Resource Allocation Algorithm for Physical Layer of Broadband Power Line Carrier Communication Applied to Electric Internet of Things

Xiyang Yin*, Long Yan, Guoyuan Lv
State Grid Tianjin Electric Power Information and Communications Company, Tianjin, 300010, China
*Corresponding author’s e-mail: xiyang.yin@tj.sgcc.com.cn

ABSTRACT: Broadband power line carrier communication adopts adaptive orthogonal frequency division multiplexing OFDM technology to effectively increase the communication rate, and provides ample communication resource guarantee for the realization of power multi-service applications. Aiming at the problem of broadband power line carrier communication resource allocation, this paper proposes a low-complexity physical layer resource allocation algorithm. First, based on the equal power allocation method, the set of subcarriers required by each user to meet their minimum rate requirements is determined, and the multi-user resource allocation problem is reduced to a single-user optimal power allocation problem, and then the Lagrange multiplier method is used to optimize the power of the sub-carrier set used by each user to further improve the system throughput. Experiments show that the algorithm in this paper has higher throughput and can meet the minimum rate requirements of more users.

1. Introduction
In order to realize the interconnection of all things, human-computer interaction, and comprehensive situational awareness of the power grid, the power Internet of Things needs to rely on a strong and reliable communication network as support. Therefore, the communication system is at the core of the power Internet of Things. Power Line Communication (PLC) uses power lines as the medium for data transmission. It naturally has electrical equipment connections, realizes flexible access of various terminal equipment, and is characterized by low construction costs, and it is also an effective communication method to solve the "last mile" information interaction problem. Power line carrier communication technology has gradually developed from traditional narrowband communication to today's broadband power line carrier communication. Using OFDM technology to increase the communication rate from several thousand bps to several megabits to tens of megabits per second, the communication performance has been greatly improved. With the increasing demand of smart grid for terminal equipment communication, traditional OFDM resource allocation algorithm has been unable to meet the demand of information transmission and user service quality assurance. Therefore, how to efficiently and rationally utilize limited system resources to meet QoS requirements of various services has become the key to solve the resource allocation problem of broadband power line carrier communication.

At present, some scholars have carried out research on the problem of power line carrier communication resource allocation. Among them, literature proposed a maximum throughput algorithm, which uses the difference between different users of the same subcarrier to allocate
subcarriers to the best channel quality Users to achieve multi-user diversity gain. Because this method seeks to maximize system throughput, users with poor channel quality often cannot obtain sufficient resources, resulting in unsatisfactory user QoS requirements and impairing fairness among users. Literature [6] proposed the max-min algorithm, which allocates a large amount of system resources to users with poor channel quality and a small amount of resources to users with better channel quality to achieve absolute fairness between users, but obviously, the network communication performance cannot be fully utilized, and the total average throughput of the system is often low. Literature [7] proposed a combination of genetic algorithm and water injection algorithm to optimize the distribution based on the rate maximization (RA) criterion. It is proved through simulation that the improved algorithm has a great improvement in performance, and the average throughput of the system has a certain increase, but the algorithm does not distinguish between services, and there are situations that cause the QoS requirements of some services cannot be met. Literature [8] uses equal power allocation method to load power for each sub-carrier, and allocates system resources to users based on the principle of the maximum accumulated fairness deviation, and controls the stability of user rate by adjusting the deviation degree. However, this algorithm can easily cause non-real-time users to not meet their QoS requirements when the system capacity is insufficient.

2. Description of power line carrier communication problem
The power line carrier communication network topology is shown in Fig.1. The power line channel is an open and shared channel [9], and each phase has an independent PLC gateway. Each PLC device needs to compete for the original phase resources on the shared power channel. The essence of the problem of multi-user dynamic resource allocation is to dynamically allocate different sub-carriers for real-time (RT) users and non-real-time (NRT) users in each OFDM symbol according to the status information of the power line channel, and use the corresponding sub-carriers. The above adaptively selects different modulation modes according to the size of the channel gain, and loads the corresponding bits according to the Shannon formula. Multi-user dynamic resource allocation must not only meet the QoS rate requirements of various users, but also consider the fairness between different users. It should not occupy a large amount of system resources due to a user's good channel quality, and a user's channel quality is poor for a long time. If the service is not available, the overall throughput of the system is improved on the basis of meeting the QoS rate requirements of each busines.

Assume that there are \( N \) sub-carriers in the carrier communication system, \( h \) RT users, and \( l \) NRT users,
the set of RT users is $\Omega_h$, and the set of NRT users is $\Omega_l$. When the multi-user broadband power line carrier communication system performs resource allocation, considering that RT users have higher requirements for delay, the system first allocates subcarriers to RT users to meet the rate requirements of RT users $R_{QoS}^{RT}$, and allocates resources for RT users. When meeting its QoS rate requirements, the resource occupancy rate of RT users should be reduced as much as possible in order to reserve sufficient resources to meet the QoS rate requirements of NRT users $R_{QoS}^{NRT}$. After meeting the QoS rate requirements of all users, if the system has remaining resources, continue to allocate all the remaining resources to the users to improve the overall throughput of the system. Through the above allocation ideas, the dynamic resource allocation mathematical model of broadband power line carrier communication is as follows:

$$\max \sum_{n=1}^{N} \sum_{i=1}^{l} \sum_{k=1}^{K} C_{n,i,k} R_{n,i,k}$$

s.t. $C_{n,i,k} \in \{0,1\} \quad \forall n, i, k$  
$C2: \sum_{i=1}^{l} C_{n,i,k} \leq 1 \quad \forall n, i$  
$C3: \sum_{n=1}^{N} \sum_{i=1}^{l} C_{n,i,k} P_{n,i,k} \leq P_{total} \quad \forall i$  
$C4: P_{n,i,k} \leq P_{max} \quad \forall n, i, k$  
$C5: \sum_{n=1}^{N} \sum_{i=1}^{l} C_{n,i,k} R_{n,i,k} \geq R_{QoS}^{RT} \quad \forall k \in \Omega_h$  
$C6: \sum_{n=1}^{N} \sum_{i=1}^{l} C_{n,i,k} R_{n,i,k} \geq R_{QoS}^{NRT} \quad \forall k \in \Omega_l$  

In the formula, $C_{n,i,k}$ are subcarrier allocation flag bits, $C_{n,i,k}=0$ means that subcarrier $n$ is not allocated to user $k$ in the $i$-th OFDM symbol, $C_{n,i,k}=1$ means that subcarrier $n$ is allocated to User $k$; $R_{n,i,k}$ are the bits loaded on the subcarrier $n$ allocated to user $k$ in the $i$-th OFDM symbol; $P_{total}$ is the upper limit of the total transmit power of the system; $P_{max}$ is the upper limit of the transmit power of each subcarrier under the power spectrum limit; $R_{QoS}^{RT}$ $k$ is the QoS rate requirement of user $k$.

The constraints in this mathematical model: C1 is the allocation of flag bits for subcarriers, C2 indicates that in any OFDM symbol, subcarrier $n$ can only be allocated to one user; C3 indicates the power allocated on $N$ subcarriers in any OFDM symbol The sum does not exceed the total transmit power limit; C4 means that the transmit power on each subcarrier does not exceed the single carrier maximum transmit power under the power spectrum limit; C5 is at any $i$-th OFDM symbol, and the rate obtained by user $k$ is greater than that of RT user QoS rate requirement; C6 is at any $i$-th OFDM symbol, the rate obtained by user $k$ is greater than the QoS rate requirement of NRT users.

4. Physical layer resource allocation algorithm

In order to reduce the complexity of solving the resource allocation problem, a step-by-step method is used to allocate subcarriers and system power to each user. The algorithm first divides the sub-carrier set for scheduling users to ensure that users meet their QoS requirements, and loads the system power with $N$ sub-carriers in the broadband power line carrier frequency band based on equal power sub-carrier allocation. At this time, the system power obtained by each sub-carrier is[^16]:

$$p_n = \frac{P_{total}}{N}$$  

Where $P_{total}$ is the total transmit power of the system, and $p_n$ is the power loaded on subcarrier $n$.

The physical layer calculates the number of sub-carriers $n_k$ required to meet the user's QoS rate requirements in the sub-carrier power mode. Calculate the system power $P_k = n_k p_n$ allocated to user $k$ from the number of sub-carriers $n_k$, where:

$$\sum_{k=1}^{K} P_k \leq P_{total}$$

After determining the set of sub-carriers used by each user to meet its service QoS rate requirements, the $n_k$ sub-carriers used by user $k$ are optimally allocated with the Lagrange multiplier method to maximize the actual throughput of each user. At this time, the multi-user resource allocation model is reduced to a single-user resource allocation model, as shown below:
\[
\max \sum_{n=1}^{n_k} \log_2^{(1)} \frac{P \cdot \gamma_{n,k}^2}{\sigma_{n,k}^2} \\
\text{s.t. } C1: \sum_{n=1}^{n_k} p_{n,k} \leq P_k \\
C2: p_{n,k} \leq P_{\max} \quad \forall n \\
C3: \sum_{n=1}^{n_k} \log_2^{(1)} \frac{P \cdot \gamma_{n,k}^2}{\sigma_{n,k}^2} \geq R_{QoS}^k
\]  

(4)

The Lagrange function of the above problem is:

\[
L(\lambda_k, \mu_k, \nu_k) = \sum_{n=1}^{n_k} \log_2^{(1)} \frac{P \cdot \gamma_{n,k}^2}{\sigma_{n,k}^2} + \lambda_k (P - \sum_{n=1}^{n_k} p_{n,k}) + \mu_k (P_{\max} - p_{n,k}) + \nu_k (\sum_{n=1}^{n_k} \log_2^{(1)} \frac{P \cdot \gamma_{n,k}^2}{\sigma_{n,k}^2} - R_{QoS}^k)
\]  

(5)

Where \(\lambda_k, \mu_k,\) and \(\nu_k\) are the Lagrange multipliers corresponding to the inequality constraints of C1, C2, and C3, respectively.

So the Lagrange dual problem of problem (4) can be expressed as:

\[
\min L(\lambda_k, \mu_k, \nu_k) \\
\text{s.t. } \lambda_k \geq 0, \mu_k \geq 0, \nu_k \geq 0
\]  

(6)

In this paper, the gradient descent method is used to solve the optimal Lagrangian coefficient. Let \(\lambda^*, \mu^*, \nu^*\) be the optimal solutions of \(\lambda_k, \mu_k,\) and \(\nu_k\) respectively, and the optimal solution of \(P_{n,k}\) is:

\[
P_{n,k}^* = \left( \frac{1 + \nu^*}{(\lambda_k^* + \mu_k^*) \ln 2 - \sigma_{n,k}^2} \right)^{-1}
\]  

(7)

The flow chart of the physical layer resource allocation algorithm for broadband power line carrier communication under the multi-user mixed service is shown in Fig.2. The specific steps are as follows:

1. **Step1:** Initialize \(i=0, R_i(0)=0, S=\{1,2,\ldots,N\} \)

2. **Step2:** Select the sub-carrier with the best channel quality for user \(k^*\) from the set \(S\) of available sub-carriers in the system, where \(n^*=\arg\max_{n \in S} \text{SNR}_{n,k^*} \) and \(S=\{1,2,\ldots,N\} \).

3. **Step3:** Determine whether user \(k^*\) satisfies \(R_i(i) \geq R_{QoS}^k\). If it is satisfied, remove user \(k^*\) from the set \(\Omega_k\), update the user set \(\Omega_k = \Omega_k \setminus \{k^*\} \), and enter Step 4. If not, return to Step 2 to continue allocating subcarriers for user \(k^*\).
Step4: Determine whether the user set $\Omega_k$ is an empty set. At this time, there are two situations:

1. If the user set $\Omega_k$ is not an empty set, and the available subcarrier set $S$ is also not an empty set, return to Step2 to allocate subcarriers to the remaining users in $\Omega_k$ until the available subcarrier set $S$ in the system is an empty set.

2. If the user set $\Omega_k$ as the empty set, then the moment all users get rate were greater than the business rate of QoS requirements, at this time if the system subcarrier $S$ and remaining in the collection resources are available, and reset user set $\Omega_k=\Omega_h \cup \Omega_l$, will continue to assigned to the remaining undistributed subcarrier channel quality the best user, until the system available subcarrier set $S$ is empty.

Step5: According to the set of subcarriers allocated by the user, the Lagrange multiplier method is used to optimize the power of the set of subcarriers in a single user $k^*$, and the actual rate $R_k^*(i)$ obtained by the user is updated to end the physical layer resource configuration. Let $i=i+1$ enter Step2.

5. Experimental simulation analysis

In order to verify the effectiveness of the proposed method, 4 users connected to the broadband power line carrier communication system are taken as an example to analyze on the matlab simulation platform. The system parameters are shown in Table 1:

| Parameter name          | Parameter value          | Parameter name          | Parameter value          |
|-------------------------|--------------------------|-------------------------|--------------------------|
| Number of subcarriers   | 131                      | The length of the guard | 18.32us                  |
| Range of frequency      | 2.441MHz-5.615MHz        | interval                |                          |
| Power spectrum limit    | -45dBm/Hz                | System transmit power   | 50mW                     |
| Length of FFT/IFFT      | 40.96us                  | RT rate requirement     | 200Kbp/s                 |
|                         |                          | NRT rate requirement    | 150Kbp/s                 |

The system contains 2 RT users and 2 NRT users. The channel quality from high to low is RT$_1$>RT$_2$ and NRT$_1$>NRT$_2$. In order to verify the performance of the algorithm in this paper, the proposed algorithm is compared with the literature[5] maximum throughput algorithm and the literature[8] Gong algorithm on the throughput of RT users and NRT users under two environments with sufficient system capacity and insufficient system capacity.

Fig.3 and Fig.4 shows the simulation results. The proposed algorithm divides the set of subcarriers used by each user based on the equal power allocation method, and then uses the Lagrange multiplier method to perform optimal power allocation for the subcarriers within each user, which improves the actual throughput of each user. User RT$_3$ as an example, the proposed algorithm is 16.94% and 6.47% higher than the maximum throughput algorithm and the Gong algorithm. shows the throughput of different users under each algorithm when the system capacity is insufficient.

![Fig. 3 User throughput with sufficient capacity](image1)

![Fig. 4 User throughput with insufficient capacity](image2)
6. Conclusion

Aiming at the problem of broadband power line carrier communication resource allocation, this paper proposes a low-complexity physical layer resource allocation algorithm. The algorithm first determines the set of subcarriers required by each user to meet their QoS rate requirements based on the equal power allocation method. The resource allocation problem is reduced to a single-user optimal power allocation problem, and then the Lagrange multiplier method is used to optimize the power of the sub-carrier set used by each user to further improve the throughput of each user. Through two simulation environments of sufficient system capacity and insufficient system capacity, it is verified that the algorithm proposed in this paper can not only improve the throughput of the system, but also meet the QoS requirements of more users in the broadband power line carrier communication system.

Acknowledgments

This paper was supported by the Research Projects of State Grid Tianjin Electric Power Company “Research on Electric Internet of Things’ information and communication architecture and key technologies” (KJ20-1-16).

References

[1] Yang T., Zhao L.Y., Wang C.S. (2019) Overview of application of artificial intelligence in power system and integrated energy system. Automation of Electric Power Systems, 43(01): 2-14(in Chinese).
[2] Jin X., Xiao Y., Zeng Y.G., et al. (2020) Modeling and Error Compensation of broadband Carrier Communication Channel for low voltage power line. Proceedings of The Chinese Society for Electrical Engineering, 40(09): 2800-2809(in Chinese).
[3] Ahmed M.O., Lampe L. (2013) Power Line Communications for Low-Voltage Power Grid Tomography. IEEE Transactions on Communications, 61(12): 5163-5175.
[4] Qi J.J., Chen X.P., Liu X.S. (2010) Research progress of low voltage power line carrier communication technology. Power System Technology, 34(05): 161-172(in Chinese).
[5] Jang J., Lee K.B. (2003) Transmit power adaptation for multiuser OFDM systems. IEEE Journal on Selected Areas in Communications, 21(2): 171-178.
[6] Zhang X., Wang W. (2006) Multiuser frequency-time domain radio resource allocation in downlink OFDM systems: Capacity analysis and scheduling methods. Computers & Electrical Engineering, 32(1-3): 118-134.
[7] Yang R., Cao W.B., Yin C.Q. (2019) Dynamic subcarrier allocation of PLC channel based on adaptive genetic algorithm. Power System Protection and Control, 47(12): 111-116(in Chinese).
[8] Gong G.J., Lu J., Xiong C., et al. (2015) An orthogonal frequency division multiplexing (OFDM) system with hybrid service equity for cross-layer resource allocation. Proceedings of The Chinese Society for Electrical Engineering, 35(06): 1390-1398(in Chinese).
[9] Li S.N., Hu X.R., Zheng K., et al. (2018) Measurement and analysis of attenuation characteristics of low voltage power line carrier communication channel. Power System Protection and Control, 46(4): 99-106(in Chinese).
[10] Chong J.G., Nan S.H., Zhang F., et al. (2019) Multi-user OFDM adaptive resource allocation scheme based on artificial bee colony algorithm. Journal of Jilin University: Engineering and Technology Edition, 49(2): 624-630(in Chinese).