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An Adaptive Resource Allocation Model With Anti-Jamming in IoT Network

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ABSTRACT With the booming expansion of the Internet of Things (IoT), flexible and configurable resource allocation in an interference environment is a key issue. In this paper, we investigate resource allocation with anti-jamming for the IoT nodes and propose a novel automatic control allocation (ACA) model to get an adaptive allocation and anti-jamming transmission. More specifically, the spreading-time technology is utilized to satisfy the low-power and band-limited requirements of the IoT node, and by mapping into an orthogonal frequency division multiplexing waveform, the ACA mathematical model is obtained. Then in the model, a new joint stepwise extreme recursion algorithm is used to allocate resource with anti-jamming. The simulation results demonstrate the effectiveness of the proposed model and algorithm.

INDEX TERMS IoT, OFDM, adaptive resource allocation, anti-jamming, low power, limited band.

I. INTRODUCTION

With the development of the Internet of Things (IoT) [1]–[4], the number of nodes in the IoT network is rapidly increasing. As the resource is limited, it usually appears that spectrum resource is much scarce. How to effectively allocate resource is the key issue at present [5], [6].

Considering the large-scale and heterogeneous nature of the IoT, it is vulnerable to suffer to multiple interference threats [7]–[11]. Therefore, improving automatic allocation ability and ensuring anti-jamming communication between IoT communication nodes is crucial. As jamming has a non-negligible impact on resource allocation in the IoT, research has concentrated on anti-jamming resource allocation in recent years [12]–[14]. However, there are still several issues that remain unsolved. Firstly, in the study of resource allocation, most existing work is separated from the realistic communication system, and a resource allocation mathematical model at system level is urgently required to verify the practicality of these existing allocation algorithms. Secondly, in terms of anti-jamming, most existing work rarely considers the low power and limited band of IoT nodes. Increasing power to reduce interference is not possible in the power-constrained IoT network. Besides, due to the deficiency of spectrum resources, common anti-jamming methods (e.g., spread spectrum and frequency hopping) occupy a large frequency band, and are not appropriate for band-limited IoT nodes.

In this paper, anti-jamming resource allocation for multi-node of the IoT with low power and limited band is the focus. A novel automatic control allocation (ACA) mathematical model at system-level is proposed for intelligent and anti-jamming information transmission.

The key to the ACA model is that the optimal allocation solution is mapped into an orthogonal frequency division multiplexing (OFDM) waveform. Utilizing its assignment flexibility [15], OFDM mainly allocates subcarriers and power to users based on various fading characteristics of different users on the same subcarrier. The application of OFDM in the IoT network has been researched recently in [16]–[18], and it can be considered as an efficient communication scheme for the IoT network. The ACA system-level model, which can improve the independent configuration capability of resource allocation for multi-user OFDM, is the key to carry out intelligent information transmission.

In addition, spreading-time technology is applied to prevent interference when resources are being allocated. Spreading-time technology was first proposed by Weine and Selehi in laser communication [19], and can be considered to have a dual relationship with the spread spectrum technique,

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utilizing a narrow bandwidth and low power to achieve anti-jamming.

When constructing the ACA model, an objective function of maximum anti-jamming transmission rate is established to enable multi-node resource allocation and anti-jamming simultaneously. It is very complicated to determine the optimal solution due to its NP-hard nature. Then a new joint stepwise extreme recursion (JSER) algorithm is proposed to determine the suboptimal solution of the objective function. The solution process is divided into two steps, subcarriers allocation and joint spreading-time code with power allocation. In the subcarrier allocation step, a method based on [20] and [21] is improved in order to further reduce allocation complexity. The main contributions of this paper can be summarized as follows:

- An ACA mathematical model for intelligent resource allocation is established, which can automatically allocate resource according to the current environment, to achieve adaptive communication for IoT nodes.
- Spreading-time technology is introduced into the ACA model to make up for the shortcomings of low-power and band-limited IoT nodes, and improve the anti-jamming ability.
- An objective function of maximum anti-jamming transmission rate is constructed. In order to solve the suboptimal solution of objective function, a new JSER algorithm is proposed.

The remainder of the paper is organized as follows. In Section II, the related work is reviewed. In Section III, the problem is formulated, and in Section IV, the derivation process of the algorithm is described. Numerical results are presented to evaluate the performance of the proposed scheme in Section V, and Section VI concludes the paper.

II. RELATED WORK

With the rapid expansion of the IoT, demands on wireless communication and the number of IoT nodes have been greatly increased, and resource allocation is especially important.

Under the background of the OFDM system in the IoT network, there are various target requirements for OFDM resource allocation issues. Aiming to maximize the transmission rate of cognitive user, a cooperative spectrum sharing program has been put forward using joint subcarrier and power allocation in [22]. To maximize the harvested energy, a joint subcarrier and power allocation problem was formulated using the dual decomposition method [23]. A joint scheme based on the intelligent water drop optimization method has been proposed to maximize the total network utility with the subcarrier fairness requirements [24]. To improve the energy efficiency, [25] investigated utility-based joint subcarriers and power allocation algorithm in multi-user two-way regenerative relay network. An adaptive subcarriers assignment and fair power control strategy in OFDM network was considered in [26], to minimize average relay power.

For anti-jamming resource allocation for multi-user OFDM system in the IoT network, constructing the maximum signal to noise ratio (SNR) or signal to interference plus noise ratio (SINR) as the objective function, is generally employed in multi-user OFDM system. A maximin game model was constructed to allocate communication resource for a total maximum SNR and a total minimum delay in transmission [27]. The joint subcarriers and power allocation in OFDM system was modeled as an optimization problem. An asymptotically optimal algorithm and a heuristic algorithm were proposed to maximize the secrecy sum rate in [28], and an anti-jamming scheme for OFDM-based IoT network was proposed in [29]. Through a Colonel Blotto game, power was distributed among subcarriers to decrease the bit error rate (BER). Nash equilibrium can be solved by the proposed evolutionary algorithm to preserve the communication performance of the IoT network under jamming attack. A Stackelberg dynamic game model is proposed to get the optimal allocated resources in [30], which is effective to allocate resource in threat Defense for IoT. Facing an unknown jamming attack, an equilibrium strategy in water-filling form was derived in OFDM system, and an algorithm was proposed to determine the parameters of the waterfilling equation. Numerical experiments demonstrated the effectiveness of this scheme [31]. Evolutionary game theory is also proposed under low channel availability, showing a better performance than the Stackelberg game method [32].

In contrast to most of the existing studies, a mathematical framework of automatic resource allocation is built at system-level in this paper, which is realistic for the IoT network. Flexibility and reconfiguration is improved, and considering the low power and band-limited nature of IoT nodes, anti-jamming resource allocation measures to satisfy the requirement of IoT notes are discussed.

III. PROBLEM FORMULATION

A. SYSTEM MODEL

Table 1 summarizes the most used notations in this paper, and the structure of the multi-node OFDM system based

TABLE 1. **A list of the main symbols in the paper.**

Symbol	Meaning
K	Set of IoT node serial numbers
N	Set of OFDM subscarrier serial numbers
A	Sequence index matrix between nodes and subcarriers
P	Assignment power matrix
R_k	Transmission rate of kth node
u	The objective function
l	Length of spreading-time code
B	OFDM system bandwidth
$j_{k,n}$	Jamming power of kth node on nth subcarrier
N_0	Power spectral density of noise
h	Channel gain
τ	Cost factor
c_k	Cost function of kth node
$w^{\boxtimes}$	Optimal parameter obtained
$S_k(n)$	Frequency domain waveform on the nth subcarrier of kth node
$S(f)$	Frequency domain waveform of OFDM
$s(m)$	Time domain waveform of OFDM

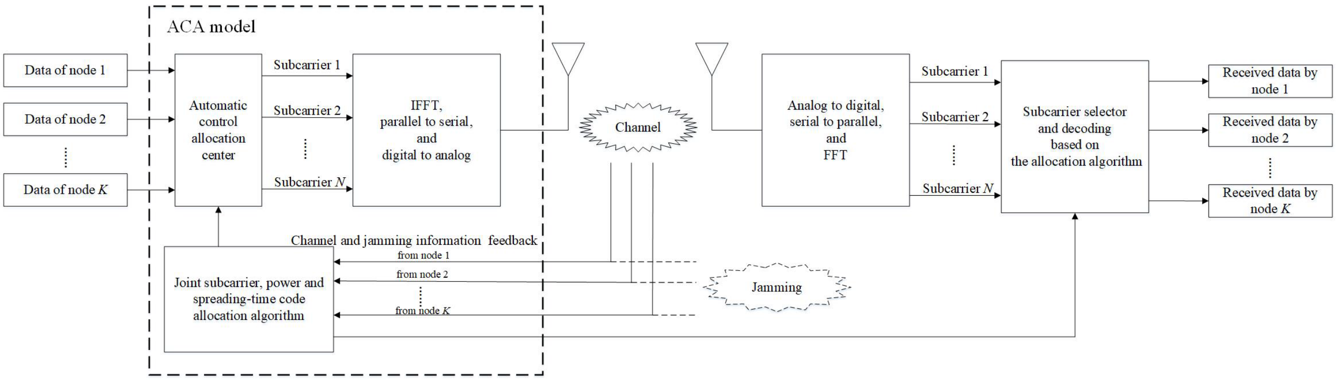


FIGURE 1. The OFDM system based on ACA model in multi-node IoT network.

on ACA model in the IoT network is shown in Fig. 1. By receiving channel and jamming information from all IoT nodes, the allocation center uses the allocation algorithm to automatically configure parameters. According to the changing environment, it is a flexible allocation scheme for IoT nodes to enable adaptive resource allocation and anti-jamming transmission.

In the system, without loss of generality, it is assumed that there are K pairs of nodes in the IoT network, and N number of subcarriers. For the convenience of description, a pair of communication nodes is called one node. In the system, $\boldsymbol{K} = [1, 2, \cdots, K]$ and $\boldsymbol{N} = [1, 2, \cdots, N]$, which represent nodes sequence vector and subcarriers sequence vector, respectively. Assuming that one subcarrier is not allowed to be shared with more than one node in the OFDM system of IoT network, then a sequence index matrix $\mathbf{A}$ between nodes and subcarriers is denoted as:

$$\mathbf{A} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,N} \\ \vdots & \ddots & \vdots \\ a_{K,1} & \cdots & a_{K,N} \end{bmatrix}, \quad a_{k,n} \in \{0, 1\}, \tag{1}$$

where $a_{k,n} = 1$ means the nth subcarrier is occupied by kth node, and $a_{k,n} = 0$ denotes that the nth subcarrier is not occupied by kth node.

Similarly, let $p_{k,n}$ be the assigned power for the kth node on nth subcarrier. The assignment power matrix $\mathbf{P}$ is then defined as:

$$\mathbf{P} = \begin{bmatrix} p_{1,1} & \cdots & p_{1,N} \\ \vdots & \ddots & \vdots \\ p_{K,1} & \cdots & p_{K,N} \end{bmatrix}, \quad p_{k,n} \in \{0, 1\}, \tag{2}$$

Defining P as the total power allocated, the distribution equation is

$$P = \sum_{k=1}^{K} p_k = \sum_{k=1}^{K} \sum_{n\in\Omega_k} a_{k,n} p_{k,n}, \tag{3}$$

where Ω_k is a set of all subcarriers assigned to kth node.

Equation (3) is the result of subcarriers and power allocation for a multi-node OFDM system in the IoT network. However, the parameter cannot be adjusted automatically to enable optimal allocation of spectrum resource for IoT multi-node. Thus, an intelligent allocation model based on equation (3) is constructed.

B. ACA MODEL

Before implementing adaptive resource allocation, an allocation objective function in the OFDM system of the IoT network must be initially determined.

It is assumed that each node is able to estimate the channel perfectly by using channel estimation [33] and spectrum sensing [34], and these estimations are known to the node via a dedicated feedback channel, which is slowly time-varying. These channel information estimations are then used as the input amount for the resource allocation algorithm. Referring to Shannon's theorem and [35], the transmission rate of kth node is

$$R_k = \sum_{n\in\Omega_k} a_{k,n} \frac{B}{N} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 \frac{B}{N}}\right), \tag{4}$$

where B is the bandwidth of OFDM system, h_{kn} is channel gain of kth node on the nth subcarrier, and N_0 is the power spectrum density of additive white Gaussian noise.

Thus, the objective function of maximum transfer rate is expressed as:

$$\max_{a_{k,n}, p_{k,n}} u = \sum_{k=1}^{K} \sum_{n\in\Omega_k} a_{k,n} \frac{B}{N} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 \frac{B}{N}}\right). \tag{5}$$

Due to the openness of space, when spectrum resource are being allocated, they are highly vulnerable to human malicious interference. Considering the interference power $j_{k,n}$ on the nth subcarrier used by the kth node, the transmission rate in the interference environment [36]–[38] which is a function of $a_{k,n}$, $p_{k,n}$, is formulated as:

$$R_k \left(a_{k,n}, p_{k,n}\right) = \sum_{n\in\Omega_k} a_{k,n} \frac{B}{N} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{j_{k,n} + N_0 \frac{B}{N}}\right). \tag{6}$$

As the power is limit for IoT nodes, it is a waste of energy to use the method of increasing power to suppress interference. Spreading-time technology is introduced to prevent interference during resource allocation. By introducing a spreading-time code in the time domain, power consumption can be reduced.

In addition, there is competition between nodes in code length and power allocation. A cost mechanism [39] is recommended to solve the competition problem between nodes. The linear combination cost function of kth node in this paper is

$$c_k\left(l_{k,n}, p_{k,n}\right) = \sum_{n\in\Omega_k} \tau l_{k,n} p_{k,n}\,, \tag{7}$$

where τ is cost factor, which represents the intensity of the penalty, and it is generally determined by experience. $l_{k,n}$ denotes the length of spreading-time code of kth node on nth subcarrier.

Therefore, the objective function of the maximum anti-interference transmission rate is constructed as follows,

$$\begin{aligned} \max_{a_{k,n},p_{k,n},l_{k,n}} \; & u_J = \sum_{k=1}^{K} \left\{R_k\left(a_{k,n}, p_{k,n}\right) - c_k\left(l_{k,n}, p_{k,n}\right)\right\}, \\ \text{subject to } \mathbf{C}_1 : & \sum_{k=1}^{K} a_{k,n} \le 1 \\ \mathbf{C}_2 : & \sum_{k=1}^{K}\sum_{n=1}^{N} a_{k,n} \le N \\ \mathbf{C}_3 : & \sum_{n\in\Omega_k} a_{k,n} p_{k,n} \le P_{k\_total} \\ \mathbf{C}_4 : & l_{k,n} \ge 1, log_2 l_{k,n} \in \{0, 1, 2, \ldots\} \\ \mathbf{C}_5 : & R_1 : R_2 : \cdots : R_K = \lambda_1 : \lambda_2 : \cdots : \lambda_K \\ \mathbf{C}_6 : & \text{SINRo} \ge \gamma_0 \end{aligned} \tag{8}$$

where P_{k_total} is the total transmit power constraint of kth node. The value range of code length $l_{k,n}$ is a positive integer power of 2, R_k is the total data rate of node k, and $\lambda_1 : \lambda_2 : \cdots : \lambda_K$ are the transmission rate ratio constraints, which are the normalized proportionality where $\sum_{k=1}^{K} \lambda_k = 1$. Note that constraint $\mathbf{C}_1$ in equation (8) reflects that each subcarrier can only be allocated to one node, and constraint $\mathbf{C}_2$ means the total number of subcarriers used by all nodes does not exceed the number of subcarriers in the OFDM system. Subscripts $\mathbf{C}_3$ and $\mathbf{C}_4$ are the power and code length constraints, respectively. $\mathbf{C}_5$ is proportional rate constraints, and $\mathbf{C}_6$ is the condition of output SINR. The solution of equation (8) is denoted as: $\omega^*\left(a_{k,n}, p_{k,n}, l_{k,n}\right) = arg\max \sum_{k=1}^{K} \left\{R_k\left(a_{k,n}, p_{k,n}\right) - c_k\left(l_{k,n}, p_{k,n}\right)\right\}$, which is given by

$$\omega^*\left(A, P, L\right) = \left(\mathbf{A}^*, \mathbf{P}^*, \mathbf{L}^*\right)\,, \tag{9}$$

where

$$\mathbf{A}^* = \begin{bmatrix} a^*_{1,1} & \cdots & a^*_{1,n} \\ \vdots & \ddots & \vdots \\ a^*_{K,1} & \cdots & a^*_{K,N} \end{bmatrix} \tag{10}$$

$$\mathbf{P}^* = \begin{bmatrix} p^*_{1,1} & \cdots & p^*_{1,n} \\ \vdots & \ddots & \vdots \\ p^*_{K,1} & \cdots & p^*_{K,N} \end{bmatrix} \tag{11}$$

$$\mathbf{L}^* = \begin{bmatrix} l^*_{1,1} & \cdots & l^*_{1,n} \\ \vdots & \ddots & \vdots \\ l^*_{K,1} & \cdots & l^*_{K,N} \end{bmatrix} \tag{12}$$

The optimal adaptive allocation model will be obtained by mapping the solution to the waveform of the OFDM system. The frequency domain waveform expression of the kth node occupying the optimal nth subcarrier transmission is

$$S_k\left(n\right) = \left\{a^*_{k,n} p^*_{k,n} c_{l^*_{k,n}}\right\} d_{k,n} e^{-j\left(\theta_{d_{k,n}}\right)}\,, \tag{13}$$

where $a^*_{k,n}, p^*_{k,n}$ and $l^*_{k,n}$ are the element of row k, column n in $\mathbf{A}^*$, $\mathbf{P}^*$ and $\mathbf{L}^*$, respectively. $c_{l^*_{k,n}}$ is the spreading-time code whose length is $l^*_{k,n}$. $d_{k,n}$ is modulated data, and $\theta_{d_{k,n}}$ is phase of kth node on the nth subcarrier, caused by modulation.

Inspired by [40], data modulation is rewritten as:

$$d_{k,n} e^{-j\left(\theta_{d_{k,n}}\right)} = \left(\alpha_{k,n} + j\beta_{k,n}\right)\,, \tag{14}$$

where $\alpha_{k,n}$ and $\beta_{k,n}$ are determined by the data modulation being used, e.g., $\alpha_{m,k}, \beta_{m,k} \in \{\pm 1\}$ indicates quadrature phase-shift key (QPSK), and $\alpha_{m,k}, \beta_{m,k} \in \{\pm 1, \pm 3\}$ represents 16-QAM. Substituting into equation (13), the frequency domain OFDM expression is

$$S\left(f\right) = \sum_{k=1}^{K}\sum_{n\in\Omega_k} \left\{a^*_{k,n} p^*_{k,n} c_{l^*_{k,n}}\right\} \left(\alpha_{k,n} + j\beta_{k,n}\right). \tag{15}$$

The OFDM time domain waveform combined with resource allocation is obtained by taking the inverse fast Fourier transform (IFFT) of equation (15).

$$\begin{aligned} s\left(m\right) = \frac{1}{N} \sum_{k=1}^{K}\sum_{n\in\Omega_k} & \left\{a^*_{k,n} p^*_{k,n} c^*_{l_{k,n}}\right\} \\ & \times \left(\alpha_{k,n} + j\beta_{k,n}\right) e^{j\left(2\pi f t_m\right)}. \end{aligned} \tag{16}$$

The ACA model is built here in OFDM system for the IoT network. According to this model, automatic resource allocation of multiple nodes at system level can be carried out.

IV. PROPOSED SOLUTION

As equation (8) is a non-deterministic polynomial-time (NP) hard combinatorial optimization problem with non-linear constraints [41], it is very difficult to solve the optimal solution. To reduce the computational complexity, the JSER algorithm is proposed to solve the suboptimal solution in this section. The solution process is divided into two steps, subcarriers allocation and joint code length with power allocation. Details of each step are discussed in the following subsections.

A. SUBCARRIERS ASSIGNMENT

In the subcarriers allocation step, the number of subcarriers allocated to each node should first be determined. A method based on [20] and [21] is improved in order to further reduce allocation complexity.

Above all, simplification is required to reduce the complexity of the problem. As the proportion of rates need not be strictly enforced in practical systems, a rough proportionality is acceptable to obtain the maximum transmission rate and low complexity. In order to meet the low power requirements of IoT nodes, the same power is initially assigned, which is the maximum acceptable value to the already assigned subcarriers. That is to say, the power of the node on the subcarriers is an average allocation.

Considering the proportional rate constraint, the following equation is created to roughly determine the subcarrier number of different nodes. Based on the same reasonable assumption with [20], in the initial step, N_k is described to satisfy

$$N_1 : N_2 : \cdots : N_K = \lambda_1 : \lambda_2 : \cdots : \lambda_K\,. \tag{17}$$

The subcarrier ratio assigned to each node is approximately the same with rate ratio in the constraint condition. Thus, for the convenience of description, it is defined as:

$$\frac{h_{k,n}^2}{j_{k,n} + N_0 \frac{B}{N}} = H_{k,n}\,, \tag{18}$$

where the larger the $H_{k,n}$ value, the better the channel state.

The problem caused by the assumption is that if the number of subcarriers is not an integer multiple of the number of nodes, there are still idle subcarriers in the system that are not utilized, resulting in wastage and reduction of spectrum utilization efficiency. Specifically, the number of subcarriers allocated is

$$N_k = \lfloor \lambda_k N \rfloor\,. \tag{19}$$

So, $N^r = N - \sum_{k=1}^{K} N_k$ denotes unallocated subcarriers.

As mentioned above, the subcarriers are assigned and this process is divided into three steps as follows.

Step 1: The remaining unallocated subcarriers N^r are first allocated to the node which has the minimum λ_k, and where subcarriers have the maximum $H_{k,n}$.

Step 2: The $H_{k,n}$ is arranged in ascending order for every node on the N_k subcarriers, and subcarriers which have the best channel state are allocated to the corresponding nodes.

Step 3: To ensure fairness, the node with the smallest R_k/λ_k constraint is assigned to the largest subcarrier of $H_{k,n}$. This step allocates N_k subcarriers per node.

The specific description of these steps is explained in Algorithm 1. Applying the algorithm, all subcarriers are assigned per node with a rough rate ratio. Additionally, every node employs the subcarrier with the least interfered for information transmission when possible. This process will prepare for the subsequent power allocation and code length decision.

Algorithm 1 Algorithm for Subcarriers Assignment of Multi-User OFDM System in IoT Network

```
Input: $K, N, N0, B, j_{k,n}$;
Output: A*; subcarriers allocation matrix;
    Step 1:
repeat
    $k = \arg\min_{k\in\mathbb{K}} \lambda_k$; $n = \arg\max_{n\in\mathbb{N}} \{H_{k,n}\}$; $a_{k,n} = 1$;
    $R_k = R_k + \frac{B}{N}\log_2(1 + p_{k,n}H_{k,n})$;
    $\mathbb{K} = \mathbb{K} - \{k\}$;
until $N^r = 0$
    Step 2:
repeat
    $k = k + 1$; $n = \arg\max_{n\in N} \{H_{k,n}\}$; $a_{k,n} = 1$;
    $N_k = N_k - 1$; $\mathbb{N} = \mathbb{N} - \{n\}$;
    $R_k = R_k + \frac{B}{N}\log_2(1 + p_{k,n}H_{k,n})$;
until $k = K$;
    Step 3:
repeat
    $k = \arg\min_{k\in\mathbb{K}}\{R_k/\lambda_k\}$; $n = \arg\max_{n\in\mathbb{N}} \{H_{k,n}\}$;
    if $N_k > 0$ then
        $a_{k,n} = 1$; $N_k = N_k - 1$, $\mathbb{N} = \mathbb{N} - \{n\}$;
        $R_k = R_k + \frac{B}{N}\log_2(1 + p_{k,n}H_{k,n})$;
    else
        $\mathbb{K} = \mathbb{K} - \{k\}$;
    end if
until $\mathbb{N} = \emptyset$
```

B. JOINT CODE LENGTH AND POWER ALLOCATION

After subcarriers allocation is completed, the code length and power is jointly allocated. As the maximum value of the objective function can be achieved by deriving $p_{k,n}$ of equation (8), code length can be determined based on equation (20). That is to say, the code length allocated on this subcarrier should satisfy

$$\begin{aligned}\frac{\partial u_J}{\partial p_{k,n}} &= \frac{B}{N}\left\{\frac{h_{k,n}^2}{\ln 2\left(j_{k,n} + N_0\frac{B}{N} + p_{k,n}h_{k,n}^2\right)}\right\} - \tau l_{k,n}\\ &= 0.\end{aligned} \tag{20}$$

Thus, the length of the spreading-time code $l_{k,n}$ will be solved.

As $l_{k,n}$ is an integer power of 2, the solved $l_{k,n}$ must be revised. To ensure that the cost will not increase and balance the code length and power, $l_{k,n}$ and $p_{k,n}$ are adjusted according to equation (7).

Algorithm 2 Algorithm for the Joint Code Length and Power Allocation

```
Input: $A^*, \tau, H_{k,n}; p_{k,n} = p_{total\_k}/N_k, \forall k \in \mathbb{K}$;
Output: $P^*, L^*$; power and code length allocation matrix;
for $k = 1 : K$ do
    $\mathbb{N}_k^* = \arg\left\{a_{k,n}^* = 1\right\}$;
    for $n = 1 : length(\mathbb{N}_k^*)$ do
        $l_{k,n} = \arg\left\{\frac{\partial u_J}{\partial p_{k,n}} = 0\right\}$;
        $c_{k,n}\left(p_{k,n}\right) = \tau l_{k,n} p_{k,n}$;
        $l_{k,n} = 2^{\lceil log_2 l_{k,n} \rceil}$;
        $p_{k,n} = c_{k,n}\left(p_{k,n}\right)/l_{k,n}$;
        while output SINR$\leq \gamma 0$ do
            $l_{k,n} = 2^{\lceil log_2 l_{k,n}+1 \rceil}$;
        end while
    end for
end for
```

According to [42], when the modulation is QPSK, it can be concluded that the output SINR of the spread-time system is

$$\mathrm{SINRo} \approx 10 \lg \frac{\left(l_{k,n}/2\right) p_{k,n} h_{k,n}^2}{j_{k,n} + N_0 \frac{B}{N}}. \tag{21}$$

The code length $l_{k,n}$ is then increased gradually, based on $l_{k,n} \leftarrow 2^{\log_2 l_{k,n}+1}$, until the output SINR is greater than the acceptable threshold γ_0. Thus, the final $l_{k,n}^*$ is the solution for the following equation,

$$\left\lfloor 10 \lg \frac{\left(l_{k,n}/2\right) p_{k,n} h_{k,n}^2}{j_{k,n} + N_0 \frac{B}{N}} \right\rfloor = \gamma_0 . \tag{22}$$

Based on the above discussion on the determination of code length and power allocation, an algorithm for the joint code length and power allocation is established here. In this way, anti-jamming is achieved without occupying an additional frequency band at low power.

As a result, through the JSER algorithm, the suboptimal solution of the objective function can be obtained. subcarriers and power can be allocated, and the length of code per subcarrier of every node can be determined.

V. NUMERICAL RESULTS

A. INFLUENCE OF COST FACTOR

In this section, the performance of the proposed model and algorithm is assessed using experimental simulations. In order to better display the allocation results and analyze the results, we choose a smaller number of IoT nodes, and the mode of interference is narrowband interference, whose bandwidth is the same with each subcarrier.

In Fig. 2, as the cost factor increases, the total code length utilized by all nodes in the system is smaller, and the total power allocated is larger. Under the same interference, increasing the length of the spreading-time code can reduce the power consumption, satisfying the low power requirements for the IoT node, and causing no interference to adjacent nodes. When the cost factor is larger, the code length will be smaller. Thus, at large cost factors, interference is suppressed with no choice by increasing power.

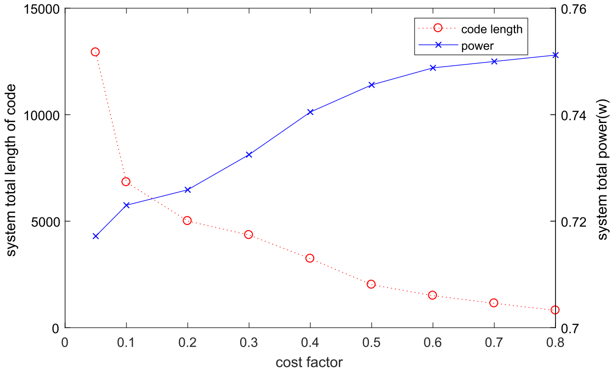


FIGURE 2. Relationship between power, code length, and cost factor. The jamming power is 2*w*, the system total power is 1*w*, the nodes number is 4, and the number of subcarriers is 64.

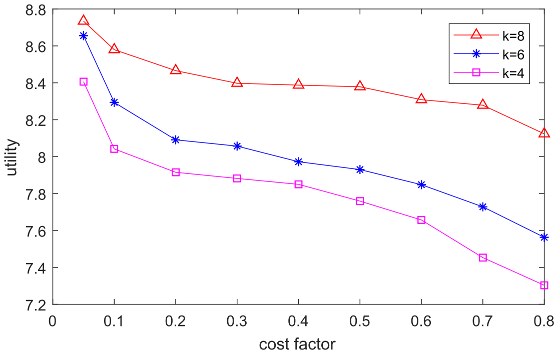


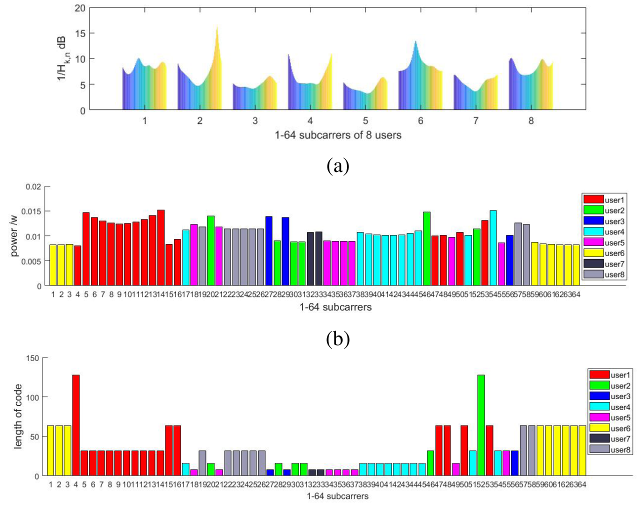
FIGURE 3. Relationship between the objective function value and the cost factor. The jamming power is 2*w*, the system total power is 1*w*, and the number of subcarriers is 64.

In Fig. 3, the objective function value increases as the number of nodes increase, however, the function value decreases as the cost function increases. This occurrence is analyzed here using an extreme case. When the IoT has only one node, it uses all subcarriers for information transmission. There must be subcarriers in an extremely harsh channel environment, in which case the power and code length will increase to carry out anti-jamming communication. When the node number increases, the node competes for limited subcarriers. The node selects the most suitable channel for transmission owing that the channel state of the node is different. Thus, as the number of nodes increase, the power and code length decrease.

B. ALLOCATE RESULTS

Fig. 4(a) shows the channel status of eight different nodes. The vertical axis is $\frac{1}{H_{k,n}}$, which indicates the degree of interference. The larger the value, the greater the interference. The node selects subcarriers with small values, which is the recessed area in the figure, to transmit information.

Depending on the intention that the minimum transmission rate of the node is maximized, Fig. 4(b) shows different power



(a)

(b)

(c)

FIGURE 4. **Allocation results. Jamming power is $2w$. The total power of OFDM system in IoT is $1w$. The number of subcarriers is 64, and the number of nodes is 8. (a) Allocated power corresponding to assigned subcarrier for 8 nodes. Different colors represent different nodes. (b) Code length corresponding to power and channel state for 8 nodes. The length is a power of 2.**

which is assigned per node on every subcarrier, and Fig. 4(c) illustrates the final code length, corresponding to the channel state of Fig. 4(a). These figures reflect the results of the JSER algorithm in subcarriers, as well as power and code length allocation.

C. PERFORMANCE COMPARISON

The performance of the JSER algorithm for resource allocation is compared with random allocation and fixed allocation in three terms: the utility of anti-jamming communication rate, anti-jamming performance, and rate fairness.

This method of random allocation is to randomly assign a channel with good state perceived to each node. The simulation conditions of random allocation are that the range of code length is $\{1, 2, 4, 8, 16, 32, 64, 128\}$, every node randomly assigns N/K subcarriers, and power on every subcarrier is average. Fixed allocation is to assign a channel with good state to fixed nodes. The simulation conditions of fixed allocation is that the code length is 32, every node allocates the first N/K subcarriers in order, and power on every subcarrier is average. In Fig. 5, the more nodes, the larger the utility function value. Compared with these methods, the JSER algorithm demonstrates notable advantages, indicating that this algorithm can provide better resource configuration parameters for the allocation center in Fig. 1.

The anti-jamming performance of the three methods of resource allocation is compared in Fig. 6. Under the condition of the same power, the JSER algorithm has the largest output SINR, and the SINR of other three algorithms is less. This result illustrates that the JSER algorithm is effective in anti-jamming transmission. Fig. 7 shows the comparison of the proportional fairness between the nodes using the three resource allocation methods. It is demonstrated here that the

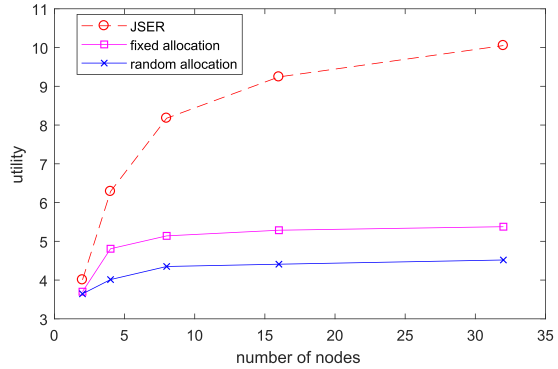


FIGURE 5. **Utility of anti-jamming transmission rate with three allocation methods. The jamming power is $2w$, the cost factor is 0.2, and the number of subcarriers is 64.**

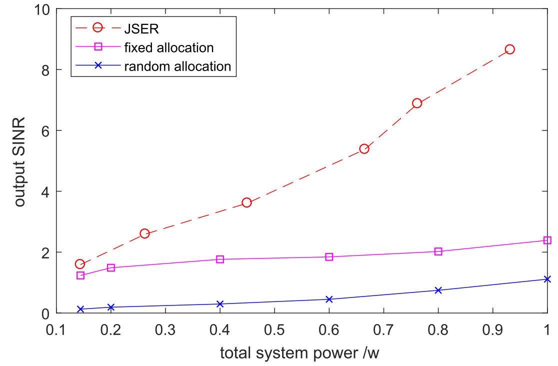


FIGURE 6. **Relationship between the output SINR and the total system power with three allocation methods. The jamming power is $2w$, the cost factor is 0.2, and the number of subcarriers is 64.**

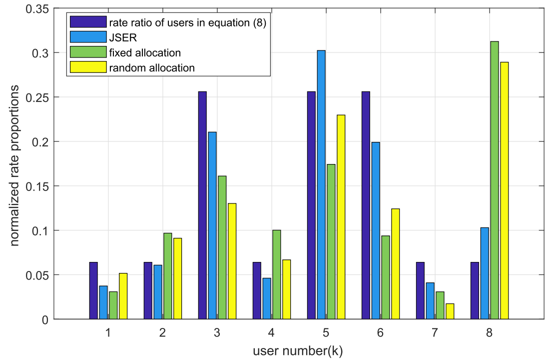


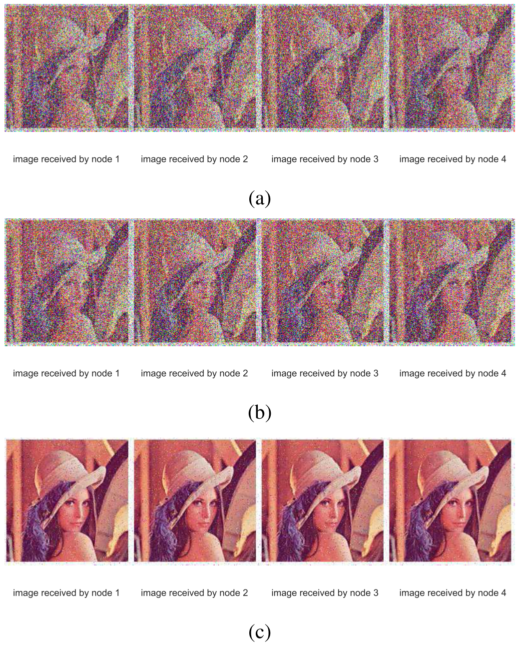
FIGURE 7. **Normalized rate ratios per user for eight users averaged over 16 channels, with the required proportions shown as the leftmost bar for each user. The proposed JSER method has minimal deviation from the required proportions.**

JSER algorithm is better than random allocation and fixed allocation. The rate ratio of the JSER algorithm is not exactly the same as the required ratio, and sacrifices some fairness in exchange for superior anti-jamming performance.

D. APPLICATION OF ACA MODEL

A communication simulation experiment is used to verify the feasibility and effectiveness of the ACA model and the JSER allocation algorithm.

Four nodes send the same picture, and are configured as resource parameters by loading three allocation methods,



(a)

(b)

(c)

FIGURE 8. Anti-jamming effect of the ACA model with four nodes by loading three allocation methods. The jamming power is 2w, the system total power is 1w, and the number of subcarriers is 64. (a) Images received by 4 different nodes using random allocation method through OFDM system based on ACA model. The same image is sent by nodes at the transmitting end. (b) Images received by 4 different nodes using fixed allocation method through OFDM system based on ACA model. The same image is sent by nodes at the transmitting end. (c) Images received by 4 different nodes using JSER algorithm through OFDM system based on ACA model. The same image is sent by nodes at the transmitting end.

according to the current channel and interference environment, to achieve anti-jamming transmission. The number of OFDM carriers is 64, and QPSK modulation mode is adopted. The total power of the system is 1w, the interference power is 4w, the spreading-time code is the Walsh code, the channel is the multipath channel, the path number is 6, and the Doppler frequency shift is a 30 degree frequency deviation. The channel noise is Gaussian white noise, and the bandwidth is 10 kHz. Results detailed in Fig. 8(a), Fig. 8(b), and Fig. 8(c) verify the effect of the ACA model and the JSER algorithm. It indicates that the model can adaptively allocate resource and reliably transmit information with the JSER allocation algorithm.

VI. CONCLUSION

This paper proposed a novel ACA model to implement resource allocation with anti-jamming for IoT nodes. By imposing the spreading-time code, a maximum anti-jamming transmission rate objective function was established. To adaptively transmit information according to the current environment, the solution was determined by the JSER algorithm. Then subcarriers, power, and code are automatically allocated in the ACA model. Simulation results show that the ACA model is effective, and it is suitable for the low-power and band-limited IoT network. In next work, we will jointly allocate modulation mode to make algorithm more applicable.

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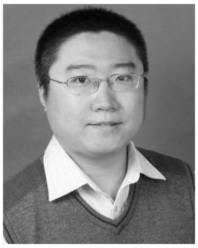

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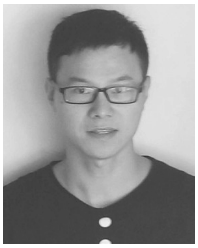

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