Broadband Power Line Carrier Communication MAC Layer Scheduling Algorithm for Multi-service Transmission Requirements in Electric Internet of Things

Xiyang Yin*, Yizhao Liu, Hao Ji
State Grid Tianjin Electric Power Information and Communications Company, Tianjin, 300010, China
*Corresponding author’s e-mail: xiyang.yin@tj.sgcc.com.cn

Abstract. Since traditional power line carrier communication resource allocation algorithm does not consider the mixed services QoS requirements and the queue buffer the MAC layer, the user could not be reasonably scheduled in mixed service flow, which causes the problem of poor distribution balance among different users. This paper proposes a MAC layer user scheduling algorithm for broadband power line carrier communication in a concurrent mixed service scenario. The algorithm dynamically prioritizes the data packets in the user buffer area according to the QoS requirements of the application layer power multi-service and the queue length in the data link layer buffer area, and gives the minimum physical layer required to meet the QoS requirements of mixed services transmission rate, and then realize the MAC layer user scheduling process of broadband power line carrier communication in the concurrent mixed service scenario.

1. Introduction
With the massive access to smart sensor devices, there are various types of communication needs in power systems, causing an explosion in data volume, which poses a serious challenge to existing communication methods [1–3]. Power Line Communication (PLC) uses power lines as a medium for data transmission [4], which naturally has the characteristics of electrical equipment connection, flexible access of various terminal equipment, and low construction cost. Therefore, power carrier communication is an effective communication method to solve the "last mile" information exchange problem [5][6]. It is widely used in power grid information physical system. For example, the remote automatic meter reading network of hundreds of millions of users [7], the million-level smart distribution transformer zone solution, the power Internet of Things represented by distribution automation, smart city traffic, street lighting, intelligent monitoring and control system. With the growth of power grid cyber-physical system's demand for terminal equipment communication, traditional broadband power line communication MAC layer user scheduling algorithm has been difficult to meet the needs of information transmission and ensuring user service quality. Therefore, how to efficiently and reasonably schedule users to meet the QoS requirements of various services has become the focus of the research on MAC layer user scheduling algorithm of broadband power line carrier communication.

At present, some scholars have carried out research on the user scheduling algorithm of power line carrier communication, and the literature [8] proposed the maximum throughput scheduling algorithm,
in order to maximize throughput, the algorithm schedules the user with the best channel quality at each OFDM moment to achieve multi-user diversity gain. However, because this method blindly pursues maximizing system throughput without considering the fairness between users, the QoS requirements of some users cannot be met. However, it is obvious that the network communication performance cannot be fully utilized, and the total system throughput is low. Literature [9] proposes to schedule users based on the principle of maximum cumulative fairness deviation, and to control the stability of user rate by adjusting the cumulative fairness deviation. However, this algorithm will cause non-real-time users to fail to meet 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 Figure 1. The power line channel is an open and shared channel, and each phase has an independent PLC gateway. Each PLC device needs to compete for the carrier communication resources of the phase on the shared power line channel. The essence of the problem of multi-user dynamic resource allocation is to dynamically schedule real-time (RT) users and non-real-time (NRT) users to allocate physical layer resources in each OFDM symbol according to the status information of the power line channel. The multi-user dynamic scheduling algorithm not only meets the QoS requirements of various users, but also considers the fairness between different users, which means that users with poor channel quality cannot be unavailable for a long time, and users with better channel quality cannot be occupied a lot of resources, and finally improve the overall throughput of the system on the basis of meeting the QoS requirements of various services.

![Power Line Carrier Communication Network topology](image)

**Fig. 1** Power Line Carrier Communication Network topology

3. Analysis of buffer queue status

It is assumed that the queue length of each user is unchanged within a very short OFDM symbol period. Here, user $k$ is taken as an example, suppose that the buffer area can store at most $B$ packets, and the size of each packet is $L$ bit. The number of packets when the $i$-th OFDM symbol user $k$ arrives is $A_k(i)$, the queue length of the $i$-th OFDM symbol user $k$ is $Q_k(i-1)$, and the MAC layer user is completed in the $i$-th OFDM symbol After scheduling and subcarrier and power allocation of the physical layer, user $k$ obtains the service rate of $R_k(i)$, and the queue length in the $i$-th OFDM symbol buffer area is:

$$B_k(i) = \max(0, Q_k(i-1) + A_k(i) - \lceil R_k(i)/L \rceil)$$

Among them, the symbol (\lceil \cdot \rceil) is rounded down. Since only $B$ packets can be stored in the buffer area, at the $i$-th OFDM symbol, the actual queue length of user $k$ is:

$$Q_k(i) = \min(B, B_k(i))$$

Assuming that the queue length in the buffer area does not exceed $B$, considering the existing
queue length in the buffer area, the number of data packets that can also be allowed to enter the buffer area at this time is:

\[
P_k(i) = B - \max(0, Q_k(i-1) + A_k(i) - \left\lfloor \frac{R_k(i)}{L} \right\rfloor)
\]

(3)

When the queue length in the buffer area of the \(i\)-th OFDM symbol is \(Q_k(i)\), the data packets of user \(k\) follow the first-in-first-out principle. At this time, the waiting delay of data packets is:

\[
D_k(i) = \frac{Q_k(i)}{R_k(i)/L}
\]

(4)

If the number of packets of the \(i\)-th OFDM symbol user \(k\) arriving in the buffer area satisfies \(A_k(i) < P_k(i)\), all data packets will be temporarily placed in the buffer area to be served; If the number of packets of the \(i\)-th OFDM symbol user \(k\) arriving in the buffer area satisfies \(A_k(i) > P_k(i)\), due to the limitation of the maximum queue length in the buffer area, only \(P_k(i)\) data packets are allowed to enter the buffer area. At this time, \(A_k(i) - P_k(i)\) data packets exceeding the maximum queue length \(B\) will be discarded. Therefore, the MAC layer data packet loss phenomenon occurs. Here, the packet loss rate \(P_{loss}^k(i)\) is defined as:

\[
P_{loss}^k(i) = \frac{A_k(i) - P_k(i)}{A_k(i)}
\]

(5)

4. MAC layer user scheduling based on queue status information
Various power communication services in the power grid cyber-physical system have different QoS requirements. According to the real-time requirements of power services, various services can be divided into RT services and NRT services. The RT service has higher requirements for real-time performance, while the NRT service has higher requirements for the packet loss rate. For different power communication services, this paper designs the utility functions of RT services based on delay requirements and NRT services based on packet loss rate requirements, and gives the minimum transmission rate required by each service to ensure its QoS requirements.

4.1 Real-time user scheduling based on delay requirements
For the RT user set, assuming the maximum allowable delay of user \(k\) is \(T_k\). In order to make RT users satisfy \(D_k(i) < T_k\), when RT user \(k\) is in the \(i\)-th OFDM symbol, to avoid the data packet waiting delay in the buffer area from exceeding the minimum rate \(R_{RT}^k(i)\) of maximum allowable delay. The expression is derived as follows:

\[
R_{RT}^{\min}(i) = L \left\lfloor \frac{Q_k(i-1) + A_k(i)}{T_k + 1} \right\rfloor
\]

(6)

Where \(\left\lfloor \cdot \right\rfloor\) is rounded up.

Thus, the utility function of RT users based on the data packet waiting delay is defined as follows:

\[
Y_{RT}^k(i+1) = \frac{R_{RT}^k(i)D_k(i)}{R_k(i)T_k}
\]

(7)

4.2 Non-real-time user scheduling based on packet loss rate requirements
For the NRT user set, assuming that the maximum allowable packet loss rate of user \(k\) is \(P_{Loss}^k\), in order to make the packet loss rate of NRT users satisfy \(P_{loss}^k(i) < P_{Loss}^k\), when NRT user \(k\) is in the \(i\)-th OFDM symbol, to avoid the data packet loss rate in the buffer area from exceeding the minimum rate \(R_{Loss}^{\min}(i)\) of maximum allowable value. The expression is as follows:

\[
R_{Loss}^{\min}(i) = L \left\lceil A_k(i)(2 - P_{Loss}^k) + Q_k(i-1) - B \right\rceil
\]

(8)

Thus, the utility function of NRT users based on the packet loss rate is defined as follows:

\[
Y_{NRT}^k(i+1) = \frac{R_{Loss}^{\min}(i)P_{loss}^k(i)}{R_k(i)P_{Loss}^k}
\]

(9)
4.3 MAC layer user scheduling based on utility function

Aiming at the resource allocation of broadband power line carrier communication under concurrent mixed services, this paper designs a MAC layer user scheduling algorithm based on a utility function. The algorithm arranges users in descending order according to the value of the utility function. Since RT services have high real-time requirements, the system first meets the QoS requirements of RT services, and then uses the remaining resources to meet the QoS requirements of NRT services. Therefore, when setting the service scheduling sequence, this paper puts the RT scheduling sequence before the NRT sequence, and schedules them according to the utility function value within the same service type. The algorithm flow chart is shown in Fig.2. The specific implementation process steps are as follows:

\begin{itemize}
  \item **Step 1:** Initialize \(i=0\), user instantaneous rate \(R_k(0)=0\), and queue length of user \(k\) \(Q_k(0)=0\) in the buffer area.
  \item **Step 2:** Determine the user category:
    \begin{itemize}
      \item If user \(k\) is an RT user, obtain the maximum allowable delay \(T_k\) requirement, calculate the packet waiting delay \(D_k(i)\) according to \(Q_k(i)\) at the current moment, and substitute it into equation (7) to calculate the utility function value \(Y_k^{RT}(i+1)\) of RT user \(k\) at the next moment.
      \item If user \(k\) is an NRT user, obtain the maximum allowable packet loss rate \(P_{LossMax}^{k}\) requirement, and calculate the packet loss rate \(P_k(i)\) according to the current \(Q_k(i)\), and substitute it into equation (9) to calculate the utility function value \(Y_k^{NRT}(i+1)\) of NRT user \(k\) at the next moment.
    \end{itemize}
  \item **Step 3:** Arrange the utility function values of \(h\) RT users and \(l\) NRT users in descending order, generate a scheduling sequence based on the utility function, place the RT user scheduling sequence before the NRT user, and pass the scheduling sequence at this moment to the physical Layer, and allocate physical layer resources for scheduling users.
  \item **Step 4:** After the physical layer completes the resource allocation, update the actual rate \(R_k(i)\) of the user and the queue length \(Q_k(i)\) in the user \(k\) buffer area, and then end the MAC layer user scheduling process. Let \(i=i+1\) and enter Step 2.
\end{itemize}

5. Experimental simulation analysis

In order to verify the effectiveness of the proposed method, the user 4 accessing the broadband power line carrier communication system is taken as an example to analyze on the MATLAB simulation.
The system parameters are shown in Tab.1 below:

| Parameter Name                          | Parameter Value |
|-----------------------------------------|-----------------|
| Maximum queue length B                  | 500Bytes        |
| Message sending interval                | 2ms             |
| Message length                          | 40-60Bytes      |
| Error rate $P_e$                        | $10^{-3}$       |
| Number of RT users                      | 2               |
| Maximum allowable delay for RT users    | 10ms            |
| Number of NRT users                     | 2               |
| NRT user maximum allowable packet loss rate | 1%             |

The experiment includes 2 RT users and 2 NRT users using PLC cascade connection to communicate with the gateway, and the channel quality from high to low is $RT_1 > RT_2, NRT_1 > NRT_2$. In a simulation environment with insufficient system capacity, the proposed algorithm is compared with the maximum throughput algorithm in literature [8] and the Gong algorithm in literature [10] to compare the RT user data packet waiting delay and NRT user data packet loss rate.

Figure 3 shows the waiting delay of RT user data packets. The data packet is not processed in time, and its packet waiting delay is as high as 12.46ms, which exceeds the maximum allowable delay of 10ms. While the Gong algorithm and the algorithm in this paper are scheduling users, taking into account the high requirements of RT users for delay, the priority scheduling of RT users with packet waiting delay is less than 10ms, which meets the QoS requirements of RT users.

Figure 4 shows the packet loss rate of NRT users. Since the Gong algorithm uses the principle of maximum cumulative fairness deviation for scheduling of NRT users, the NRT users will exceed the threshold in an environment with insufficient system capacity, which is 2.89% and 2.67% respectively. In this algorithm, when the system capacity is insufficient, NRT users only exceed the packet loss rate...
threshold at some intermittent moments. The average packet loss rates of NRT1 and NRT2 are 0.89% and 0.92% respectively, and the average packet loss rate does not exceed the threshold 1.00%. Taking NRT2 users as an example, the proposed algorithm reduces the packet loss rate by 72.04% and 65.54% respectively than the maximum throughput algorithm and the Gong algorithm.

6. Conclusion
Aiming at the MAC layer user scheduling problem of broadband power line carrier communication, this paper proposes a MAC layer user scheduling algorithm based on utility function, establishes the utility function of real-time/non-real-time users, and generates a real-time user scheduling sequence based on delay requirements. And a non-real-time user scheduling sequence based on packet loss rate requirements, and the minimum transmission rate required to ensure user QoS requirements is given. The algorithm proposed in this paper enables the system to dynamically prioritize services according to service QoS requirements and current network status. Experiments have verified that the algorithm proposed in this paper can effectively reduce the data packet waiting delay of RT users and the packet loss of NRT users. It can meet the QoS requirements of more users and improve the transmission performance of broadband power line carrier communication.

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