Resource Optimization of Power Line Communication Network Based on Monte Carlo Method

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Abstract. The power system communication network uses power lines as a medium, which is an important means to ensure the safe, stable, and economic operation of the power grid. In order to improve the throughput of the power line communication (PLC) network and realize the optimization of network resources, a method based on the machine learning algorithm, namely the Monte Carlo method, is proposed to optimize the media access control (MAC) layer protocol of the PLC. Firstly, based on the lognormal fading and impulse noise in the physical layer of the PLC channel, and the IEEE 1901 CSMA backoff mechanism in the MAC layer, the main factors leading to packet loss are analyzed. Secondly, the throughput calculation model based on the above packet loss factors is established. Finally, according to the idea of Monte Carlo algorithm, the MAC layer contention window selection algorithm is established based on the principle of maximum throughput. And compared with the original algorithm standard simulation results, the effectiveness of the method is verified. The results show that the contention window value obtained based on the proposed algorithm can achieve higher system throughput, and has certain practical reference value in the corresponding PLC network scenario.

Keywords: Power line communication · IEEE 1901 · Resource optimization · Monte Carlo

1 Introduction

The widespread use of power line communication (PLC) networks and distribution lines makes PLC become an excellent choice for industrial command and control and facility automation systems [1].

The problem of power line energy consumption has always been a hot research topic. Reference [2] proposed a household energy management system, which can actually record household energy consumption and optimize energy consumption. [3] proposed

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a program to design a PLC system. For parameter optimization, it is committed to finding the best compromise between maximizing bit rate, minimizing bit error rate, and minimizing signal power. [4] proposed an optimal content placement algorithm to reduce the backhaul energy consumption of each size and content.

For resource allocation and routing optimization, there are also many literatures using machine learning algorithms to conduct research. Literature [5] uses orthogonal frequency division multiple access technology to achieve cross-layer optimization of PLC systems, and it is better for multi-objective resource allocation. For other multi-user algorithms, [6] proposed an ant colony algorithm that can optimize PLC routing. Among them, the shortest path and the optimal path are found through route optimization. This is the optimization of network resources by optimizing routing. [7] proposed a customized opportunistic routing, and fully investigated its feasibility in PLC access network. This opportunistic routing can reduce the transmission delay of the packets without reducing the reliability of the transmission. [8] proposed a solution based on the greedy method, which can effectively improve the system performance. [9] described a framework, that is, the control and communication network of an interactive power electronic network that jointly optimizes network control. This framework includes two coupling blocks to ensure the best performance of the power network within its stability range and to optimize the flow of information in the communication network.

Self-organizing protocols and scheduling methods can also optimize the resources of the PLC network to a certain extent, [10] based on the problem of deploying the PLC network on the medium voltage network. In a multi-objective optimization method, the cost of enabling access points is minimized and the reliability of the PLC network path is maximized, and it also considers the network resilience and capacity constraints. [11] proposed a channel self-organization protocol in which two domains are allowed to cooperate to achieve dynamic sharing and the transmission capacity optimization. And each system will detect interference from its neighbors and organize its resources to maximize channel utilization. [12] proposed an application of a scheduling method to allocate the available channel set to PLC units better and more equitably. The advantage of this kind of scheduling is reflected in the improvement of algorithm convergence.

The above research does not involve the improvement of the PLC protocol. [13] proposed an adaptive MAC protocol, which improves the system throughput by adjusting the data transmission rate and contention window (CW) size according to the station transmission delay and channel conditions. However, it did not point out the CW value corresponding to the best throughput, and the specific analysis of the best CW value corresponding to the physical layer (PHY) parameters and different numbers of stations were not mentioned.

In this paper, we propose a power line MAC layer protocol optimization algorithm based on Monte Carlo method. The main contributions of this paper are as follows. Firstly, we analyze the main factors that cause packet loss based on the fading and noise of the power line PHY and the IEEE 1901 CSMA backoff mechanism of the MAC layer. Secondly, we establish a system throughput calculation model based on the packet loss factors. Finally, according to the Monte Carlo algorithm, the CW selection algorithm is established based on the principle of maximum throughput. Compared with the original algorithm standard, the effectiveness of the method is verified through the simulation results.

2 System Model

We consider the MAC layer and PHY in the single-hop power line. For the MAC layer, we consider the IEEE 1901 CSMA protocol for characterization, as for PHY, we consider lognormal fading and impulse noise in the channel.

2.1 IEEE 1901 MAC Layer

The implementation of the CSMA/CA backoff algorithm in the IEEE 1901 standard uses the following three counters: backoff procedure counter (BPC): BPC indicates the number of backoff stages; backoff counter (BC): BC indicates the random backoff time; deferral counter (DC): DC is used to evaluate the busyness of the current channel, moreover, it also makes the station react to the high load in the network without the collision.

The following describes the specific usage of these three counters through the working mechanism: After the station firstly undergoes initialization, BC is randomly selected in $\{0, \ldots, \mathrm{CW}_0 - 1\}$, where CW_0 is the value of the CW corresponding to the 0th backoff stage. DC_i and CW_i corresponding to the backoff stage i are shown in [14].

The station detects the channel every time it goes through a time slot. When the station detects that the channel is idle, BC is reduced by one, and when the channel is detected to be busy, BC and DC are reduced by one respectively. If the station detects that the channel is busy and DC is equal to 0 and the value of BC has not decreased to 0, the station enters the next backoff phase, BPC is increased by one (or re-enters the last backoff phase, if it is already in this phase), BC is revalued without trying to transmit, and DC is revalued at the same time. If BC of the station is reduced to 0, the station attempts to send the packet. If the transmission is successful, the station is initialized, and if the transmission fails, the station enters the next backoff stage.

2.2 IEEE 1901 PHY Layer

We assume a single-hop transmission model and consider log-normal fading and impulse noise in the channel. We assume that S is the source node and D is the destination node. Then the signal received at D can be expressed as:

$$y_{\mathrm{D}} = \sqrt{P_{\mathrm{S}}} H_{\mathrm{SD}} x_{\mathrm{S}} + \mathrm{n} \tag{1}$$

In the formula: P_{S} is the transmission power, and x_{S} is the transmission signal, which satisfies $\mathrm{E}\left[(x_{\mathrm{S}})^2\right] = 1$. H_{SD} represents the influence of log-normal fading in the channel when the signal experience the transmission. And $H_{\mathrm{SD}} = h_{\mathrm{SD}}/(d_{\mathrm{SD}})^{\alpha}$, where h_{SD} is the log-normal fading coefficient, and d_{SD} is the distance between the source node and the destination node,α is the path attenuation factor, n is the noise model modeled by

Bernoulli Gaussian model [15], which consists two parts, namely background noise and impulse noise. Its probability density function form can be expressed as:

$$f(n) = p_0 N(0, N_{\mathrm{G}}) + p_1 N(0, N_{\mathrm{G}} + N_{\mathrm{I}}) \tag{2}$$

where p_0 represents the probability of background noise, and p_1 represents the probability that background noise and impulse noise are coexisted. N_{G} and N_{I} represent the power of background noise and impulse noise, respectively, and $N(0, N_{\mathrm{G}})$ and $N(0, N_{\mathrm{G}} + N_{\mathrm{I}})$ represent the normal distribution, we set $k = N_G/N_I$.

2.3 Characterize Throughput Based on PHY-MAC Layer

Based on the MAC layer model, if two or more packets are sent at the same time, the packets will be collided, causing the failure of transmission. As for PHY, if the signal-to-noise ratio (SNR) is less than the threshold, the transmission will be interrupted, which will also cause the failure of transmission. These two transmission failure situations will affect the performance of the system, especially the factors of fading parameter in PHY and the value of CW in MAC layer.

The Packet Loss of Physical Layer. Based on the modeling in Sect. 2.2, the outage probability of the channel can be characterized as:

$$P_{\mathrm{out}} = \mathrm{P_r}\left[\frac{P_{\mathrm{S}} h_{\mathrm{SD}}^2}{d_{\mathrm{SD}}^{2\alpha} N_{\mathrm{v}}} < b\right] = \int_0^b \sum_{v=0}^{1} \frac{p_v}{\sqrt{2\pi}\sigma_{N_v} x} \exp\left[-\frac{\left(\ln x - \mu_{N_v}\right)^2}{2\sigma_{N_v}^2}\right] dx \tag{3}$$

where b is the threshold, N_{v} is the noise power, μ_{N_v}, σ_{N_v} respectively represent the mean and variance of the variable $\ln h_{\mathrm{SD}}$ under the corresponding noise environment. Let h_{SD} $LN\left(\mu, \sigma^2\right)$, according to the conversion properties of log-normal variables, then $[\sigma_{N_0}]^2 = [\sigma_{N_1}]^2 = 4\sigma^2$, $\mu_{N_0} = 2\mu + \ln\frac{P_{\mathrm{S}}}{d_{\mathrm{SD}}^{2\alpha} N_{\mathrm{G}}}$, $\mu_{N_1} = 2\mu + \ln\frac{P_{\mathrm{S}}}{d_{\mathrm{SD}}^{2\alpha}(N_{\mathrm{G}} + N_{\mathrm{I}})}$. In order to avoid the influence of channel fading on the average power of the signal, let $\mathrm{E}\left[h_{\mathrm{SD}}^2\right] = \exp\left(2\mu + 2\sigma^2\right) = 1$, that is $\mu = -\sigma^2$.

The Packet Loss of MAC Layer. Based on the collision probability model defined in [16]:

$$\mathrm{p} = 1 - (1 - \tau)^{N-1} \tag{4}$$

It can be seen that when multiple stations send packet at the same time, it will cause packet loss, while considering PHY, the overall packet loss probability p can be characterized as [17]:

$$\mathrm{p} \ = 1 - (1 - \tau)^{N-1}(1 - P_{\mathrm{out}}) \tag{5}$$

The system throughput based on PHY-MAC. The system throughput $\mathrm{S_{th}}$ is characterized as:

$$\mathrm{S_{th}} = \frac{\mathrm{p_s} D}{\mathrm{p_s} T_{\mathrm{s}} + \mathrm{p_c} T_{\mathrm{c}} + \mathrm{p_e} T_{\mathrm{e}} + \mathrm{p_o} T_{\mathrm{o}}} \tag{6}$$

where p_s, p_c, p_o, and p_e respectively represent the probability that the packet is successfully sent, the transmission fails due to collision, the transmission fails due to interruption, and the channel is sensed to be idle. The corresponding multiplication is the corresponding time consumed.D represents packet transmission duration. The four parts of the denominator are all reflected in the Monte Carlo simulation in the next section.

3 Realize System Performance Optimization Based on Monte Carlo Algorithm

Based on the Monte Carlo method, the CW value corresponding to the optimal throughput can be obtained, which can provide a certain reference value for the selection of the backoff window value under the condition of the certain PHY channel parameter and the certain number of stations.

The Monte Carlo method is a type of machine learning algorithm. In this Monte Carlo method, we set the size of the cycle period to 10^6. The meaning of this value is the number of successfully transmitted packets. In each round of the loop, we let a certain number of stations experience the backoff of CSMA, and we set the initial value of the minimum backoff window to 4, and each station performs the independent backoff process. In this process, if the backoff CW of X stations are reduced to 0, these stations will be sent. And if X is greater than one, these packets will be collided. If the transmission fails, the number of failures will be counted.

If X is equal to one, the station will be transmitted in the channel, but due to the possible poor channel conditions, the transmitted packet is affected by lognormal fading and noise. For $X = 1$ in each cycle, we generate a random number that obeys lognormal fading under the certain variance and generate the noise concerning Bernoulli-Gaussian process. According to these two parameters and the transmission power, the SNR expression is constructed, and it will be compared with the threshold, if the SNR is lower than the threshold, the channel will be interrupted, and the packet transmission fails, otherwise, the packet will be transmitted successfully. And the *Success* and *Fail* will be counted according to the success or failure of the transmission.

After 10^6 packets are successfully transmitted, the throughput of the system is calculated and the CW value is recorded, then the value of the CW is doubled, the process on the right side of the diagram is repeated again. If the throughput corresponding to CW value is lower than the previous value, the experiment is terminated, and the corresponding CW value and the throughput are recorded. The basis for this is that with the increase of the CW value, the throughput can only have the two trends: 1. Keep decreasing (when the number of stations is small); 2. First increase and then decrease (the number of stations is slightly larger).

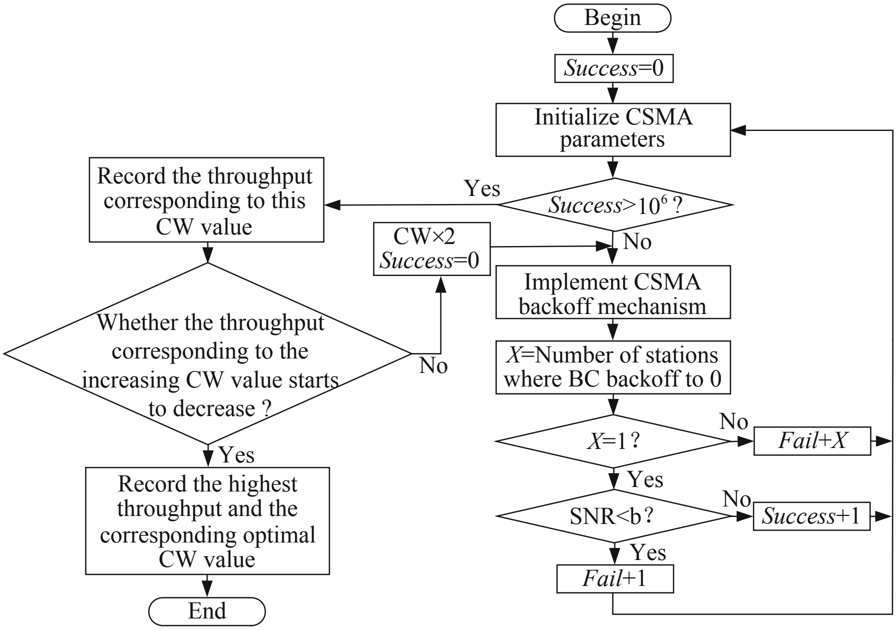

Fig. 1. Flow chart of finding the optimal CW based on Monte Carlo algorithm

Based on this experiment, the CW value corresponding to the highest throughput under the certain number of stations can be obtained, because for the certain number of sending stations, a lower or higher CW value may cause performance degradation, that is, there is always exist the most suitable CW value. The specific Monte Carlo algorithm flow chart is shown in Fig. 1. Based on the theoretical framework, the normalized throughput S_{th} is expressed as:

$$S_{th} = \frac{Success}{Success + Fail} \tag{7}$$

where *Success* represents the number of successfully transmitted packets, and *Fail* represents the number of the lost packets.

4 Simulation and Result Analysis

We use the Monte Carlo algorithm to conduct multiple experiments on the events in which packets are sent under the corresponding number of stations. When the number of successfully transmitted packets reaches to 10^6, the experiment stops. The number of successfully transmitted packets and the number of lost packets are used to calculate the normalized throughput corresponding the PHY channel environment and the MAC layer parameter configuration. And the initial CW value is set to 4, DC is set to [0 1 3 15]. Without loss of generality, the transmission power and distance are both normalized in the simulation. And if there is no special instructions, the parameter settings are shown in Table 1.

Table 1. Simulation parameters

Parameter	Time(us)
T_e	35.84
T_o	2602.64
T_c	2920.64
T_s	2542.64
Frame duration D	2050

Figure 2 shows the throughput performance curve under different initial CW values and N. It can be seen from the curve that as the number of stations N increases, the corresponding throughput first increases and then decreases. Therefore, for different N, there is an optimal window value corresponding to the maximum throughput. We select the number of stations to participate in the Monte Carlo simulation. In addition to collecting the results of the algorithm described in the Sect. 3, we also separately simulate the throughput under the adjacent CW to verify the effectiveness of the algorithm. It can be seen from the graph that the Monte Carlo algorithm can indeed help to find the best window value and the corresponding maximum throughput, and as the window value increases (from 4 to 8), the more stations there are, the faster the throughput will increase. However, as the window value continues to increase, the throughput will decrease first when the number of stations is small, indicating that in order to ensure the better system performance, when the number of stations is larger, it is suitable to use the larger window value.

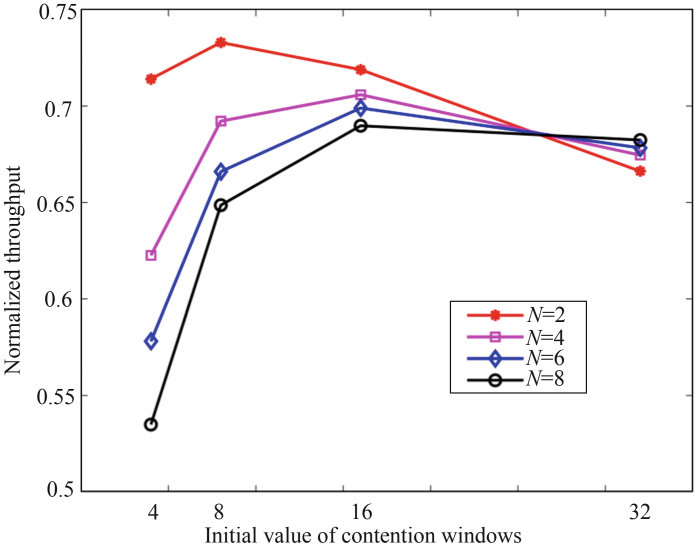

Fig. 2. Numerical results of throughput with different numbers of stations N and CW, $\sigma = 1$ dB, $p_1 = 0.1$, $k = 0.02$, $P_S = 1$ W, SNR $= 10$ dB

Figure 3 shows the initial value of the CW corresponding to the extreme point of throughput under the number of stations *N* from 1 to 15. It can be seen that as the number of stations *N* increases, the corresponding optimal CW increases. This is because, as *N* increases, the larger CW value can lead to the lower packet loss probability, so the corresponding throughput can be improved. Because in the algorithm, we increase CW by a multiple of two, the fewer the number of stations, the more obvious the change in the CW value of the corresponding best system performance. The result in the figure is not only the result of the number of stations, but also the result of the combined effect of the CSMA backoff mechanism and the PHY parameters.

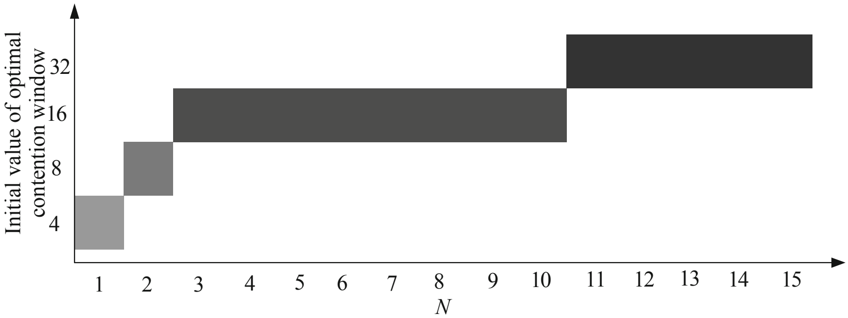

Fig. 3. The CW value corresponding to the maximum throughput under different number of stations, $\sigma = 1$ dB, $p_1 = 0.1$, $k = 0.02$, $P_S = 1$ W, SNR = 10 dB

Figure 4 shows the performance results based on the IEEE 1901 CSMA protocol standard and the curve comparison chart of the throughput corresponding to the optimal CW value under different fading coefficients obtained based on the Monte Carlo algorithm. As shown in the figure, the CW value found by the Monte Carlo algorithm is actually the optimal solution, and its performance is better than that of the calculation in the IEEE 1901 standard. And the smaller the channel fading coefficient is, the more obvious this advantage is. This is because when the channel fading coefficient is smaller, the SNR is larger at this time, so the outage probability of system is smaller, resulting in a smaller system packet loss probability and the higher throughput. Therefore, if the channel fading become severe, the system performance will has the negative impact, but even so, the Monte Carlo algorithm is still better than the original standard performance. To a certain extent, this algorithm can not only improve the system performance, but also in the face of unpredictable and inevitable fading in the channel, the system performance will not be affected too much.

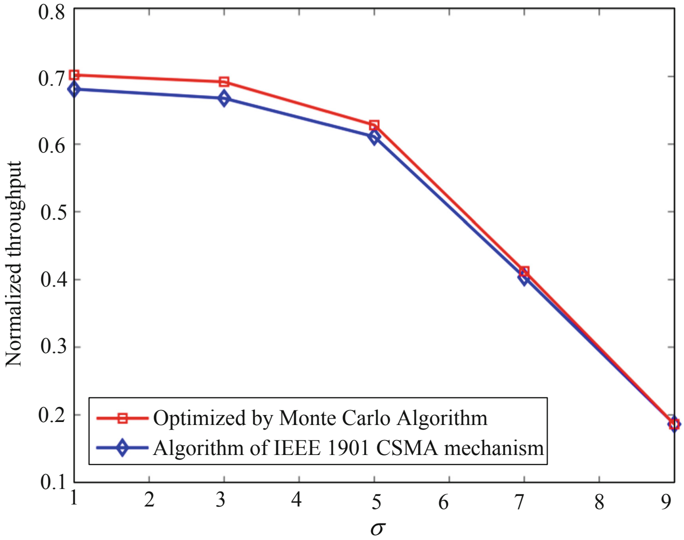

Fig. 4. Throughput of two algorithms under different channel fading coefficients, $N = 5, p_1 = 0.1$

Figure 5 shows the performance results based on the IEEE 1901 CSMA protocol standard and the throughput corresponding to the optimal CW value under different impulse noise occurrence probabilities based on the Monte Carlo algorithm. It can be seen that the Monte Carlo algorithm finds the performance of obtained CW value is obviously better than the performance corresponding to CW = [8 16 32 64] in the IEEE 1901 protocol standard. Regardless of the probability of impulse noise, the performance

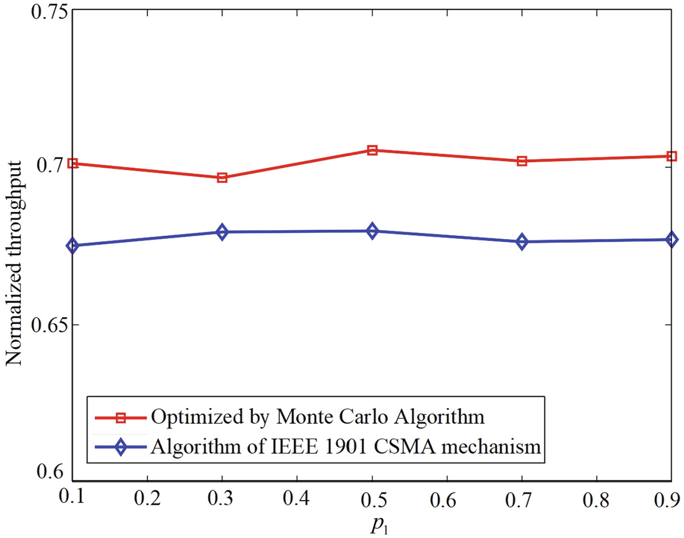

Fig. 5. Throughput of two algorithms under different impulse noise probabilities, $N = 5$, $\sigma = 1$ dB, $k = 0.02$, $P_S = 1$ W, SNR = 10 dB

of these two algorithms does not change significantly. This is because under a certain SNR, even if the probability of impulse noise is changed, the noise power is actually not affected so much, and the impact on SNR is not obvious. Therefore, compared with fading, noise has an not obvious impact on system performance.

5 Conclusion

This paper uses Monte Carlo algorithm to optimize the performance of the power line system. Considering the lognormal fading in the channel, impulse noise and the backoff mechanism in the MAC layer, the corresponding PHY-MAC throughput performance is analyzed. Furthermore, how to obtain the CW value under the optimal performance through the Monte Carlo algorithm is studied. The results show that based on the Monte Carlo optimization algorithm, the optimal CW value under the corresponding number of stations can be obtained, and for the low-fading environment, the degree of optimization is particularly obvious, thereby optimizing the network resources of the PLC.

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