rho)\left(p_s\|h\|^2+\sigma_1^2\right) \geq \gamma_0 \tag{18}$$

The asymptotically optimal solution is also derived in a closed form by using the Lagrangian multiplier method through some manipulations.

Firstly, equation (18) can be rewritten as:

$$\min_{p_s} \frac{ap_s+b}{\log_2(1+\Phi p_s)}$$
$$s.t.\ p_s \geq \frac{\gamma_0-\sigma_E^2}{\|h\|^2\left(\|f\|^2(1-\rho)\right)} - \frac{\sigma_1^2}{\|h\|^2} \triangleq \xi \tag{19}$$

The constraint can be calculated as:

$$\frac{1}{\log_2(1+\Phi p_s)} \leq \frac{1}{\log_2(1+\Phi\xi)} \tag{20}$$

Substituting equation (20) into equation (19):

$$\min_{p_s} \frac{ap_s+b}{\log_2(1+\Phi p_s)}$$
$$s.t.\ \frac{1}{\log_2(1+\Phi p_s)} \leq \frac{1}{\log_2(1+\Phi\xi)} \tag{21}$$

Equation (21) is represented by Lagrangian function:

$$\tilde{\psi} = \frac{ap_s+b}{\log_2(1+\Phi p_s)} + \lambda\left\{\frac{1}{\log_2(1+\Phi p_s)} - \frac{1}{\log_2(1+\Phi\xi)}\right\} \tag{22}$$

Therefore, the optimal p_s can be expressed as follows and the similar manipulations as [18]:

$$p_s = \left(\frac{\ln 2}{W\left\{2^{\ln 2}\frac{1}{\ln 2\Phi\lambda+b\Phi-a}\right\}} - 1\right)\frac{1}{\Phi} \tag{23}$$

where $W\{\cdot\}$ is the Lambert function [19].

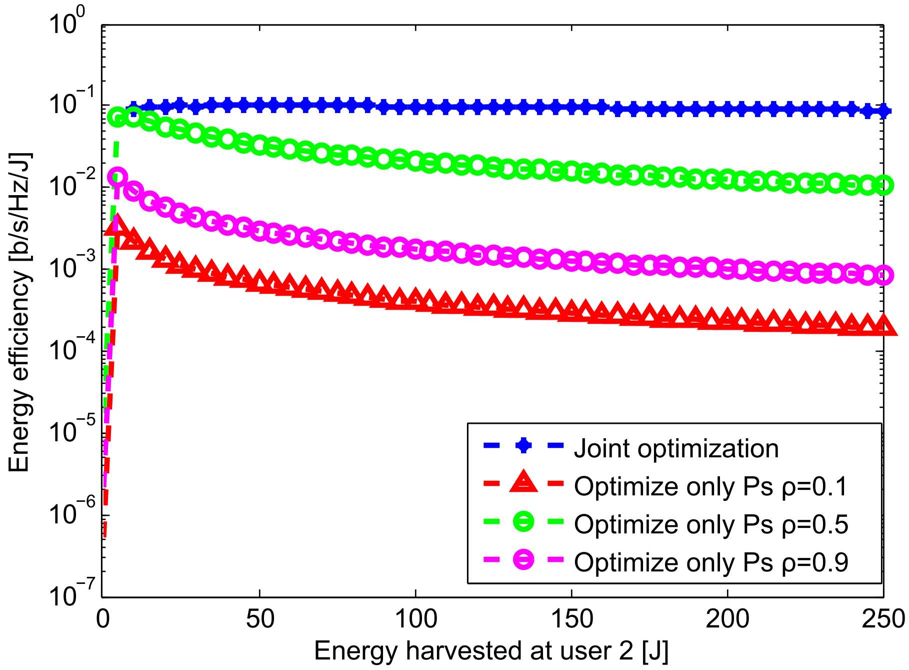


FIGURE 8. The energy efficiency of the ABCS of IoT system when a=5, b=10.

C. THE JOINTLY OPTIMAL SOLUTION THROUGH ITERATIVE ALGORITHM

Taking equation (23) into equation (16), the optimal relay scaling factor under approximate method can be obtained, then the optimal power scaling factor can be substituted back to the formula (23), and the iterative loop can result in the joint optimization solution of transmission power and scaling factor.

In order to elaborate the optimization method of the ABCS multi-hop network based on energy harvesting, the proposed iterative algorithm can be expressed as the form as follows.

Finally, the optimal transmit power and the power scaling factor can be calculated conveniently for the ABCS networks in IoT system.

V. RESULTS AND DISCUSSION

In this section, numerical simulations of the fronthaul and backhaul are performed separately. Firstly, the optimization problem is simulated for fronthaul. The energy efficiency of the IoT system optimized by the transmit power and the relay splitting scheme is numerically simulated, the channel coding in the simulation use convolutional coding and the number of Monte Carlo cycles is 10,000. The parameter a in the power consumption ($p_{total} = ap_t + b$)ranges from 5 to 10, and b ranges from 100 to 300. All noise covariance is set to $\sigma_I^2 = \sigma_E^2 = \sigma_z^2 = \sigma_1^2 = 1$. All channel parameters are subject to the normal distribution of $\mathcal{CN}(0,1)$.

Fig.8 depicts a comparison of the energy efficiency of the entire IoT system in different optimization scenarios when $a = 5$ and $b = 10$. Obviously, when the source power transmission and the relay scaling factor are jointly optimized, the energy efficiency of the system is always higher than that of optimizing the source power at $\rho = 0.1$, $\rho = 0.5$ and $\rho = 0.9$, which further proves the effectiveness of the joint optimization proposed in this paper.

TABLE 1. The proposed optimization algorithm of ABCS network.

Algorithm 1 : Optimization method of the ABCS multi-hop network with energy harvesting
1) While Tag/Sensor or BackFi AP acts as a relaying node, then they can receive signal from upper nodes (The received signal can be seen as equation(1)); 2) The signal received in the relaying nodes can be divided into two part, one is to send information, another is energy, the information and the energy part can be distinguished with power scaling factor ρ; 3) The optimization problem in the subject of energy efficiency maximization can be solved through iterative way with the transmit power and the power scaling factor of relaying node (The optimization problem can be shown as equation(9)); 4) In view of the non convex property of the optimization problem, then the high SNR approximation method can be used to obtain the equation(10); 5) The Lagrange multiplier method is used to solve the relay scaling factor and the transmit power respectively, then the two parameters can be jointly and iteratively solved to achieve the optimal solution as shown in equation(16) and (23). 6) The iterative method can be further used to obtain more accurate and optimal solution of the two variables.

Fig. 9 is the energy efficiency of the entire ABCS for jointly optimizing the source transmit power and the relay scaling factor with respect to the minimum energy required at the second destination node. Where the channel follows the Rayleigh distribution and involves two tags/sensors of the received signal. It can be seen from the simulation analysis

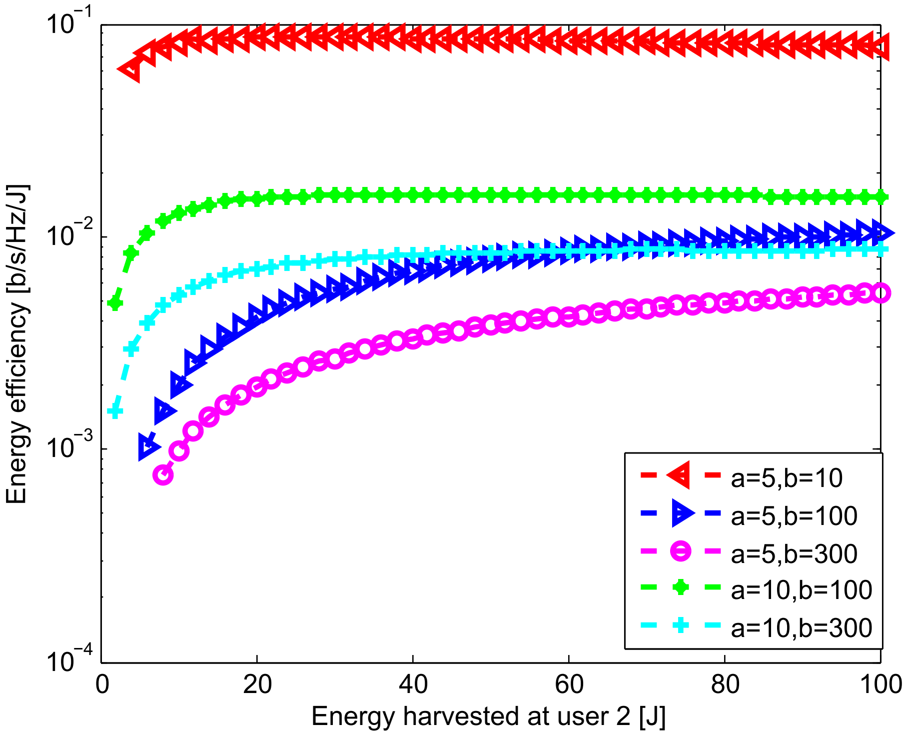


FIGURE 9. The energy efficiency of the entire ABCS with respect to the minimum required energy at the second destination node after joint optimization.

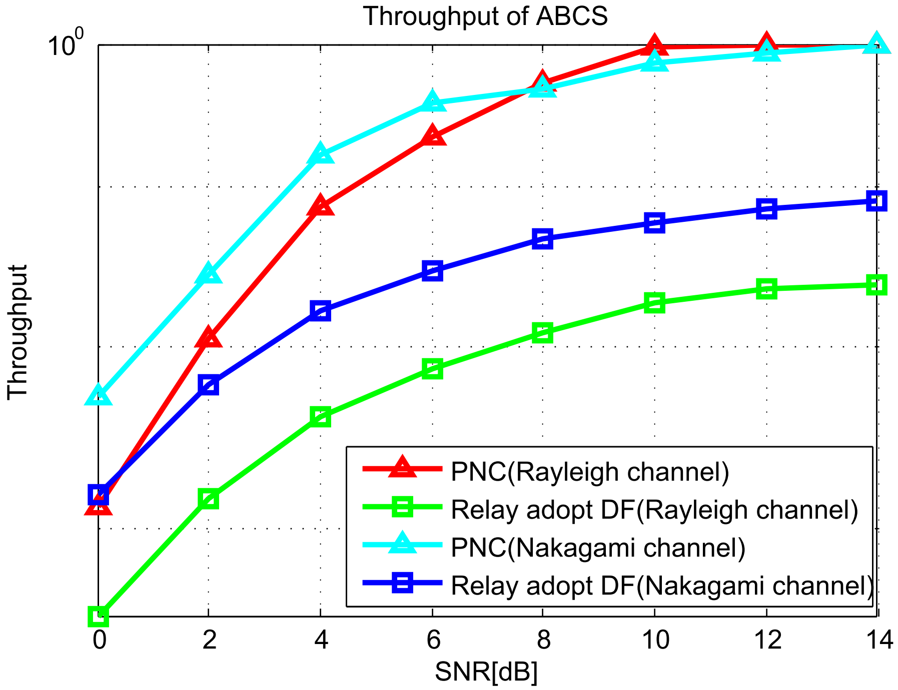


FIGURE 10. The throughput of the backhaul link in the proposed system.

that the energy efficiency rises with γ_0 increasing, which indicates that the entire system can offset the energy consumption after joint optimization and obtain good energy efficiency. In addition, when the parameter value a is constant, the smaller the b value, the higher the energy efficiency. However, when the b value is constant, the system energy efficiency can be improved significantly with value of a growing. The joint optimization diagram proves that the overall system

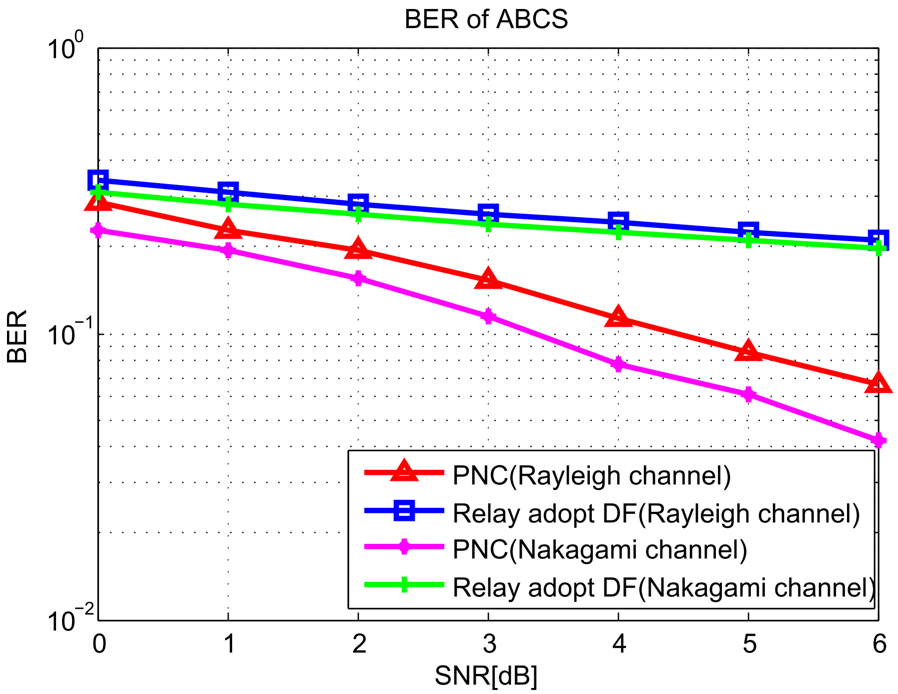


FIGURE 11. The BER of the backhaul link in the proposed system.

energy efficiency can be increased through the transmission scheme proposed in the paper.

Next, the backhaul performance of the system is analyzed. As shown in Fig.10, the physical network coding (PNC) was used in the backhaul link to improve the stability of the system.

Fig.10 shows the throughput of the backhaul link in the ABCS. It can be seen that the system throughput is compared when the backhaul uses PNC. Obviously, no matter what channels, the throughput performance using PNC for backhaul is significantly higher than that of relay amplify-and-forward way. It can be mentioned that the parameter m plays an important role in the Nakagami channels, moreover, the larger the m can be, the better performance the system can have. Fig.11 compared the BER of the ABCS with different scenarios. As the diagram shown that the proposed hierarchical PNC method has significantly improved the system performance compared with the traditional transmission. This is because the network coding can better recover the transmitted signal and the processing method of the PNC reduce the BER to a certain extent, therefore, the throughput of the system can be also significantly improved.

VI. CONCLUSION

This paper investigated the BackFi ambient backscatter communication with massive tags/sensors multi-hop cooperation for IoT. The ambient backscatter transmission methods with energy harvesting were designed in detail based on Wi-Fi architecture (So-called BackFi). The multi-hop cooperation transmission signaling interaction mechanism was mainly developed and the relevant structure of frames were modified compatibly with current Wi-Fi architecture. Then the optimal solution of the proposed communication network subjected to maximum energy efficiency with multiple parameters constraint was derived in detail. Meanwhile, the high signal-to-noise ratio approximation and the Lagrange multiplier method were used to jointly optimize the transmit power of the source node and the scaling factor of the relay node. Finally, the simulation analysis verified the effectiveness of the proposed schemes/protocols and the correctness of the theoretical derivations.

DECLARATIONS

A. ABBREVIATIONS

ABCS	Ambient backscatter communication systems
IoT	Internet of Things
CSMA/CA	Carrier sensing multiple access with collision avoidance
NAV	Network Allocation Vector
RTS/CTS	Request to Send/Clear to Send
AP	Access Point
AWGN	Additive white Gaussian nois
SINR	Signal to Interference and Noise Ratio
PNC	Physical Network Coding

B. AVAILABILITY OF DATA AND MATERIALS

The simulation data supporting this paper can be found and part source files can be shared.

C. COMPETING INTERESTS

The authors declare that they have no competing interests.

REFERENCES

[1] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient Backscatter: Wireless communication out of thin air," in *Proc. ACM SIGCOMM*, Hong Kong, Jun. 2013, pp. 1–13.

[2] G. Yang, Y.-C. Liang, R. Zhang, and Y. Pei, "Modulation in the air: Backscatter communication over ambient OFDM carrier," *IEEE Trans. Commun.*, vol. 66, no. 3, pp. 1219–1233, Mar. 2017.

[3] D. M. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*. Amsterdam, The Netherlands: Elsevier, 2008.

[4] C. Boyer and S. Roy, "Backscatter communication and RFID: Coding, energy, and MIMO analysis," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 770–785, Mar. 2014.

[5] J. D. Griffin and G. D. Durgin, "Gains for RF tags using multiple antennas," *IEEE Trans. Antennas Propag.*, vol. 56, no. 2, pp. 563–570, Feb. 2008.

[6] J. D. Griffin and G. D. Durgin, "Multipath fading measurements at 5.8 GHz for backscatter tags with multiple antennas," *IEEE Trans. Antennas Propag.*, vol. 58, no. 11, pp. 3694–3700, Nov. 2010.

[7] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[8] N. Van Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, "Ambient backscatter communications: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2889–2922, 4th Quart., 2018.

[9] A. N. Parks, A. Liu, S. Gollakota, and J. R. Smith, "Turbocharging ambient backscatter communication," in *Proc. ACM SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 4, pp. 619–630, 2015.

[10] A. Wang, V. Iyer, V. Talla, J. R. Smith, and S. Gollakota, "FM backscatter: En abling connected cities smart fabrics," in *Proc. 14th USENIX Symp. Netw. Syst. Design Implement.*, 2017, pp. 243–258.

[11] D. Bharadia, K. R. Joshi, M. Kotaru, and S. Katti, "BackFi: High throughput with backscatter," in *Proc. ACM Conf. Special Interest Group Data Commun.*, London, U.K., Aug. 2015, pp. 283–296.

[12] J. Qian, F. Gao, G. Wang, S. Jin, and H. B. Zhu, "Noncoherent detections for ambient backscatter system," *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 1412–1422, Apr. 2016.

[13] P. Zhang, M. Rostami, P. Hu, and D. Ganesan, "Enabling practical backscatter communication for on-body sensors," in *Proc. ACM SIGCOMM*, Florianópolis, Brazil, Aug. 2016, pp. 370–383.

[14] V. Liu, V. Talla, and S. Gollakota, "Enabling instant feedback with full duplex backscatter," in *Proc. 20th Annu. Int. Conf. Mobile Comput. Netw.*, Maui, HI, USA, Sep. 2014, pp. 67–78.

[15] B. Kellogg, "Passive Wi-Fi: Bringing low power to Wi-Fi transmissions," in *Proc. 13th Usenix Conf. Networked Syst. Design Implement.*, Santa Maria, CA, USA, Mar. 2016, pp. 151–164.

[16] D. Munir, S. T. Shah, W. J. Lee, and M. Y. Chung, "Low-power backscatter relay network," in *Proc. 11th Int. Conf. Ubiquitous Inf. Manage. Commun.*, 2017, p. 52.

[17] G. Wang, F. Gao, R. Fan, and C. Tellambura, "Ambient backscatter communication systems: Detection and performance analysis," *IEEE Trans. Commun.*, vol. 64, no. 11, pp. 4836–4846, Nov. 2016.

[18] B. Ji, K. Song, C. Li, W.-P. Zhu, and L. Yang, "Energy harvest and information transmission design in Internet-of-Things wireless communication systems," *AEU-Int. J. Electron. Commun.*, vol. 87, pp. 124–127, Apr. 2018.

[19] B. Kellogg, A. Parks, S. Gollakota, and J. R. Smith, "Wi-Fi backscatter: Internet connectivity for RF-powered devices," in *Proc. SIGCOMM*, vol. 14, no. 4, pp. 607–618, 2014.

[20] X. Liu and N. Ansari, "Green relay assisted D2D communications with dual batteries in heterogeneous cellular networks for IoT," *IEEE Internet Things J.*, vol. 4, no. 5, pp. 1707–1715, Oct. 2017.

[21] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3622–3636, Jul. 2013.

[22] B. Bai, W. Chen, K. Ben Letaief, and Z. Cao, "RBG matching based optimal relay selection and subchannel allocation," *IEEE ICC*, 2011, pp. 1–5.

[23] Y. Huang, C. Zhang, J. Wang, Y. Jing, L. Yang, and X. You, "Signal processing for MIMO-NOMA: Present and future challenges," *IEEE Wireless Commun.*, vol. 25, no. 2, pp. 32–38, Apr. 2018.

[24] B. Wang, F. Gao, S. Jin, H. Lin, and G. Y. Li, "Spatial- and frequency-wideband effects in millimeter-wave massive MIMO systems," *IEEE Trans. Signal Process.*, vol. 66, no. 13, pp. 3393–3406, Jul. 2018.

[25] C. Li, S. Zhang, P. Liu, F. Sun, J. M. Cioffi, and L. Yang, "Overhearing protocol design exploiting intercell interference in cooperative green networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 441–446, Jan. 2016.

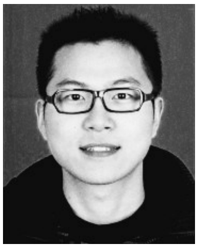
[26] I. Krikidis, H. A. Suraweera, P. J. Smith, and C. Yuen, "Full-duplex relay selection for amplify-and-forward cooperative networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4381–4393, Dec. 2012.

[27] B. Ji *et al.*, "Performance analysis of two-way full-duplex relay with antenna selection under Nakagami channels," *EURASIP J. Wireless Commun. Netw.*, vol. 2018, p. 265, 2018.

[28] Z. Chang, Z. Wang, X. Guo, C. Yang, Z. Han, and T. Ristaniemi, "Distributed resource allocation for energy efficiency in OFDMA multicell networks with wireless power transfer," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 2, pp. 345–356, Feb. 2019.

[29] Z. Chang *et al.*, "Energy efficient resource allocation for wireless power transfer enabled collaborative mobile clouds," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3438–3450, Dec. 2016.

[30] C. Li, H. J. Yang, F. Sun, J. M. Cioffi, and L. Yang, "Multiuser overhearing for cooperative two-way multiantenna relays," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3796–3802, May 2016.



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