Progress In Electromagnetics Research C, Vol. 148, 117-125, 2024

PIER C

(Received 5 June 2024, Accepted 19 September 2024, Scheduled 3 October 2024)

A Cross-Layer Resource Allocation Algorithm for Broadband Power Line Communication OFDM Systems

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ABSTRACT: Adaptive orthogonal frequency division multiplexing (OFDM) technology is used in OFDM systems for broadband power line communications to effectively increase the communication rate. Existing research is mostly based on the single-layer network state for the resource allocation, and the required rate is often a static preset value. When there are significant differences in the signal-to-noise ratios of the sub-carriers, the system cannot adaptively adjust the required resources according to the quality-of-service (QoS) demand and the actual network, resulting in the waste of communication resources or the inability to meet some user communication needs. In this paper, a cross-layer resource allocation model is established for the system's cross-layer resource allocation problem through the data mapping among the application layer, data link layer, and physical layer. In the medium access control (MAC) layer, according to the quality of service (QoS) requirements of electric power multi-service, the data packet waiting delay and the packet loss are mapped to transmission rate proportionality constraints of real-time/non-real-time users through the utility function. A physical layer resource allocation model based on proportional constraints is constructed, and then an improved genetic algorithm is used for the resource allocation. Finally, through the simulation experiments in a typical power line channel environment, it is found that the proposed algorithm improves the total throughput by $4\% \sim 6\%$ over the existing two power line carrier resource allocation algorithms under the multi-service cross-layer resource allocation, and its proportional fairness is better. The proposed algorithm is able to maximize the system capacity while ensuring the QoS requirements, effectively improving communication quality.

1. INTRODUCTION

Power line communication (PLC) is an effective communication method to solve the problem of "last kilometre" information interaction by using power line as the medium for data communication. This method has the characteristics of reliable connection of electrical equipment, flexible access to various terminal equipment, and low construction cost [1]. PLC has a wide range of application prospects in smart grid, such as remote automatic meter reading, intelligent distribution substation solutions, power internet of things, smart city traffic, street lighting, intelligent monitoring, and smart home. However, there are multi-path effects, time-varying characteristics, and frequency selective fading in the power line channel [2]. At the same time, due to the variety of access devices, the channel contains various types of noise, such as colored noise and impulse noise [3]. To address the above problems, broadband power line communication using orthogonal frequency division multiplexing (OFDM) technology can effectively overcome the multi-path effect, reduce the inter-symbol interference (ISI) and the sub-carrier interference, and improve the communication rate [4].

Most traditional OFDM resource allocation algorithms allocate a fixed communication rate for each service, which cannot be flexibly and dynamically deployed according to the current physical networks in the case of limited resources [5]. It is difficult to meet the demand for information transmission and user quality of service after a large number of services are accessed to the system. In order to improve the transmission capacity of the system, it is important to study how to efficiently and reasonably use the limited system resources to satisfy the QoS demand of multi-services [6].

There have been studies on the resource allocation problem of power line communication, and there are corresponding resource allocation algorithms for different constraints and limitations. Ref. [7] proposes a maximum throughput algorithm, which allocates the sub-carrier to the user with the best channel quality to achieve the diversity gain of multiple users. However, this method only seeks to maximize the system throughput, often failing to provide sufficient resources to users with poorer channel quality, thereby not meeting the QoS requirements of all users and violating the principle of fairness among users. Ref. [8] proposes a max-min algorithm, which distributes a large number of system resources to users with poorer channel quality while allocating fewer resources to users with better channel quality to achieve relative fairness among users. Yet, this reduces network communication performance and results in low system throughput. Ref. [9] describes the satisfaction of each service to the QoS by calculating the cumulative fair deviation of the rate at the moment of the first N OFDM symbols and controls the smoothness of the user's rate, but the algorithm adopts an equal power allocation method, which does

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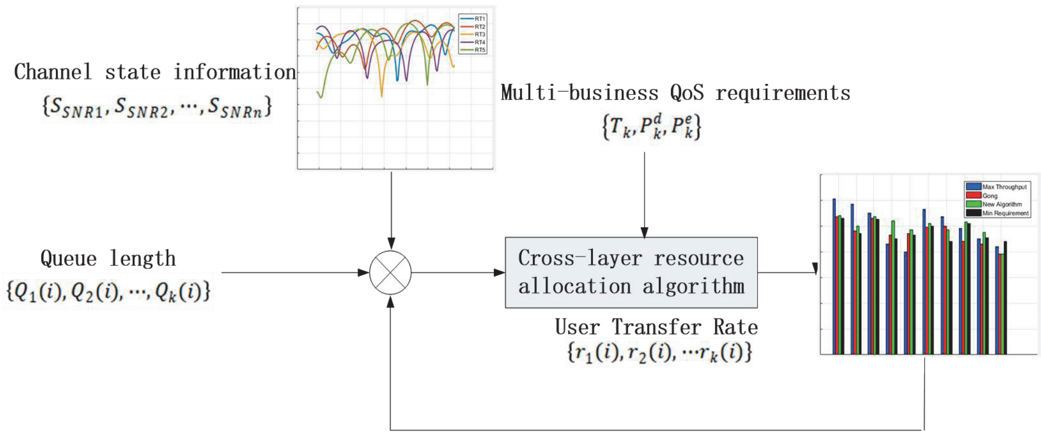

FIGURE 1. Cross-layer resource allocation structure.

not take into account the variability of the sub-carriers, and the system throughput is low. Ref. [10] proposes an algorithm that considers access control policies to maintain the overall system throughput by denying access to users with high power consumption when channel quality is poor, though this can lead to packet loss due to excessive queue lengths within user buffers.

These algorithms are mostly based on a single layer of network state for resource allocation, with the service communication rate set to a fixed value and not dynamically adjusted according to user QoS needs and the actual network. Consequently, they fail to allocate resources reasonably according to service flow, resulting in imbalance among different users and lower resource utilization rates. To meet the QoS needs of more users with limited resources, this paper proposes a new method of cross-layer resource allocation for broadband power line communications. The algorithm is a cross-layer resource allocation algorithm based on utility function for MAC layer user scheduling and an improved genetic algorithm for physical layer resource allocation. The algorithm maps data packet waiting delay and packet loss into user transmission rate proportionality constraints through the utility function, forming a physical layer resource allocation model with proportional constraints. Then, an improved genetic algorithm is used at the physical layer for sub-carrier and power allocation, maximizing the system's total capacity while ensuring the fairness of the quality of service (QoS) requirements for users within the network.

2. RESOURCE ALLOCATION MODEL

2.1. Description of Resource Allocation

Usually, each phase of a low-voltage power line communication system contains multiple terminal devices for real-time (RT) and non-real-time (NRT) user services, and these devices compete for native power line open shared channel resources. Due to the difference of user's access points, transmission distances, and load impedance of terminal connections, the same sub-carrier experiences different attenuation conditions for different users. Therefore, when allocating resources for OFDM-based broadband power line communication, it is necessary to reasonably allocate sub-carriers to different users according to the channel gain size to realize the diversity gain of multiple users.

Figure 1 shows the design structure of the proposed cross-layer resource allocation algorithm. When designing the MAC layer user scheduling and physical layer resource allocation algorithm, the system calculates the minimum transmission rate of each service $r_{k\min}^{RT}$ and $r_{k\min}^{NRT}$ based on real-time channel status for each user $\{S_{SNR1}, S_{SNR2}, \ldots, S_{SNRn}\}$, the queue length of each type of service data packet after it arrives at the buffer $Q_1(i), Q_2(i), \ldots, Q_k(i)$, the service QoS index set T_k, P_k^d, P_k^e, and the current actual obtained rate $r_1(i), r_2(i), \ldots, r_k(i)\}$. The algorithm passes real-time scheduling information from the MAC layer to the physical layer through the constructed utility function, and then power and sub-carrier allocation is accomplished at the physical layer.

2.2. MAC Layer Queue State Analysis and Modelling

It is assumed that the service data of each user in the broadband power line communication system arrives at the MAC layer buffer waiting for scheduling after processing at the application layer [11]. At this time, the waiting data packets are transmitted according to the principle of first-in-first-out, and the length of each user's queue remains unchanged within a very short OFDM symbol period. Here, we take user k as an example to establish a user queue state model based on data packets. Assuming that up to M packets can be stored in the buffer and that each packet size is fixed to L/bit, the number of packets arriving at user k in the i-th OFDM symbol is $D_k(i)$. In the previous OFDM symbol, the queue length for user k is $Q_k(i-1)$. After completing the resource allocation, user k receives a rate of $r_k(i)$. The queue length within the i-th OFDM symbol buffer is

$$M_k(i) = \max(0, Q_k(i-1) + D_k(i) - \lfloor r_k(i)/L \rfloor) \quad (1)$$

where ($|\lfloor\cdot\rfloor|$) is rounded down. Since at most M packets can be stored in the buffer, the actual queue length for user k within the i-th OFDM symbol is

$$Q_k(i) = \min(MM_k(i)) \tag{2}$$

If the length of the queue in the buffer does not exceed M, the number of data packets that can be allowed to enter, considering the length of the existing queues in the buffer, is

$$P_k(i) = M - M_k(i) \tag{3}$$

The queue length in the i-th OFDM symbol buffer is $Q_k(i)$. The waiting delay of the data packet at this time is

$$\tau_k(i) = \frac{Q_k(i)}{\lfloor r_k(i)/L \rfloor} \tag{4}$$

If the number of packets arriving at the buffer by the i-th OFDM symbol for user k satisfies $D_k(i) < P_k(i)$, all data packets are temporarily placed in the buffer waiting for service. When the number of packets arriving at the buffer by the i-th OFDM symbol for user k satisfies $D_k(i) > P_k(i)$, only data packets $P_k(i)$ are allowed to enter the buffer due to the maximum queue length limit, and the $D_k(i) - P_k(i)$ data packets exceeding the maxi-mum queue length M will be discarded, thus generating the phenomenon of data packet loss at the MAC layer. The data packet loss ratio is defined as

$$P_k^d(i) = \frac{D_k(i) - P_k(i)}{D_k(i)} \tag{5}$$

In this paper, it is considered that each code element signal will be subjected to various kinds of interference in the power line communication process, resulting in the phenomenon of error code. Therefore, the packet error rate P_k^e is defined as:

$$P_k^e = 1 - (1 - P_e)^L \tag{6}$$

where P_e is the bit error rate (BER) of a single code element, and L is the number of bits contained in each data packet.

The magnitude of packet loss depends on the packet loss rate and error rate. By the above analysis, the packet loss $P_k^l(i)$ is defined as

$$P_k^l(i) = 1 - (1 - P_k^d(i))(1 - P_k^e) \tag{7}$$

2.3. Model for Cross-layer Resource Allocation

According to power application requirements, users can be classified into real-time users (RT, e.g., power quality monitoring recording) and non-real-time users (NRT, e.g., power consumption information collection) based on timeliness. For RT users, timeliness is the primary QoS indicator, and when the delay exceeds the maximum allowable delay, the quality of service of RT users will be greatly reduced. For NRT users, the QoS performance is mainly considered in terms of packet loss, and when the packet loss exceeds the maximum allowable packet loss, the quality of service of NRT users will also be greatly reduced. When crosslayer resource allocation is performed, the system should first satisfy the minimum QoS requirements of RT users according to the different service requirements of each user, then continue to allocate resources for NRT users. If the minimum QoS requirements of all users are satisfied, and the system still has remaining resources, the remaining resources are allocated to the users with the best channel quality to improve the average throughput of the system.

The cross-layer resource allocation model for broadband power line communication is defined as

$$\begin{cases} \max \sum\limits_{i=1}^{I} \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} w_{i,k,n} r_{i,k,n} & \\ s.t.\ C1: w_{i,k,n} \in \{0,1\} & \forall i,k,n \\ C2: \sum\limits_{k=1}^{K} w_{i,k,n} \leq 1 & \forall i,n \\ C3: \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} w_{i,k,n} p_{i,k,n} \leq P_{total} & \forall i \\ C4: p_{i,k,n} \leq P_{\max} & \forall i,k,n \\ C5: \tau_k(i) \leq T_k & \forall i, k \in \Omega_h \\ C6:\ P_k^l(i) \leq P_k^{l\max} & \forall i, k \in \Omega_l \end{cases} \tag{8}$$

where $w_{i,k,n,}$ is the sub-carrier allocation flag bit; $w_{i,k,n} = 0$ indicates that sub-carrier n is not assigned to user k in the i-th OFDM symbol; $w_{i,k,n} = 1$ indicates that sub-carrier n is allocated to user k; $r_{i,k,n}$ and $p_{i,k,n}$ are the bits and transmitting power loaded on sub-carrier n assigned to user k within the i-th OFDM symbol, respectively; P_{total} is the upper limit of the total transmit power of the system; considering that the electromagnetic radiation generated during the transmission of high-frequency signals over power lines will cause interference to other communication services, the $P_{\max}$ is the upper limit of the transmit power of each sub-carrier under the power spectrum limitation; T_k is the maximum allowable delay for the real-time user k; $P_k^{l\max}$ is the maximum allowable packet loss for the non-real-time user k.

The constraints in the model are: C1 is the sub-carrier assignment flag bit; C2 indicates that sub-carrier n can only be assigned to one user within any OFDM symbol; C3 indicates that the sum of the power assigned to N sub-carriers does not exceed the total transmitting power limit within any OFDM symbol; C4 indicates that the transmitting power on each sub-carrier does not exceed the maximum transmitting power of a single carrier under the power spectrum limit; C5 is the data packet waiting delay constraint, indicating that at any i-th OFDM symbol, the data waiting delay in the buffer should be less than the maximum allowable delay of RT_k; C6 indicates that the packet loss shall be less than the maximum allowable packet loss of NRT_k at any i-th OFDM symbol. The goal of optimization is to maximize the total system capacity while satisfying the above constraints and guaranteeing the QoS for both real-time and non-real-time users [12].

Due to the limited modulation used in the broadband power line communication system, the upper limit of bits per sub-carrier is $r_{\max}$; therefore the actual bits loaded on the sub-carriers should be decided according to Shannon's formula and the minimum value of the bit upper limit value $r_{\max}$ [13], which is expressed as

$$r_{i,k,n} = \min\left\{ \left\lfloor \log_2\left(1 + \frac{|h_{i.k.n}|^2 p_{i,k,n}}{\sigma_{i,k,n}^2 \Gamma}\right) \right\rfloor r_{\max} \right\} \tag{9}$$

where $h_{i,k,n}$ and $\sigma^2_{i,k,n}$ are the channel gain and noise power of sub-carrier n on user k at the moment of the i-th OFDM symbol, respectively; Γ is the signal-to-noise ratio (SNR) interval.

3. CROSS-LAYER RESOURCE ALLOCATION ALGORITHMS

For the above cross-layer resource allocation model for broadband power line communication, the degrees of freedom increase due to the increase of inter-layer information. The model is a mixed integer nonlinear programming nondeterministic polynomial (NP)-hard problem, which is difficult to solve to the global optimal solution in polynomials. To reduce the complexity of the algorithm, the complex problem is divided into two steps: user scheduling at the MAC layer and resource allocation at the physical layer. Resource allocation at the physical layer is further divided into two sub-problems: sub-carrier allocation and power allocation.

3.1. MAC Layer User Scheduling Based on Queue State Information

For the RT user set Ω_x, the maximum allowable delay of user k is T_k. When the waiting delay of data packets placed in the buffer exceeds T_k, the communication quality of RT users will be seriously affected. Therefore, the resource allocation for RT users should satisfy $\tau_k(i) < T_k$, and the minimum rate $r^{RT}_{k\,\min}$ at which RT user k can avoid the data packet waiting timeout in the buffer at the i-th OFDM symbol is

$$r^{RT}_{k\,\min}(i) = L\left\lceil \frac{Q_k(i-1) + D_k(i)}{T_k + 1} \right\rceil \tag{10}$$

where ($\lceil\cdot\rceil$) is the upper rounding. For RT users, the utility function based on the data packet waiting delay is

$$U^{RT}_k(i+1) = \frac{r^{RT}_{k\,\min}(i+1)}{r_k(i)} \exp\left(\tau_k(i) - T_k\right) \tag{11}$$

For the NRT user set Ω_y, the maximum allowable packet loss of user k is $P^{l\max}_k$. When the packet loss of user k exceeds the maximum allowable value, the communication quality of the NRT users will also be affected. Therefore, the resource allocation for NRT users should satisfy $P^l_k(i) < P^{l\max}_k$. The minimum rate $r^{NRT}_{k\,\min}(i)$ at which NRT user k can avoid the data packet loss exceeding the maximum permissible value in the buffer at the i-th OFDM symbol is

$$r^{NRT}_{k\,\min}(i) = \max\left\{v_{k\,\min} L\left\lceil D_k(i)\left(1+\frac{1-P^{l\max}_k}{1-P^e_k}\right) + Q_k(i-1) - M\right\rceil\right\} \tag{12}$$

where $v_{k\,\min}$ is the minimum rate of data packets for user k that satisfies the packet loss requirement. For NRT user's, the utility function based on the packet loss can be derived as

$$U^{NRT}_k(i+1) = \frac{r^{NRT}_{k\,\min}(i)}{r_k(i)} \exp\left(\lg P^l_k(i) - \lg P^{l\max}_k\right) \tag{13}$$

Various types of electric power communication services in the smart grid have different QoS requirements. In this paper, we design utility functions for RT services based on delay requirements and NRT services based on packet loss requirements, respectively. The system has to satisfy the QoS requirements of RT and NRT services simultaneously in resource scheduling. When setting the service scheduling sequence, the scheduling is done according to the size of the utility function value. The specific process includes the following steps:

1) Initialization: $i = 0$, user initial rate $r_k(0) = 0$, queue length for user k in the buffer $Q_k(0) = 0$.

2) Judge the user category. If user k is an RT user, the user obtains the maximum allowable delay T_k. Calculate the group waiting delay $\tau_k(i)$ according to the current moment of $Q_k(i)$ and then substitute it into Eq. (11) to calculate the utility function value of RT user k at the next moment $U^{RT}_k(i+1)$. If user k is an NRT user, the user obtains the maximum allowable packet loss $P^{l\max}_k$. Calculate the packet loss $P^l_k(i)$ according to Eq. (7) and then substitute it into Eq. (13) to calculate the utility function value of NRT user k at the next moment $U^{NRT}_k(i+1)$.

3) To facilitate the physical layer resource allocation, we arrange the utility function values of x RT users and y NRT users in descending order, respectively, to generate the utility function-based scheduling sequence. Pass the scheduling information at that moment to the physical layer to invoke the physical layer resource allocation algorithm to optimally allocate the sub-carriers and system power.

4) After the physical layer completes the resource allocation, update the actual rate obtained by user k and the queue length in the user's buffer, then end this MAC layer user scheduling, make $i = i + 1$, and go to step 2.

3.2. Physical Layer Resource Allocation

The physical layer resource allocation includes sub-carrier and system power allocation. The resource allocation model introduces proportionality constraints when allocating resources at the physical layer. The utility function values of RT users and NRT users are sorted in descending order. The proportionality constraints are generated based on the utility function values, and then it is normalized to form the normalized proportionality constraints: $\varphi_{i,1} : \ldots : \varphi_{i,k} : \ldots : \varphi_{i,K}$

At the physical layer, the downlink of a multi-user OFDM system in a communication environment is considered, assuming a total of K users and N sub-carriers, and the total power of the system is P_{total}. The system capacity is maximized by optimising the sub-carriers and power allocation, subject to the total power and proportional rate constraints.

Within the i-th OFDM symbol, it is assumed that each user experiences independent fading; the channel gain of user k on sub-carrier n is $h_{i,k,n}$; the noise in the channel is additive Gaussian white noise (AWGN); the one-sided power spectral density (PSD) of the noise is N_0; then the noise power on each carrier is $\delta^2 = N_0(B/N)$, where B is the band-width, and N is the number of carriers. The received signal-to-noise ratio per user is $s_{i,k,n} = p_{i,k,n} h^2_{i,k,n}/N_n$, where $p_{i,k,n}$ is the power of the user k on the sub-carrier n in the i-th OFDM symbol. The BER of multiple quadrature amplitude modulation (MQAM) is related to the received SNR $s_{i,k,n}$ and the number of bits $r_{i,k,n}$ [14]. When $r_{i,k,n} \geq 1$ and $BER \leq 10^{-3}$, the BER within 1 dB approximately satisfies the following relationship:

$$BER_{MQAM}(s_{i,k,n}) \approx 0.2 \exp\left(\frac{-1.6 s_{i,k,n}}{2^{r_{i,k,n}} - 1}\right) \tag{14}$$

Solving for $r_{i,k,n}$:

$$r_{i,k,n} = \log_2\left(1 + \frac{s_{i,k,n}}{\Gamma}\right) \tag{15}$$

where $\Gamma \approx -\ln(5BER)/1.6$ is a constant signal to interference plus noise ratio (SINR) gap. The object function of resource allocation problem with the proportional fairness constraint is formulated as [15]:

$$\begin{cases} \max \sum\limits_{i=1}^{I} \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} w_{i,k,n} \log_2\left(1 + \frac{p_{i,k,n} h_{i,k,n}^2}{\Gamma * \delta_{i,k,n}^2}\right) & \\ s.t.\ C1: w_{i,k,n} \in \{0,1\} & \forall i,k,n \\ C2: \sum\limits_{k=1}^{K} w_{i,k,n} \leq 1 & \forall i,n \\ C3: \sum\limits_{k=1}^{K} \sum\limits_{n=1}^{N} w_{i,k,n} p_{i,k,n} \leq P_{total} & \forall i \\ C4: p_{i,k,n} \geq 0 & \forall i,k,n \\ C5: R_{i,1} : \ldots : R_{i,k} : \ldots : R_{i,K} & \\ \quad = \varphi_{i,1} : \ldots : \varphi_{i,k} : \ldots : \varphi_{i,K} & \end{cases} \tag{16}$$

In the above equation, C1 and C2 indicate the sub-carrier allocation; $w_{i,k,n}$ is the sub-carrier allocation indication matrix; $w_{i,k,n} = 1$ means that the sub-carrier n is assigned to user k in the i-th OFDM symbol, and users cannot share the same subcarrier at the same moment. C3 and C4 are power constraints. C5 is the proportionality constraint. $\varphi_{i,1} : \ldots : \varphi_{i,k} : \ldots : \varphi_{i,K}$ is the normalized proportionality constraint value, where $R_{i,k} = \frac{B}{N} \sum\limits_{n=1}^{N} w_{i,k,n} r_{i,k,n}$. The utility function is used to construct the proportionality constraints to ensure that each user can get a better quality of service.

Notice that Eq. (16) is an NP-hard combinatorial optimization problem with nonlinear constraints. A single conventional algorithm is difficult to solve the problem. An improved genetic algorithm is presented below to solve the problem.

Here, we use an improved genetic algorithm for joint subcarrier, power allocation. The process is as follows:

Within the i-th OFDM symbol.

(1) Set the basic parameters.

First set the maximum number of genetic generations GENMAX, maximum total power required by the system P_{total}, system bandwidth B, total number of sub-carriers N, and the number of users K. The scaling constraints are formed by the normalized scaling constraints $\varphi_{i,1} : \ldots : \varphi_{i,k} : \ldots : \varphi_{i,K}$ after the MAC layer scheduling. Here, it is necessary to know the channel state information (CSI), which is represented by the channel gain matrix $G_{i,k,n}$.

(2) Population coding.

Binary coding is used here. The sub-carrier indication matrix itself is a 0-1 matrix and does not need to be coded. For $p_{i,k,n}$, encoding is performed. We determine the encoding length m by the following equation: $2^{m-1} < (p_{\max} - p_{\min}) \times 10^e \leq 2^m - 1$, where $p_{\max}$ and $p_{\min}$ are the upper and lower limits for each sub-carrier power, respectively, and e denotes the required precision. The initialized population is encoded as a 3D matrix at $K \times mN \times NIND$.

(3) Constructing the fitness function.

In this paper, the resource allocation model is to find the maximum value, so we directly take the objective function as the fitness function:

$$fitness = \sum_{k=1}^{K} \sum_{n=1}^{N} w_{i,k,n} \log_2\left(1 + \frac{p_{i,k,n} h_{i,k,n}^2}{\Gamma * \delta_{i,k,n}^2}\right) \tag{17}$$

Next, the constraints in the objective function are processed. Conditions C1 ∼ C4 can be directly adopted in the algorithmic procedure. To satisfy the proportionality fairness condition C5, we adopt a proportional fairness strategy [16].

Firstly define the interference-to-noise ratio of the user on the sub-carrier within the i-th OFDM symbol as:

$$H_{i,k,n} = g_{i,k,n}^2 / (N_0/(B/N)) \tag{18}$$

where $g_{i,k,n}$ is the noise ratio of the user k on the sub-carrier n within the i-th OFDM symbol.

Let $\Omega_{i,k}$ be the set of sub-carriers occupied by the user k within the i-th OFDM symbol. The steps are as follows:

(I) Initialize the total data rate for user k. Let $R_{i,k} = 0$, $\Omega_{i,k} = \phi$, $A = \{1, 2, \ldots, N, k = 1, \ldots, K$.

(II) For the user k.

a) Find the sub-carrier n that satisfies $|H_{i,k,n}| \geq |H_{i,k,j}|$, where $j \in A$;

b) Let $\Omega_{i,k} = \Omega_{i,k} \cup \{n\} A = A - \{n\}$, and then recalculate $R_{i,k}$.

(III) If $A \neq \emptyset$.

a) Look for user k who fulfills the requirements of $R_{i,k}/\varphi_{i,k} \leq R_{i,m}/\varphi_{i,m}$, where $1 \leq m \leq K$;

b) For this user k, find the sub-carrier n that satisfies $|H_{i,k,n}| \geq |H_{i,k,j}|$, where $j \in A$;

c) Let $\Omega_{i,k} = \Omega_{i,k} \cup \{n\} A = A - \{n\}$, and then recalculate $R_{i,k}$.

After passing the above proportional fairness strategy, the sub-carrier indication matrix $w_{i,k,n}$ can be determined, which means that the sub-carrier allocation is complete. The resource allocation model can be simplified as:

$$\begin{aligned} &\max \sum_{k=1}^{K} \sum_{n \in \Omega_{i,k}} \log_2 (1 + \frac{p_{i,k,n} h_{i,k,n}^2}{\Gamma * \delta_{i,k,n}^2}) \\ &s.t. C1: \ p_{i,k,n} \geq 0 \ \forall k, n \\ &C2: \sum_{k=1}^{K} \sum_{n \in \Omega_{i,k}} p_{i,k,n} \leq P_{total} \end{aligned} \tag{19}$$

(4) Selection.

We use roulette wheel selection method to choose. The steps are as follows:

1) Calculate the value of the fitness function for the individual chromosome L_t:

$$fitness_t = \sum_{k=1}^{K} \sum_{n=1}^{N} w_{i,k,n} \log_2 (1 + \frac{p_{i,k,n} h_{i,k,n}^2}{\Gamma * \delta_{i,k,n}^2}) \quad (20)$$

2) Calculate the value of the fitness function for the population:

$$fitness_{total} = \sum_{t=1}^{NIND} fitness_t \quad (21)$$

3) Calculate the selection probability of the corresponding chromosome L_t:

$$P_t = fitness_i / fitness_{total} \quad (22)$$

4) Calculate the cumulative probability of each chromosome L_t:

$$Q_t = \sum_{s=1}^{t} P_s \quad (23)$$

5) Generate a random number r between $[0, 1]$. If $r \le Q_1$, select chromosome L_1; otherwise, select the t-th chromosome $L_t (2 \le t \le NIND)$. Here, $Q_{t-1} \le r \le Q_t$. Each time the number r is randomly generated, generate NIND times to form a new generation of the population.

In order to improve the convergence of the genetic algorithm, an elite chromosome retention strategy is used here [17]. The individual or individuals with the largest fitness function are not genetically manipulated and enter directly into the next generation as the parent.

(5) Crossover and variation.

We use two-point crossovers and basic bit variants.

Two-point crossover: this means that two intersections are randomly generated in the coding of two individuals, and the parts between the two intersections are exchanged with each other with a certain probability, thus generating two new individuals.

Basic bit variation: a change in the value at one or more randomly designated loci in the coding of a single individual with a certain probability.

(6) Reorganisation

Recombine individuals that have undergone elite retention, selection, crossover, and mutation. Determine whether the maximum number of genetic generations has been reached, and if so, terminate the cycle; otherwise, go to step (3).

4. ALGORITHM SIMULATION

To verify the performance of the cross-layer resource allocation algorithm is proposed. The cross-layer resource allocation algorithm proposed in this paper for broadband power line carrier communication under concurrent multi-service is analyzed by simulation experiments in a typical power line carrier channel environment [18]. The system simulation parameters are shown in Table 1.

TABLE 1. System simulation parameters.

Parameter name	Parameter value
Number of sub-carriers	128
Bandwidth/MHz	$2.441 \sim 5.615$
Power spectrum limitation/(dBm/Hz)	-60
FFT/IFFT length/μs	40.96
Protection interval lengthμs	18.32
System transmit power/mW	50
Maximum queue length/bytes	500
Message sending interval/ms	2
Message length/bytes	$40 \sim 60$
BER P_e	10^{-3}

This study aims to maximize the throughput of the system while meeting the QoS requirements of power multi-service. It is divided into two scenarios: insufficient total system capacity and sufficient total system capacity. The simulation experiment contains five RT real-time users (RT1, RT2, RT3, RT4, and RT5) and five NRT non-real-time users (NRT1, NRT2, NRT3, NRT4, and NRT5), in which the overall quality of the channel in descending order is $\mathrm{RT1} > \mathrm{RT2} > \mathrm{RT3} > \mathrm{RT4} > \mathrm{RT5}$ and $\mathrm{NRT1} > \mathrm{N-RT2} > \mathrm{NRT3} > \mathrm{NRT4} > \mathrm{NRT5}$.

4.1. Performance Analysis when System Capacity Is Insufficient

According to the channel transmission model given in [19], the unit power SNR curves for RT users and NRT users under AWGN with noise power spectral density of -70 dBm/Hz (poor channel quality) are shown in Fig. 2. Due to the differences in user access points, number of line branches and terminal connection loads, different users have different SNRs at the same frequency point, and different SNRs at different frequencies for a particular user. Higher SNR curve indicates that the channel quality of the user is better, in the allocation of cross-layer resources for broadband power line carrier communication.

When allocating the cross-layer resources for broadband power line communication, it should be based on the differences among the channels of each user and give full play to the diversity gain of multiple users to improve the overall throughput of the power line carrier communication system under the premise of guaranteeing the basic communication needs of each user [20]. Fig. 2 shows that the signal-to-noise ratio of each user in the system is located between 0 and 20 dB, and this paper sets the threshold value of signal-to-noise ratio of each user to 5 dB. The signal-to-noise ratio lower than the threshold value will lead to an increase in the BER because of the strong noise interference.

First, we simulate the case of poor channel quality and insufficient overall channel capacity. When the noise power spectral density is set to -70 dBm/Hz, the total system throughput of the maximum throughput algorithm, Gong's algorithm, and this paper's algorithm after simulation is 1006, 947, and 991 kbps, respectively. The average throughput of each user under different

TABLE 2. Throughput of each algorithm(kbps)(noise power spectral density of -70 dBm/Hz).

User Type	Maximum Throughput Algorithm	Gong's algorithm	The algorithms in this paper	Minimum Speed Requirement
RT1	121(15)	107(1)	108(2)	106
RT2	117(23)	96(2)	100(6)	94
RT3	110(5)	106(1)	107(2)	105
RT4	86(−4)	93(3)	104(14)	90
RT5	80(−13)	94(1)	97(4)	93
NRT1	113(13)	99(−1)	102(2)	100
NRT2	110(22)	100(12)	97(9)	88
NRT3	98(−4)	88(−14)	103(1)	102
NRT4	90(−1)	86(−5)	95(4)	91
NRT5	84(−4)	78(−10)	78(−10)	88

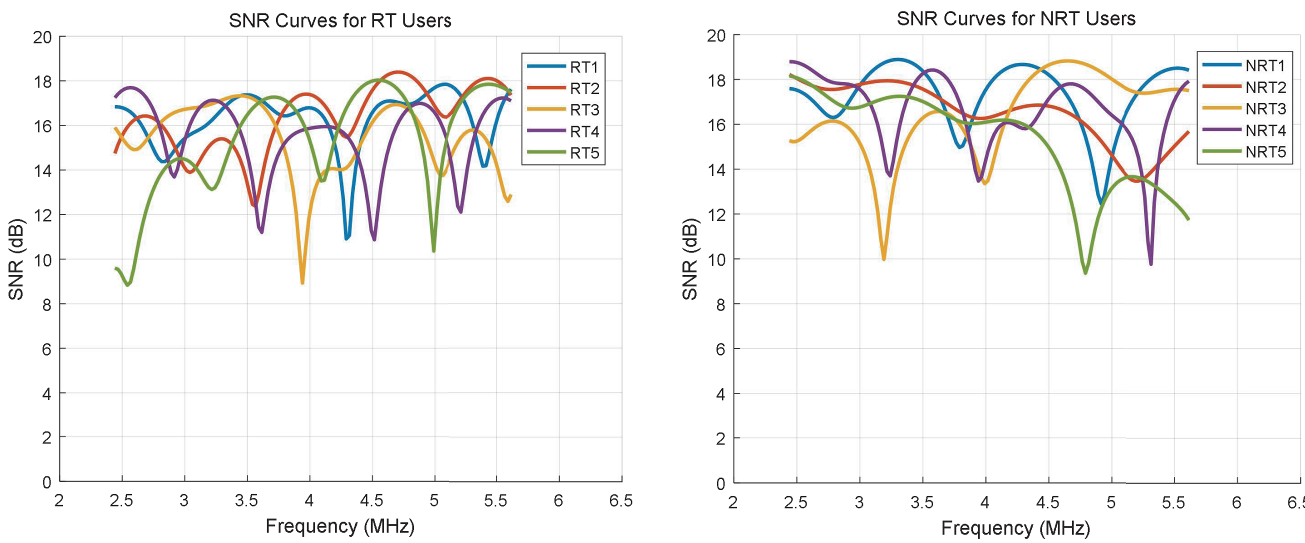

FIGURE 2. The unit power SNR curves at insufficient capacity (noise power spectral density of -70 dBm/Hz).

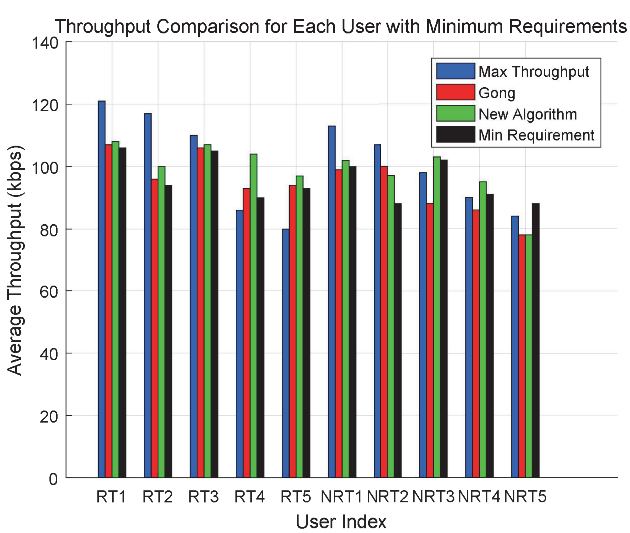

FIGURE 3. User throughput with insufficient capacity (noise power spectral density of -70 dBm/Hz).

algorithms is given in Fig. 3 and Table 2 (The numbers in parentheses in Table 2 indicate the difference between the rate configured to the user based on each algorithm and the minimum rate requirement), which shows that the maximum throughput algorithm allocates most of the system resources to users RT1, RT2, RT3, NRT1, and NRT2 with better channel quality, resulting in insufficient resources for the users RT4, RT5, NRT3, NRT4, and NRT5 with poorer channel quality. Gong algorithm performs the user scheduling in accordance with the principle of the maximum cumulative fairness deviation and allocates the remaining resources to the NRT users after satisfying the minimum rate requirement of RT users. Due to the low overall system throughput of this algorithm, none of the NRT users meet the minimum rate requirement. The algorithm proposed in this paper generates proportional constraints on the system function based on the magnitude of the utility function value and then uses an improved genetic algorithm for sub-carrier and power allocation. In the case of insufficient overall capacity of the channel (the noise power spectral density is -70 dBm/Hz), the new algorithm ensures that all the RT users as well as the ma-

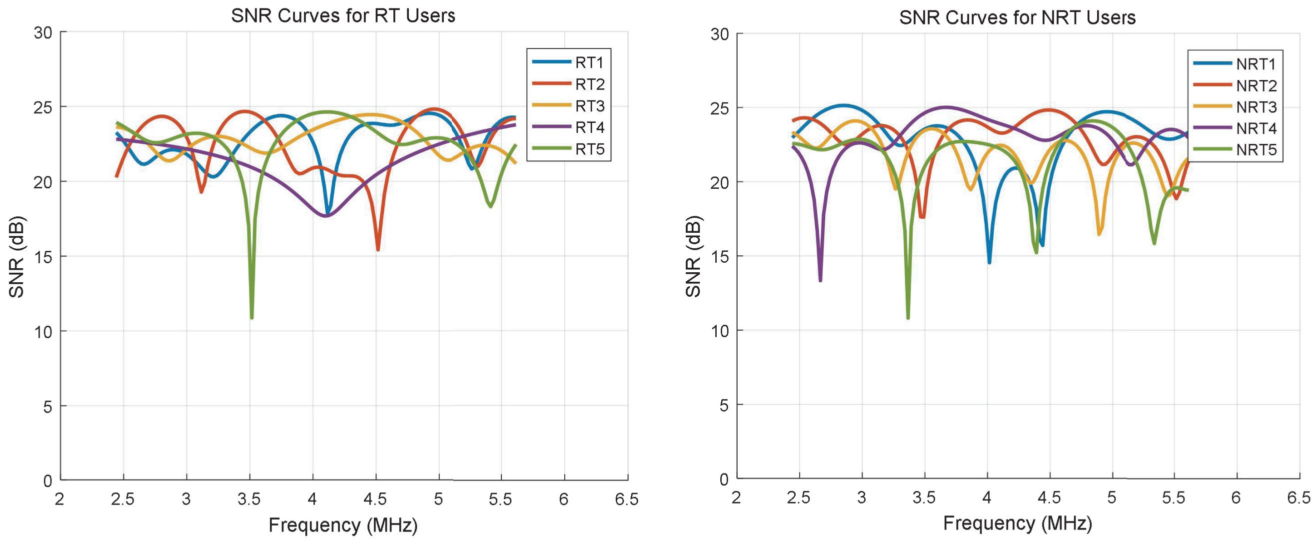

FIGURE 4. The unit power SNR curves at insufficient capacity(noise power spectral density of −90 dBm/Hz).

TABLE 3. Throughput of each algorithm (kbps) (noise power spectral density of −90 dBm/Hz).

User Type	Maximum Throughput Algorithm	Gong's algorithm	The algorithms in this paper	Minimum Speed Requirement
RT1	178(48)	139(9)	140(10)	130
RT2	169(57)	118(6)	128(16)	112
RT3	148(20)	135(7)	139(11)	128
RT4	128(21)	115(8)	135(28)	107
RT5	90(-20)	117(7)	126(16)	110
NRT1	159(39)	123(3)	132(12)	120
NRT2	151(53)	108(10)	116(18)	98
NRT3	130(7)	124(1)	130(7)	123
NRT4	100(−9)	112(3)	114(5)	109
NRT5	90(−8)	99(1)	105(7)	98

jority of the NRT users satisfy the minimum rate requirement compared with the maximum throughput algorithm. The new algorithm ensures that most of the NRT users meet the minimum rate requirement, and the system throughput is increased by 4.6% compared with the Gong algorithm.

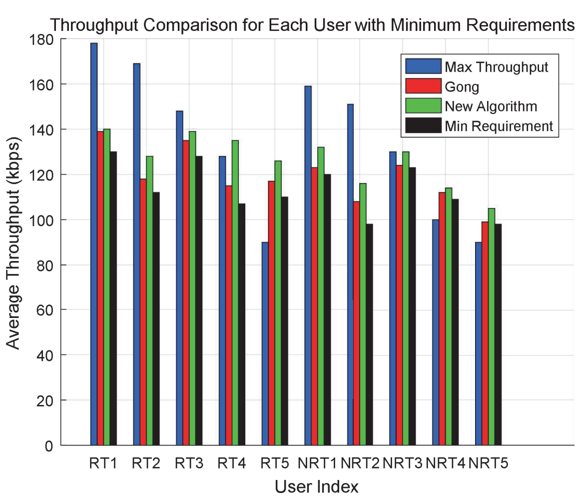

FIGURE 5. User throughput with sufficient capacity (noise power spectral density of −90 dBm/Hz).

4.2. Performance Analysis when System Capacity Is Sufficient

In the following, we simulate the case where the channel quality is good, and the overall channel capacity is sufficient. When the noise power spectral density is set to −90 dBm/Hz (the overall channel quality is good), the unit power SNR curves of RT users and NRT users under the addition of AWGN at this time are shown in Fig. 4.

It can be seen that the channel quality of each user is much improved compared to when the noise power spectral density is −70 dBm/Hz. At this time, the total system throughput of the maximum throughput algorithm, Gong's algorithm, and this paper's algorithm after simulation is 1343, 1190, and 1265 kbps, respectively. The average throughput of each user under different algorithms at this time is given in Fig. 5 and Table 3 (The numbers in parentheses in Table 2 indicate the difference between the rate configured to the user based on each algorithm and the minimum rate requirement). It can be seen that the maximum throughput algorithm allocates most of the system resources to the users RT1, RT2, RT3, RT4, NRT1, NRT2, and NRT3 with better channel quality, resulting in users RT5, NRT4, and NRT5 with poor channel quality obtaining insufficient resources, which makes them unable to satisfy the minimum rate requirement. Although Gong algorithm can satisfy the communication requirements of all users, the overall system throughput is lower due to the use of the equal power allocation method and the user scheduling based on the principle of the largest cumulative fair deviation. In contrast, the algorithm in this paper satisfies the principle of proportional fairness of each user, and with sufficient overall channel capacity, it guarantees that all users can meet the minimum rate requirement compared with the maximum throughput algorithm. Its proportional fairness is better, and the throughput of the system is also increased by 6.3% compared with the Gong algorithm.

5. CONCLUSION

This paper investigates the cross-layer resource allocation problem for broadband power line communication under multi-services. A cross-layer resource allocation model is established through the data mapping among application layer, data link layer, and physical layer. Based on the QoS requirements of the application layer power multi-service, the queue length in the data link layer buffer, and the underlying physical layer subcarrier and system power, the data packet waiting delay and packet loss are mapped into the transmission rate proportionality constraints for real-time/non-real-time users by means of a utility function. Then, MAC layer user scheduling and physical layer resource allocation algorithm based on the utility function is proposed. Simulation experiments show that the algorithm in this paper has better resource allocation capability than the maximum throughput algorithm and Gong resource allocation algorithm in multi-service scenarios, which effectively improves the system throughput, ensures the communication quality under low SNR, and improves the network transmission performance.

ACKNOWLEDGEMENT

This research was supported by Open Fund Project of Sichuan Key Laboratory of Artificial Intelligence in 2021 (No. 2021RYY02) and Project of Sichuan Engineering Laboratory of Intelligent Perception and Control Technology for Unmanned Systems in 2023 (No. WRXT2023-001).

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