IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 4, 2019, accepted March 18, 2019, date of publication March 27, 2019, date of current version April 11, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2907705

Improved CSMA/CA Algorithm Based on Alternative Channel of Power Line and Wireless and First-Time Idle First Acquisition

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This work was supported in part by the National Natural Science Foundation of China under Grant 61601182 and Grant 61771195, in part by the Natural Science Foundation of Hebei Province under Grant F2017502059 and Grant F2018502047, and in part by the Fundamental Research Funds for the Central Universities under Grant 2019MS088.

ABSTRACT Wireless and power line communication hybrid networking can complement each other, save construction costs, and satisfy the needs of different services. Few studies have investigated the MAC layer mechanism when the two networks are mixed. This paper proposes an improved CSMA/CA algorithm suitable for power line and wireless hybrid networking scenarios. The algorithm is compatible with the CSMA/CA algorithm in the existing standards, namely, IEEE 1901 and 802.11, and adopts a two-choice method of the power line and wireless first idle. As long as one of the wireless and power line channels is in the idle state, it can be levied to transmit a data packet. Based on the decoupling hypothesis, this paper establishes a system analysis model of the algorithm, uses simultaneous nonlinear equations to calculate the throughput and collision probability performance of the algorithm, and provides a uniqueness analysis of the solution. This paper also determines the latency of the algorithm. Finally, simulation verifies the effectiveness and reliability of the algorithm model and analyzes the performance in terms of throughput, time delay, and collision probability. Compared with the existing wireless and power line CSMA/CA algorithm, the proposed algorithm can improve the throughput and ensure the effectiveness of the network.

INDEX TERMS CSMA/CA, power line communication, hybrid networking, cooperative communication.

I. INTRODUCTION

In a smart grid, a real-time reliable and efficient coordinated power communication network must be established for organic integration of power and information flows and for improving the effectiveness and intelligence of information transmission, such as electricity generation, consumption, and energy storage, and reduce the occurrence of smart grid interruption, voltage sags, and so on. However, existing communication technologies cannot independently satisfy the needs of power automation at all levels and lack mature cooperation mechanisms and system standards. Therefore, the communication network of power distribution and consumption must be based on broadband communication to meet the development requirements of smart grids; the hybrid network exhibits high performance and is equipped with broadband communication as the core, power line communication (PLC), wireless communication, and optical fiber communication.

Communication system with an open, highly integrated and flexible reconfigurable electrical network topologies is the foundation of smart grid. Power line communication and wireless communication technology are important components of communication network for a distribution system and the two can complement each other. Therefore, the combined dual-medium hybrid communication technology of PLC and wireless can integrate superior communication capabilities and resources, improve the overall performance of the system, has important practical value. For example, in a smart grid, smart meter or sensor and gateway use

The associate editor coordinating the review of this manuscript and approving it for publication was Mahmoud Barhamgi.

PLC-WLC parallel communication combined with multi-hop relay to transmit grid status information or sensor data. In the G.hn standard, the nodes perform interactive communication under the coordination and control of the intelligent gateway in hybrid communication with Ethernet, PLC, and WLC. The hybrid communication technology is also very important in the future development of the Internet of Things and can also be used in smart homes, intelligent buildings, smart parking lots, smart communities and other work and living places. It also can adapt to the future information interaction scenarios with high throughput and low delay.

The development of communication technology must consider the construction cost, compatibility, and complexity factors in addition to the basic requirements of speed and reliability. For example, smart home focuses on the mobility, energy consumption, flexibility, and cost of communications. PLC can rely on existing power line infrastructure to transmit information. However, long-distance, high-reliability PLC remains a challenge due to limitations in transmission power and bandwidth, channel attenuation, and interference. Wireless communication has the advantages of flexible wireless access and simple network. The dual-media cooperative communication technology, which combines power line with wireless communication, can integrate resources and complementary advantages, save construction cost, and improve the overall system performance. Most existing studies on power line and wireless hybrid communication technologies focus on the physical layer cooperation mechanism and its performance and rarely involve the MAC layer mechanism in hybrid networking.

Ref. [17] focused on the achievable data rate analysis of the incomplete hybrid power line–wireless single relay channel (HSRC) model. The incomplete HSRC model refers to the use of the PLC single relay channel (PSRC) and wireless single relay channel (WSRC) to implement data communication between the source and destination nodes when the data communication link or the node communication interface does not exist. Ref. [18] studied the effects of two-way TCP flows and cross-services on the cooperative transmission between power line communication and wireless LAN technologies. In [19], the performance evaluation of a wireless–power line hybrid cooperative system based on decoding and forwarding was presented from the perspective of analyzing the average bit error rate. The fading in the wireless channel is modeled by the Nakagami-m distribution, and the PLC channel fading follows the lognormal distribution. Ref. [20] focused on the HSRC model, which consists of a parallel power line and a SRC model for communication and provides a closed expression of outage probability and data rate. Ref. [21] studied the heterogeneous network of power line and wireless communication technology, proposed the spectrum detection on the physical layer and the channel equalization optimization scheme in PLC and wireless communication, and then explored the fusion communication scheme of an independent MAC layer and a unified MAC layer and designed the network solution in different application scenarios. In a hybrid network, the physical layer serves as the MAC layer, which has a decisive influence on the performance of data transmission and reception, transmission delay, and the throughput of data frames in the network. Therefore, the cooperative performance of the MAC layer must be studied independently.

The MAC protocol controls a station's access channel, which is the direct controller for transmitting and receiving packets on the channel and the fastest to perceive the channel state. Therefore, whether the MAC protocol can effectively utilize limited channel resources plays an important role in enhancing the performance of the network and is also one of the key factors affecting the performance of the entire network [1]. CSMA/CA is the main MAC mechanism in the IEEE 802.11 and 1901 standards. CSMA/CA is similar in the two standards. The biggest difference is that a delay counter is included in IEEE1901, which makes the station enter the next back-off stage when the station does not attempt to transmit and reduce the collision probability. Recently, many studies on the MAC layer protocol in PLC and 802.11 were conducted.

For the energy-constrained attribute, handling mobility in WSNs is facing a significant challenge. In order to overcome these disadvantages, such as latency, extra energy consumption in fast connection for mobile nodes moving from one cluster to another, Ref. [2] puts forward a new adaptive mobility-aware MAC protocol named CM-MAC for large scale cluster-based WSNs. In [3], an adaptive p-persistent carrier sense multiple access game optimization method was proposed. The node uses the hidden Markov model to dynamically estimate the game nodes of the competing channel and adaptively adjusts the Nash equilibrium of the transceiver based on the game results. In [4], a cross-layer optimization mechanism based on the priority strategy was proposed. The mechanism uses the modulation mode and available subcarrier information given in the dynamic resource management technology to dynamically adjust the backoff counter step size of the network node. In [5], the authors propose an efficient opportunistic random access MAC protocol with short-term fairness constraint for OFDMA-based indoor PLC networks. Ref. [6] proposed a MAC mechanism based on clustering and probability competition. Ref. [7] proposed an improved IEEE 1901 MAC model that can reduce the state space of the algorithm and set the parameters. On the basis of the decoupling hypothesis model, the performance of IEEE 1901 was analyzed and evaluated in [8]. On the basis of [8], [9] proposed that coupling exists between stations and analyzed the throughput performance based on a coupling model. Ref. [10] introduced the MAC-PHY cross-layer analysis of narrow-band power line communication systems in the presence of impulse noise. Paper [11] described the backoff process of HomePlug 1.0 through a Markov chain and analyzed saturated and unsaturated throughputs and the MAC delay. Ref. [12] established a 1901 MAC model from which two equations of collision probability can be derived. Ref. [13] simplified the model of [11]. Ref. [14] introduced a MAC mechanism for adaptive switching that can switch TDMA and CSMA/CA according to the delay-throughput tradeoff. Ref. [15] simplified the Markov chain into a single fixed-point equation; the model's disadvantage is inaccuracy. Tamilarasi and Lavenya [16] simplified the analysis of [11] to calculate the delay when data is unsaturated. Ref. [23] studied the IEEE 802.11 MAC layer throughput performance under the Hoyt, Rice, and Nakagami-*m* fading conditions. The approach includes the signal capture model with the incoherent addition of interfering signals and uniform attenuation for all terminals. Ref. [24] adopted the same signal acquisition model as [23] and studied the influence of the Weibull fading channel on the 802.11 MAC layer throughput. In [25], the author used queuing theory to propose an analysis framework for bidirectional unicast flows in wireless multi-hop mesh networks and studied the throughput performance and end-to-end delay of network coding in the network. It can be seen from [23], [24] that channel fading, interference and load changes [26] have an important impact on network performance.

The above research focused on the independent MAC layer mechanism in power line and wireless communications. However, the existing CSMA/CA algorithm cannot satisfy the modern communication requirements. Therefore, the CSMA/CA algorithm for the MAC layer in power line and wireless cooperative communication must be studied. Thus, a selective CSMA/CA algorithm is proposed in this paper for this scenario, that is, the station simultaneously detects the power line and the wireless channel and selects the idle channel to transmit data. The theoretical and simulation results show that the selective CSMA/CA algorithm can reduce the collision probability and improve the network throughput. The main contributions of this paper are as follows:

(1) For the MAC layer of power line and wireless selective communication, a selective CSMA/CA algorithm is proposed, and the transmission probability is discussed according to the different values of the backoff and delay counters. Finally, the expression between the transmission probability and the collision probability is obtained.

(2) Based on the decoupling assumption between stations, a system model of power line and wireless selective communication is proposed, and the transmission probability (τ) and collision probability (p) are solved by simultaneous equations. The performance of the proposed system model is evaluated by theoretical analysis and simulation.

(3) The uniqueness of the solution of the equations is proven. The collision probability (p) is derived by the equations to obtain the monotonicity of the two functions with p, and then the initial values of the two functions are compared to prove the uniqueness of the solutions, which is verified by simulation.

This paper is structured as follows. Section II describes the CSMA/CA algorithm in IEEE 1901 and 802.11. The third section describes the selective CSMA/CA algorithm for power line and wireless selective communication. The fourth section introduces the system model of power line and wireless selective communication. Section V proves the uniqueness of the solution to the equations of p. Section VI presents the delay analysis. Section VII assesses the performance of power lines and wireless selective communication systems. Finally, the work is summarized in Section VIII.

TABLE 1. IEEE 1901 values for the contention windows CW_i under different priorities.

	Class CA0/CA1		Class CA2/CA3	
backoff stage i	CW_i	d_i	CW_i	d_i
0	8	0	8	0
1	16	1	16	1
2	32	3	16	3
3	64	15	32	15

II. CSMA BACKOFF ALGORITHM BASED ON IEEE 1901 AND 802.11 STANDARDS

CSMA Backoff Algorithm Based on IEEE 1901 Standard

The CSMA/CA algorithm of the IEEE 1901 standard involves three kinds of counters, which are briefly described below.

1) *BPC*-backoff process counter: Indicates the number of backoff stages.

2) *BC*-backoff counter: Indicates a random backoff time, which is randomly selected from {0, …, CW_i-1} where CW_i denotes the contention window used at backoff stage i.

3) *DC*-deferral counter: Used to assess the busyness of the current channel. When the station detects that the channel is occupied, the *DC* and *BC* values are automatically decremented by 1. If $DC = 0$ and the medium is busy before the *BC* value decreases to 0 (that is, before attempting to transmit data), the station enters the next backoff stage, which will reset the *BC* and perform the next round of backoff, thereby reducing unnecessary collisions. The values of the contention window and the delay counter corresponding to different backoff phases and priority levels are shown in Table 1.

A. CSMA BACKOFF ALGORITHM BASED ON IEEE 802.11 STANDARD

The CSMA/CA backoff algorithm in the IEEE 802.11 standard involves the following two counters:

1) *BPC*-backoff process counter: Indicates the number of backoff stages.

2) *BC*-backoff counter: Indicates a random backoff time, randomly taking values in {0, …, CW_i-1} where CW_i represents the contention window of the backoff phase i. $CW_i = 2^i CW_{min}$, and CW_{min} represents the minimum contention window.

From the two protocols, the IEEE 1901 CSMA/CA protocol has some similarities with the CSMA/CA mechanism adopted by IEEE 802.11. Nevertheless, the difference between 1901 and 802.11 is that the CSMA/CA mechanism of 1901 is more complicated than that of 802.11, which makes its theoretical analysis more difficult. Especially, in addition to using the backoff counter, it also uses a deferral counter. The introduction of a deferral counter increases the backoff state of the station in contrast to the relatively small state space required to analyze 802.11. From a general perspective, the conflict avoidance methods in 1901 are quite different from the usual 802.11 CSMA/CA mechanism. IEEE 802.11 can only react to competition after detecting a conflict (by doubling the contention window). In contrast, in the 1901 protocol, when a station detects that the medium is busy for a certain number of time periods (determined by the deferral counter), the station may react. This protocol design has an obvious advantage over 802.11, that is, the contention window can be added multiple times depending on the state of the channel to achieve an appropriate backoff time, thereby reducing the possibility of collision. Conversely, when using 802.11, the contention window can only be doubled after a conflict. Consequently, one or more collisions may occur before the contention window reaches the appropriate value.

III. POWER LINE–WIRELESS SELECTIVE COMMUNICATION MAC PROTOCOL

Based on the similarities and differences between the power line and the wireless backoff algorithm, a CSMA/CA algorithm for power line/wireless selective communication is introduced. In the new algorithm, the station uses two backoff counters to monitor the power line channel and the wireless channel, and the station transmits data if the value of one of the backoff counters is zero. Thus, controlled by two backoff counters, a station can transmits data in a form of parallel communication or selective one, obtaining cooperative diversity [17].

If the network has N stations and the power line backoff counter and the wireless backoff counter of each station are $BC1$ and $BC2$, respectively, then the CSMA/CA algorithm flow of the power line/wireless selective communication is as shown in Figure 1.

The backoff procedure of the CSMA/CA algorithm for the power line/wireless selective communication is described as follows. The backoff algorithm uses five counters, two backoff process counters ($BPC1$ and $BPC2$), a deferral counter (DC), and two backoff counters ($BC1$ and $BC2$). $BPC1$, $BPC2$, and BC indicate the number of retransmissions (the number of retreat stages) and the value of the backoff counter. $BC1$ indicates the value of the power line backoff counter, $BC2$ indicates the value of the wireless backoff counter, and DC indicates the value of the power line deferral counter. The contention window (CW) and DC values (d_i) corresponding to the different backoff phases of the new algorithm are shown in Table 2.

(1) Whenever a new frame must be transmitted, the values of $BPC1$ and $BPC2$ are initialized to zero, and $BC1$ and $BC2$ randomly select values from {0, ..., CW_0-1} where CW_0 represents the initial contention window size.

(2) The station simultaneously senses the power line and wireless channel status in each time slot. If the wireless channel is sensed to be idle, then $BC1$ is decremented by one; if it is sensed that the wireless channel is busy, then $BC1$ is frozen. For the power line, if the channel is sensed to be idle, then the DC value is unchanged, and $BC2$ is decremented by one; if the power line channel is sensed to be busy, then the values of $BC2$ and DC are decremented by one.

(3) When $BC1$ or $BC2$ first arrives at zero, the station uses the corresponding medium to send data frames. If the frame is successfully transmitted, proceed to step (1). If a collision occurs, the backoff mechanism under the corresponding medium is started, and the other communication mode is unaffected. The corresponding $BPC1$ or $BPC2$ plus 1, that is, the power line side communication or the wireless side communication of the station enters the next backoff phase. If the next backoff phase is i, then $BC1$ or $BC2$ randomly takes values in {0, ..., CW_i-1}. Among them, CW_i indicates the contention window of the site in backoff phase i. Notably, if a collision occurs in power line communication, DC must also retrieve the value corresponding to the retreat stage.

As shown in Figure 1 and the above steps, when a node in the network collides, the node only increases the backoff phase of the conflicting interface, while the other interface in the dual interface remains in the original state. For example, if the power line interface conflicts, the interface enters the next backoff phase; while the wireless interface is unaffected that continues to perform the algorithm steps of the original backoff phase. If the node successfully sends data, both interfaces of the node return to the initial backoff stage for the next data transmission.

TABLE 2. Values of *CW* and dc in different retreat phases.

	Class CA0/CA1		Class CA2/CA3	
BPC1/BPC2	CW	DC	CW	DC
0	8	0	8	0
1	16	1	16	1
2	32	3	16	3
≥ 3	64	15	32	15

IV. SYSTEM MODEL

We make the following assumptions:

(1) The network has N sites.

(2) All sites are saturated (packets always need sending).

(3) Regardless of the packet loss or packet error due to physical layer factors, transmission failure is only related to frame collision in the MAC layer.

(4) The station will not drop the packet until it is successfully sent.

(5) All competing sites have the same priority and use the same parameter settings.

(6) To uniformly design the power line and wireless backoff algorithm, the power line and the wireless minimum contention window are the same.

Based on the above assumptions, the backoff process of a site is independent of the attempted transmission process of the remaining N-1 sites, that is, each backoff stage (i)

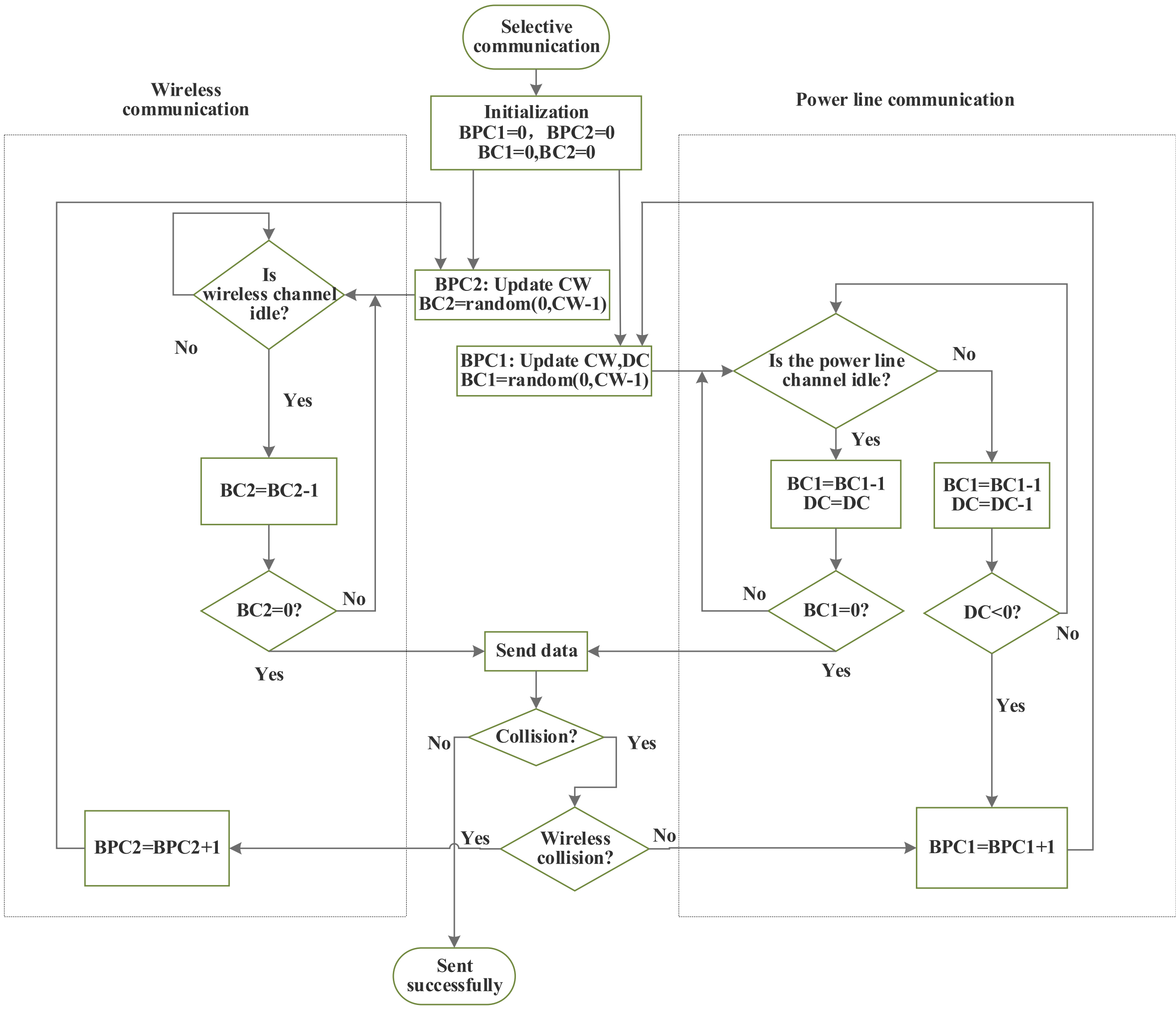


FIGURE 1. Flow chart of CSMA/CA algorithm for power line/wireless selective communication.

has N sites, and the number of sites does not increase from the collisions with sites in the previous backoff stage nor decrease from the successful transmission during this backoff stage, which is called the decoupling hypothesis and involves the following two points:

(1) At each time slot, the station has a fixed transmission probability (τ_i).

(2) The probability that at least one other station transmits is also fixed (the state is independent). Therefore, the station has a fixed collision probability (p), or the probability that the station detects that the channel is busy is p, independent of the channel state of the previous time slot.

Before the specific analysis, it is necessary to emphasize that this study aims to explore new ideas for hybrid communications and to inspire future research. Therefore, when establishing the system model, only the basic access mechanism is considered, that is, the MAC layer of the wireless interface and the power line interface follows the basic backoff and access mechanism and does not involve the RTS/CTS access mechanism. Besides, when we conduct theoretical analysis, we do not study the performance indicators of the two interfaces separately but look at the problem from the perspective of the node, that is, the two interfaces are regarded as a whole.

The variables of the model are as follows. A total of m backoff stages exist, and the number of stations is N. τ_i represents the transmission probability of the station in any time slot in backoff stage i. p is the probability that at least one other station will send, that is, the probability of collision. p_e is the probability that no station will send data frames (the probability of the channel being idle).

We can calculate the transmission probability (τ_i) of the station in backoff stage i. τ_i is a function of collision probability p. Let the power line backoff counter value be k_1, and the value of the deferral counter of the station in backoff stage i be d_{i}. The size of the contention window for each backoff stage is CW_{i}, and the value of the wireless backoff counter is k_2. k_1 and k_2 are randomly and uniformly selected from $\{0, \ldots, CW_{\mathrm{i}}\text{-}1\}$. In the 802.11 protocol, the station attempts to transmit data only when the value of backoff counter k_2 is zero. When a collision occurs, the station enters the next backoff stage. However, in IEEE 1901, two cases where the station leaves backoff stage i exist. First, transmission is attempted when the value of k_1 is zero. Second, the value of k_1 does not reach zero, and the cumulative number of time slots detected to be busy is greater than d_{i} (i.e., when the value of d_{i} is reduced to zero and the channel is detected to be busy). The station enters the next backoff stage at time slot j, $d_{\mathrm{i}}+1 \le j \le k_1$, and the station spends j time slots in backoff stage i.

Three cases are discussed based on the values of k_1 and k_2:

1) The value of the power line's backoff counter reaches zero first, and the station chooses to communicate with the power line channel.
2) The value of the wireless backoff counter reaches zero first, and the station selects the wireless channel for communication.
3) In k_1 time slots, the number of time slots when the channel is busy is greater than d_{i}, and k_2 does not reach zero. At this time, the station enters the next backoff stage.

Before the analysis, we provide the following conclusions about the size relationship of k_1 and k_2 (the proof is at the end of the article).

$$P(k_1 = k_2) = \frac{1}{CW_{\mathrm{i}}}.$$
$$P(k_1 \ge k_2) = P(k_1 \le k_2) = \frac{CW_{\mathrm{i}}+1}{2CW_{\mathrm{i}}}.$$
$$P(k_1 > k_2) = P(k_1 < k_2) = \frac{CW_{\mathrm{i}}-1}{2CW_{\mathrm{i}}}.$$

A. $k_1 < d_i \le k_2$

After each time slot is detected, k_1 is decremented by 1 regardless of whether the channel is idle or not; d_{i} is automatically decremented by 1 only when the channel is detected as busy; for k_2, it is decremented only when the wireless channel is detected as idle. Consider the most unfavorable situation for the power line: the power line channel is always busy, and the wireless channel is always idle. Given that k_1 and k_2 are decremented by 1 in each time slot and $k_1 < k_2$, the backoff counter of the power line is first reduced to zero. It will not enter the next retreat stage because $k_1 < d_{\mathrm{i}}$. Therefore, the probability of power line transmission is 1. The probability of a site attempting to send is

$$\tau_{11\mathrm{i}} = \frac{1}{CW_{\mathrm{i}}}\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}\frac{CW_{\mathrm{i}}-1}{2CW_{\mathrm{i}}}(1-\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}). \quad (1)$$

where $\frac{1}{CW_{\mathrm{i}}}$ represents the probability of each k_1, $\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}$ represents the probability of $k_1 < d_{\mathrm{i}}$, and $\frac{CW_{\mathrm{i}}-1}{2CW_{\mathrm{i}}}$ is the probability of $k_1 < k_2$(probability proof at the end of the paper).$1-\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}$ is the probability of $k_2 \ge d_{\mathrm{i}}$.

B. $k_1 < k_2 < d_i$

This situation is similar to (1). Given that $k_1 < k_2$, k_1 of the power line terminal is first reduced to 0, so the power line channel is used to transmit data. Given that $k_1 < d_{\mathrm{i}}$, it will not enter the next backoff phase.

$$\tau_{12\mathrm{i}} = \frac{1}{CW_{\mathrm{i}}}\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}\frac{CW_i-1}{2CW_i}\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}. \quad (2)$$

Combine (1) and (2):

$$\tau_{1\mathrm{i}} = \tau_{11\mathrm{i}} + \tau_{12\mathrm{i}} = \frac{1}{CW_{\mathrm{i}}}\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}\frac{CW_{\mathrm{i}}-1}{2CW_{\mathrm{i}}}. \quad (3)$$

C. $k_2 \le k_1 < d_i$

Given that $k_1 < d_{\mathrm{i}}$, the power line does not enter the next backoff phase (extreme case: the power line is always busy, and k_1 and d_{i} are simultaneously decremented by 1; thus, k_1 is first reduced to zero). At this point, we consider only two cases:

1) WIRELESS COUNTER k_2 IS FIRST REDUCED TO 0

If the station is in backoff phase i, k time slots are spent such that k_2 is reduced to zero. Considering that the wireless channel detection is busy, $k \ge k_2$ is required. Meanwhile, to ensure that the wireless counter k_2 is first reduced to 0, k must satisfy $k < k_1$. When $k = k_1$, k_2 and k_1 are simultaneously reduced to 0, and the station can simultaneously transmit data using the power line and the wireless channel. Therefore, k satisfies $k_2 \le k \le k_1$.

According to the model hypothesis, the probability that the channel is detected to be busy is p, and the total number of slots in which the channel is idle in the k slots of the wireless channel is k_2. When the value of k_2 is zero, the data is transmitted using the wireless channel. Given that the value of k_2 is reduced to zero at time slot k, the k time slot channel is idle. Of the remaining k-1time slots, k_2-1 time slots must be idle. Thus, the probability of the station using the wireless channel to send data first obeys the binomial distribution $\binom{k-1}{k_2-1}(1-p)^{k_2-1}p^{k-k_2}$. Therefore, in backoff stage i, the probability of the wireless channel preempting is

$$\frac{1}{CW_{\mathrm{i}}}\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}\frac{CW_{\mathrm{i}}+1}{2CW_{\mathrm{i}}}\sum_{k_1=0}^{d_{\mathrm{i}}-1}\sum_{k_2=0}^{k_1}\sum_{k=k_2}^{k_1}\binom{k-1}{k_2-1} \times (1-p)^{k_2-1}p^{k-k_2}(1-p). \quad (4)$$

where $\frac{1}{CW_{\mathrm{i}}}$ indicates the probability of each k_1 value. $\frac{d_{\mathrm{i}}}{CW_{\mathrm{i}}}$ indicates the probability of $k_1 < d_{\mathrm{i}}$.$\frac{CW_{\mathrm{i}}+1}{2CW_{\mathrm{i}}}$ indicates the probability of $k_1 \ge k_2$.For $\sum_{k_1=0}^{d_{\mathrm{i}}-1}\sum_{k_2=0_1^k}\sum_{k=k_2{}_1^k}$, the first sum represents the value of k_1 from 0 to d_{i}- 1 (because $k_1 < d_{\mathrm{i}}$) .The second sum represents $k_2 \le k_1$, and the third sum represents $k_2 \le k \le k_1$.

2) THE POWER LINE COUNTER k_1 IS FIRST REDUCED TO ZERO

Regardless of whether the power line channel is idle or not, k_1 is decremented by one, so the station must spend k_1 time slots to reduce counter k_1 to zero. Variable j is used to indicate the total number of time slots in which the power line channel is idle in k_1 time slots, and j follows the binomial distribution, using $j \sim B(k_1, p)$. Then, $P_j = \binom{k_1}{j}(1-p)^j p^{k-j}$. To ensure that power line counter k_1 reaches 0, the backoff counter (k_2) of the wireless channel does not decrement to zero, and j must satisfy $j < k_2$. Therefore, in backoff phase i, the probability that the station occupies the power line channel to transmit data first is

$$\frac{1}{CW_\mathrm{i}}\frac{d_\mathrm{i}}{CW_\mathrm{i}}\frac{CW_i+1}{2CW_\mathrm{i}}\sum_{k_1=0}^{d_\mathrm{i}-1}\sum_{k_2=0}^{k_1}\sum_{j=0}^{k_2-1}P_j. \tag{5}$$

In $\sum_{k_1=0}^{d_\mathrm{i}-1}\sum_{k_2=0}^{k_1}\sum_{j=0}^{k_2-1}P_\mathrm{j}$, $\sum_{k_1=0}^{d_\mathrm{i}-1}$ indicates that k_1 takes values from 0 to d_i-1 (because $k_1 < d_\mathrm{i}$). The second sum, $\sum_{k_2=0}^{k_1}$, represents $k_2 \le k_1$, and the third sum, $\sum_{j=0}^{k_2-1}$, represents $j < k_2$. By combining the two cases above, the total probability value is obtained as

$$\begin{aligned}\tau_{2\mathrm{i}} = {} & \frac{1}{CW_\mathrm{i}}\frac{d_\mathrm{i}}{CW_\mathrm{i}}\frac{CW_\mathrm{i}+1}{2CW_\mathrm{i}}\Big(\sum_{k_1=0}^{d_i-1}\sum_{k_2=0}^{k_1}\sum_{\mathrm{k}=k_2}^{k_1}\\ & \times\binom{\mathrm{k}-1}{k_2-1}(1-\mathrm{p})^{k_2}\mathrm{p}^{\mathrm{k}-k_2}+\sum_{k_1=0}^{\mathrm{d_i}-1}\sum_{k_2=0}^{k_1}\\ & \times\sum_{\mathrm{j}=0}^{k_2-1}\binom{k_1}{j}(1-p)^j p^{k-j}\Big).\end{aligned} \tag{6}$$

According to the derivation of the above formula, we can use the same analysis method to obtain the probability formula in the following cases.

D. $d_i \le k_1 \le k_2$

1) THE PROBABILITY OF THE STATION ENTERING THE NEXT BACKOFF STAGE IS

$$\begin{aligned}\tau_{3\mathrm{i}} = {} & \frac{1}{CW_\mathrm{i}}\left(1-\frac{d_\mathrm{i}}{CW_\mathrm{i}}\right)\frac{CW_\mathrm{i}+1}{2CW_\mathrm{i}}\times\sum_{k_2=d_\mathrm{i}}^{CW_\mathrm{i}-1}\sum_{k_1=d_\mathrm{i}}^{k_2}\\ & \times\sum_{k=d_\mathrm{i}+1}^{k_1-1}\binom{k-1}{d_\mathrm{i}}p^{d_\mathrm{i}+1}(1-p)^{k_1-1-d_\mathrm{i}}.\end{aligned} \tag{7}$$

where $\binom{k-1}{d_i}$ indicates all cases in which the number of busy slots is di in k-1 slots.

2) THE PROBABILITY OF SENDING DATA USING THE POWER LINE CHANNEL IS

$$\begin{aligned}\tau_{4i} = {} & \frac{1}{CW_i}\left(1-\frac{d_i}{CW_i}\right)\frac{CW_i+1}{2CW_i}\times\sum_{k_2=d_i}^{CW_i-1}\sum_{k_1=d_i}^{k_2}\\ & \times\sum_{j=0}^{d_i}\binom{k_1}{j}p^j(1-p)^{k_1-j}.\end{aligned} \tag{8}$$

where $\binom{k_1}{j}$ indicates all cases in which the number of busy slots is j in k_1 slots.

E. $d_i \le k_2 < k_1$

1) THE PROBABILITY OF THE STATION ENTERING THE NEXT BACKOFF STAGE IS

$$\begin{aligned}\tau_{5i} = {} & \frac{1}{CW_i}\left(1-\frac{d_i+1}{CW_i}\right)\frac{CW_i-1}{2CW_i}\left(1-\frac{d_\mathrm{i}}{CW_\mathrm{i}}\right)\\ & \times\Big(\sum_{k_1=d_\mathrm{i}+1}^{CW_\mathrm{i}-1}\sum_{k_2=d_\mathrm{i}}^{k_1-1}\sum_{k=d_\mathrm{i}+1}^{k_2-1}\\ & \times\binom{k-1}{d_\mathrm{i}}p^{d_\mathrm{i}+1}\times(1-p)^{k-1-d_\mathrm{i}}\\ & +\sum_{k_1=d_\mathrm{i}+1}^{CW_\mathrm{i}-1}\sum_{k_2=d_\mathrm{i}}^{k_1-1}\sum_{k=k_2}^{k_1}\\ & \times\binom{k-1}{d_\mathrm{i}}p^{d_\mathrm{i}+1}\times(1-p)^{k-1-d_\mathrm{i}}\\ & \times\sum_{j=0}^{k_2-1}\binom{k}{j}(1-p)^j p^{k-j}\Big).\end{aligned} \tag{9}$$

where $\left(0\,{k-1 \atop d_\mathrm{i}}\right)$ indicates all cases in which the number of busy slots is d_i in k-1 slots. $\binom{k}{j}$ indicates all cases in which the number of busy slots is j in k slots.

2) THE PROBABILITY OF THE STATION TRANSMITTING DATA USING THE POWER LINE CHANNEL IS

$$\begin{aligned}\tau_{6\mathrm{i}} = {} & \frac{1}{CW_\mathrm{i}}\left(1-\frac{\mathrm{d_i}+1}{CW_\mathrm{i}}\right)\frac{CW_\mathrm{i}-1}{2CW_\mathrm{i}}\left(1-\frac{d_\mathrm{i}}{CW_\mathrm{i}}\right)\\ & \times\sum_{k_1=d_\mathrm{i}+1}^{CW_\mathrm{i}-1}\sum_{k_2=d_\mathrm{i}}^{k_1-1}\Big(\sum_{j=0}^{d_\mathrm{i}}\binom{k_1}{j}p^j(1-p)^{k_1-j}\\ & \times\sum_{j=0}^{k_2-1}\binom{k_1}{j}(1-\mathrm{p})^\mathrm{j}\mathrm{p}^{k_1-\mathrm{j}}\Big).\end{aligned} \tag{10}$$

where $\binom{k_1}{j}$ indicates all cases in which the number of busy slots is j in k_1 slots.

3) THE PROBABILITY THAT A STATION SENDS DATA USING A WIRELESS CHANNEL IS

$$\begin{aligned}\tau_{7\mathrm{i}} = {} & \frac{1}{CW_\mathrm{i}}\left(1-\frac{d_\mathrm{i}+1}{CW_\mathrm{i}}\right)\frac{CW_\mathrm{i}-1}{2CW_\mathrm{i}}\left(1-\frac{d_\mathrm{i}}{CW_\mathrm{i}}\right)\\ & \times\sum_{k_1=\mathrm{d_i}+1}^{\mathrm{CW_i}-1}\sum_{k_2=\mathrm{d_i}}^{k_1-1}\sum_{\mathrm{k}=k_2}^{k_1}\Big(\binom{k-1}{k_2-1}\\ & \times(1-p)^{k_2}p^{(k-k_2)}\times\sum_{j=0}^{\mathrm{d_i}}\binom{k}{j}p^j(1-p)^{k-j}\Big).\end{aligned} \tag{11}$$

where $\binom{k-1}{k_2-1}$ indicates all cases where the number of free slots is k_2-1 in k-1 slots. $\binom{k}{j}$ indicates all cases where the number of busy slots is j in k slots.

F. $k_2 < d_i \le k_1$

1) THE PROBABILITY OF THE STATION ENTERING THE NEXT BACKOFF STAGE IS

$$\tau_{8i} = \frac{1}{CW_i}\left(1-\frac{d_i}{CW_i}\right)\frac{CW_i-1}{2CW_i}\frac{d_i}{CW_i} \times \sum_{k_1=d_i}^{CW_i-1}\sum_{k_2=0}^{d_i-1}\sum_{k=d_i+1}^{k_1}(\binom{k-1}{d_i}p^{d_i+1} \times (1-p)^{k-1-d_i} \times \sum_{j=0}^{k_2-1}\binom{k}{j}(1-p)^j p^{(k-j)}). \quad (12)$$

where $\binom{k-1}{d_i}$ indicates all cases in which the number of busy slots is d_i in k-1 slots. $\binom{k}{j}$ indicates all cases where the number of free slots is j in k slots.

2) THE PROBABILITY OF THE STATION TRANSMITTING DATA USING THE POWER LINE CHANNEL IS

$$\tau_{9i} = \frac{1}{CW_i}\left(1-\frac{d_i}{CW_i}\right)\frac{CW_i-1}{2CW_i}\frac{d_i}{CW_i} \times \sum_{k_1=d_i}^{CW_i-1}\sum_{k_2=0}^{d_i-1}(\sum_{j=0}^{k_2-1}\binom{k_1}{j}(1-p)^j p^{(k_1-j)} \times \sum_{j=0}^{d_i}\binom{k_1}{j}p^j(1-p)^{k_1-j}) \quad (13)$$

where the first $\binom{k_1}{j}$ indicates all cases in which the number of free slots is j in k_1 slots, and the second $\binom{k_1}{j}$ indicates all cases in which the number of busy slots is j in k_1 slots

3) THE PROBABILITY THAT THE STATION WILL SEND DATA USING THE WIRELESS CHANNEL

If the station transmits data using the wireless channel in the k th time slot, the k-segment is discussed.

a: $k_2 \le k < d_i - 1$

$$\tau_{101i} = \frac{1}{CW_i}\left(1-\frac{d_i}{CW_i}\right)\frac{CW_i-1}{2CW_i}\frac{d_i}{CW_i} \times \sum_{k_1=d_i}^{CW_i-1}\sum_{k_2=0}^{d_i-1} \times \sum_{k=k_2}^{d_i-1}(\binom{k-1}{k_2-1}(1-p)^{k_2}p^{(k-k_2)}). \quad (14)$$

where $\binom{k-1}{k_2-1}$ indicates all cases where the number of free slots is k_2-1 in k-1 slots.

b: $d_i \le k \le k_1$

$$\tau_{102i} = \left(1-\frac{d_i}{CW_i}\right)\frac{CW_i-1}{2CW_i}\frac{d_i}{CW_i} \times \sum_{k_1=d_i+1}^{CW_i-1}\sum_{k_2=0}^{d_i-1}\sum_{k=d_i}^{k_1}(\binom{k-1}{k_2-1} \times (1-p)^{k_2}p^{(k-k_2)} \times \sum_{j=0}^{d_i}\binom{k}{j}p^j(1-p)^{k-j}). \quad (15)$$

where $\binom{k-1}{k_2-1}$ indicates all cases where the number of free slots is k_2-1 in k-1 slots, and the $\binom{k}{j}$ indicates all cases where the number of busy slots is j in k slots.

In summary, the probability that a station uses a wireless channel to send data is $\tau_{10i} = \tau_{101i} + \tau_{102i}$.

Based on the above six cases, the probability of the station attempting to send is analyzed. A special explanation is given below. According to the IEEE 1901 standard, in the first backoff stage, d_i takes a value of zero. Therefore, the values of k_1 and k_2 must be no less than d_i. At this time, two cases, $d_i \le k_1 \le k_2$ and $d_i \le k_2 < k_1$, are necessary.

Based on the discussion of the various situations above, the sum of the probability that the station uses the power line and the wireless channel to transmit data in each backoff phase (i) is defined by τ_i as follows

$$\tau_i = \tau_{1i} + \tau_{2i} + \tau_{4i} + \tau_{6i} + \tau_{7i} + \tau_{9i} + \tau_{10i}. \quad (16)$$

In each backoff stage (i), the average probability that the wireless backoff counter has not reached zero and the counter of the power line channel enters the next backoff stage is represented by $\tau\tau_i$:

$$\tau\tau_i = \tau_{3i} + \tau_{5i} + \tau_{8i}. \quad (17)$$

m represents the number of backoff stages, τ_1 represents the transmission probability of the station in the first backoff stage. τ_i and $\tau\tau_i$ are the values of all probability cases and can be used to analyze the theoretical delay of the system. In addition, stations that need to communicate will be initialized into the first backoff stage. When a collision occurs in backoff stage i, the station enters the $i+1$ backoff stage and resets the value of the counter. Therefore, to synthesize all the backoff stages, the average sending probability of the station is

$$\begin{aligned}\tau &= \tau_1 + \sum_{i=2}^{m-1} p\tau_{i-1}\tau_i + \tau_{m-1}p\tau_m + \tau_{m-1}p\tau_m p\tau_m + \tau_{m-1}p(\tau_m p)^2\tau_m \ldots + \tau_{m-1}p(\tau_m p)^n\tau_m \\ &= \tau_1 + \sum_{i=2}^{m-1} p\tau_{i-1}\tau_i + \tau_{m-1}p\left(1+\ldots+(\tau_m p)^n\right)\tau_m \\ &= \tau_1 + \sum_{i=2}^{m-1} p\tau_{i-1}\tau_i + \frac{p\tau_{m-1}}{1-p\tau_m}\tau_m. \end{aligned} \quad (18)$$

Given that p represents the probability that at least one other station sends, it is an expression about τ:

$$p = 1-(1-\tau)^{N-1}. \quad (19)$$

Equations (18) and (19) can be used to find the values of τ and p. Thus, p_s and p_e can be calculated for the throughput of the system to be calculated.

p_s indicates the probability of successful transmission

$$P_s = N\tau(1-\tau)^{N-1}. \tag{20}$$

p_e indicates the probability of a free time slot

$$p_e = (1-\tau)^N. \tag{21}$$

p_c indicates the probability of a collision

$$p_c = 1 - p_e - p_s. \tag{22}$$

Therefore, the normalized throughput of the network can be calculated as

$$S = \frac{p_s t_L}{p_s T_s + p_c T_c + p_e \sigma}. \tag{23}$$

where σ represents the duration of the idle time slot, t_L represents the length of the data frame, T_s represents the time consumed for a successful transmission, and T_c represents the time taken for collision to occur.

At the end of this section, we will further summarize the above theories and the ideas used. When we formulate the formula, we start from the point of view of the node, that is, the power line and the wireless interface are regarded as a whole. Specifically, the transmission probability of the node in the ith backoff stage and the probability of entering the next phase are analyzed, that is, when the node is in the backoff stage i, the subscripts of the window CW_i of the wireless and power line interfaces are the same. Considering the transmission probability of the node at each stage, the average transmission probability of the node is finally obtained, as shown in formula (18). In addition, we need to explain that we only analyze the probability of a node colliding at the current stage, and once the data frame is sent, the node has left the current stage no matter whether it collides or not. In the theoretical calculations, we consider all the states that a node may have.

V. UNIQUENESS OF THE SOLUTION OF THE EQUATIONS

The solution to the equations is obtained from

$$\begin{cases} \tau_1(p) = 1 - (1-p)^{\frac{1}{N-1}} \\ \tau_2(p) = \tau_1 + \sum_{i=2}^{m-1} p \cdot \tau_{i-1} \cdot \tau_i + \frac{p \cdot \tau_{m-1}}{1-p\cdot\tau_m} \cdot \tau_m. \end{cases}$$

Therefore, the two equations are used to derive p, and the intersection of the equations is observed in the change of the equation curve. Thus, the uniqueness of the solution is proven.

Lemma (1): For function $\tau_1(p) = 1-(1-p)^{1/(N-1)}$, $\tau(p)$ monotonically increases with p.

Proof: $\tau_1(p) = 1-(1-p)^{1/(N-1)}$ can be obtained from $p = 1-(1-\tau)^{N-1}$. Deriving p through τ,

$$\frac{d\tau}{dp} = \frac{1}{N-1}(1-p)^{\frac{2-N}{N-1}}. \tag{24}$$

Given that $p \in [0,1)$, $1\text{-}p \in (0,1]$, then $(1\text{-}p)^{2-N/(N-1)} > 0$. Also, because $1/(N\text{-}1) > 0$, $d\tau/dp > 0$, τ monotonically increases with p.

Lemma (2): For function $\tau_2(p) = \tau_1 + \sum_{i=2}^{m-1} p \cdot \tau_{i-1} \cdot \tau_i + \frac{p\cdot\tau_{m-1}}{1-p\cdot\tau_m} \cdot \tau_m$, $\tau_2(p)$ monotonically decreases with p.

Proof: The above formula consists of three parts, which are respectively derived from p

$$\frac{d\tau}{dp} = \frac{d\tau_1}{dp} + \sum_{i=2}^{m-1}\left(\tau_{i-1}\tau_i + p\cdot(\tau_{i-1}\frac{d\tau_i}{dp} + \tau_i\frac{d\tau_{i-1}}{dp})\right) \times \frac{d\left(\frac{p\cdot\tau_{m-1}\cdot\tau_m}{1-p\cdot\tau_m}\right)}{dp}. \tag{25}$$

First, the monotonic change of τ_i with p is proven. The probability of transmission in different backoff stages (i) is shown by (16). Thus,

$$\frac{d\tau i}{dp} = \frac{\tau_{1i}}{dp} + \frac{\tau_{2i}}{dp} + \frac{\tau_{4i}}{dp} + \frac{\tau_{6i}}{dp} + \frac{\tau_{7i}}{dp} + \frac{\tau_{9i}}{dp} + \frac{\tau_{10i}}{dp}. \tag{26}$$

We substitute the above formula into $\frac{d\tau_i}{dp}$. Given that each part of the formula is in the form $\sum\sum(1\text{-}p)^m p^n$, where m and n represent arbitrary indices, and $m+n=k$, we let $z = \sum\sum(1\text{-}p)^m p^n$ to obtain

$$\begin{aligned} \frac{dz}{dp} &= \sum\sum -m(1-p)^{m-1}p^n + n(1-p)^m p^{n-1} \\ &= \sum\sum (1-p)^{k-n-1}p^{n-1}(n-kp). \end{aligned} \tag{27}$$

From the above formula, the following relationship can be drawn $\begin{cases} n > kp \Rightarrow \frac{n}{k} > p, & \frac{dz}{dp} > 0 \\ n \le kp \Rightarrow \frac{n}{k} \le p, & \frac{dz}{dp} \le 0. \end{cases}$

We suppose that $p*$ exists such that $dz/dp > 0$. Given that n and k take random values within a certain range, the positive and negative dz/dp are affected by n and k. When $p = p*$, $dz/dp > 0$, indicating that the set of n and k values of $n/k > p$ is larger than the set of n and k values of $n/k \le p$.

When $p < p*$, we let $p = p* - \beta$, $\beta > 0$. Compared with $p*$, because p is reduced, the n and k sets of $n/k > p$ are expanded, and the n and k sets of $n/k \le p$ are reduced. Thus, $dz/dp > 0$. Therefore, if $p*$ is present such that $dz/dp > 0$ for any $p < p*$, $dz/dp > 0$.

Equation (27) shows that $p = 0$, $dz/dp = 0$. The above assumptions contradict this. Thus, when $p \in [0,1)$, $dz/dp \le 0$. Therefore, $d\tau_i/dp \le 0$, that is, τ_i monotonically decreases with p.

Next step, we need to investigate the monotonicity of $\sum_{i=2}^{m-1}\left(p\cdot(\tau_{i-1}\frac{d\tau_i}{dp} + \tau_i\frac{d\tau_{i-1}}{dp})\right)$.

$d\tau_i/dp < 0$, $0 < \tau_{i-1} < 1$, so $d\tau_i/dp\cdot\tau_{i-1} < 0$. Similarly, $d\tau_{i-1}/dp\cdot\tau_i < 0$, $d\tau_i/dp\cdot\tau_{i-1} + d\tau_{i-1}/dp\cdot\tau_i < 0$. Given that $0 < p < 1$, $p(d\tau_i/dp\cdot\tau_{i-1} + d\tau_{i-1}/dp\cdot\tau_i) < 0$. Therefore, the evidence is

$$\sum_{i=2}^{m-1} p\cdot(\tau_{i-1}\frac{d\tau_i}{dp} + \tau_i\frac{d\tau_{i-1}}{dp}) < 0. \tag{28}$$

Then, we prove the monotonicity of of $\sum_{i=2}^{m}\tau_{i-1}\tau_i$. Deriving $\sum\tau_{i-1}\tau_i$, we can see that $d(\tau_{i-1}\tau_i)/dp = d\tau_i/dp\cdot\tau_{i-1} + d\tau_{i-1}/dp\cdot\tau_i < 0$. Therefore, $\sum d(\tau_{i-1}\tau_i)/dp < 0$, and $\sum\tau_{i-1}\tau_i$

is monotonically decreasing with p. Also, given that $0 \leq p < 1$, when $p = 0$, $\sum_{i=2}^{m} \tau_{i-1}\tau_i$ obtains the maximum value

$$\sum \tau_{i-1}\tau_i = \sum \frac{1}{CW_{i-1}}\frac{d_{i-1}}{CW_{i-1}}\frac{CW_{i-1}-1}{2CW_{i-1}}\left(1-\frac{d_{i-1}}{CW_{i-1}}\right) \times \frac{1}{CW_i}\frac{d_i}{CW_i}\frac{CW_i-1}{2CW_i}\left(1-\frac{d_i}{CW_i}\right) = \sum Q. \tag{29}$$

For each backoff phase (i), $d = \{0,1,3,15\}$, corresponding to CW=$\{8, 16, 32, 64\}$. Therefore, the value of d_i/CW_i is approximately 0. The above formula shows that Q is a multi-fraction product, and each item has a d_i/CW_i factor, so $Q \rightarrow 0$. Obviously, p is a value greater than 0, then $\sum_{i=2}^{m} \tau_{i-1}\tau_i$ is closer to zero. In fact, it can be approximated as $\sum_{i=2}^{m} \tau_i\tau_{i-1} = 0$.

Finally, we prove that $\frac{p\cdot\tau_{m-1}\cdot\tau_m}{1-p\cdot\tau_m}$ is monotonic with p. Let $y = \frac{p\cdot\tau_{m-1}\cdot\tau_m}{1-p\cdot\tau_m}$:

$$\frac{dy}{dp} = \frac{\left[\tau_{m-1}\tau_m + p\left(\tau_m\frac{d\tau_{m-1}}{dp} + \tau_{m-1}\frac{d\tau_m}{dp}\right)\right]}{(1-p\tau_m)^2} \times (1-p\tau_m) + p\tau_{m-1}\tau_m\left(\tau_m + \frac{d\tau_m}{dp}\right). \tag{30}$$

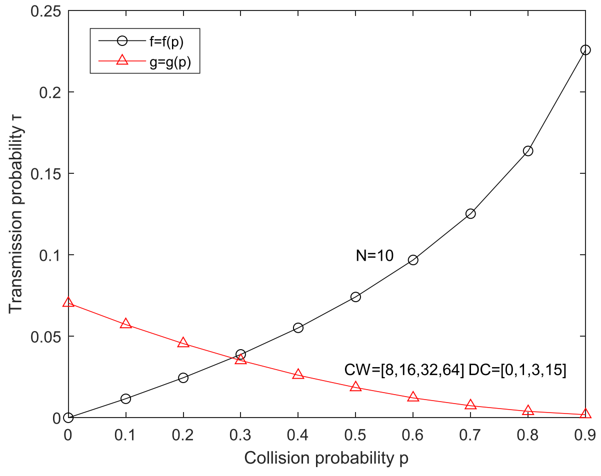
Simplified:

$$\frac{dy}{dp} = \frac{\tau_{m-1}\tau_m + p\tau_m(1-p\tau_m)\frac{d\tau_{m-1}}{dp} + p\tau_{m-1}\frac{d\tau_m}{dp}}{(1-p\tau_m)^2}. \tag{31}$$

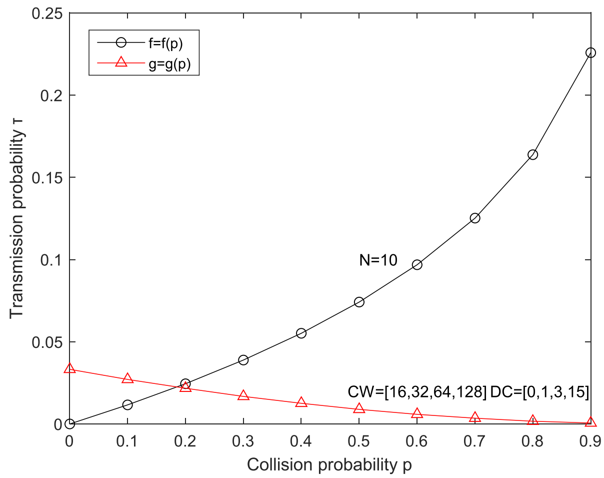
When $m \rightarrow \infty$, $\tau_{m-1}\tau_m = 0$, $p\tau_m(1-p\tau_m) > 0$. Therefore, $p\tau_m(1-p\tau_m)\frac{d\tau_{m-1}}{dp} < 0$. Similarly, $p\tau_{m-1}\frac{d\tau_m}{dp} < 0$. So, $\frac{dy}{dp} < 0$.

According to the discussion above, $\frac{d\tau}{dp} = \sum_{i=2}^{m-1}\left(\tau_{i-1}\tau_i + p\cdot(\tau_{i-1}\frac{d\tau_i}{dp} + \tau_i\frac{d\tau_{i-1}}{dp})\right) + \frac{dy}{dp} < 0$. Therefore, τ monotonically decreases with p.

The above proof indicates that the monotonicity of the two functions with p is different, and $\tau_1(p = 0) = 0$, $\tau_2(p = 0) > 0$. Thus, the equations have a unique solution. For convenience, let f(p)= τ_1(p), g(p)= τ_2(p). The following verification is performed by simulation, as shown in Figure 2. The simulation results ((a) and (b)) are obtained by taking different backoff window values. The figure indicates that the increasing and decreasing trend of curves τ_1 and τ_2 is basically consistent with the theory, and only one intersection point exists, that is, the equation group has a unique solution.



(a)



(b)

FIGURE 2. Relationship between collision probability and transmission probability. (a) CW_{min} = 8. (b) CW_{min} = 16.

VI. TIME DELAY ANALYSIS

The station spends two types of time slots:

(1) The number of time slots spent by the station backing to the next backoff stage.

(2) The number of time slots the station spends sending data at the current stage.

We use a similar approach to analyze the above delays of the algorithm for the values of k_1 and k_2.

$$k_1 < d_i < k_2$$

The probability that a station uses a power line channel to send data is

$$\tau_{11i} = \frac{1}{CW_i}\frac{d_i}{CW_i}\frac{CW_i-1}{2CW_i}\left(1-\frac{d_i}{CW_i}\right). \tag{32}$$

In this case, the backoff counter of the station is decremented to zero by k_1 time slots, and the station transmits data at the k_1+1th time slot, so the number of time slots consumed is $k_1 + 1$.

$$k_1 < k_2 < d_i$$

The probability of this value is similar to (1). The power line takes k_1 time slots to reach zero and is used to transmit data in the $k_1 + 1$th time slot:

$$\tau_{12i} = \frac{1}{CW_i}\frac{d_i}{CW_i}\frac{CW_i-1}{2CW_i}\frac{d_i}{CW_i}. \tag{33}$$

Therefore, the number of slots that the station spends is $k_1 + 1$.

$$k_2 \le k_1 < d_i$$

First, we consider the case where wireless counter k_2 is first reduced to zero.

In backoff phase i, the station spends a total of k time slots to reduce k_2 to zero. The station transmits data in the $k+1$th time slot. The probability of transmitting data on the wireless channel is

$$\frac{1}{CW_i}\frac{d_i}{CW_i}\frac{CW_i+1}{2CW_i}\sum_{k_1=0}^{d_i-1}\sum_{k_2=0}^{k_1}\sum_{k=k_2}^{k_1}\binom{k-1}{k_2-1}\times(1-p)^{k_2-1}p^{k-k_2}(1-p). \quad (34)$$

Therefore, the number of slots consumed by the station is $k+1$. Considering again that power line counter k_1 is first reduced to zero, then the probability that the station occupies the power line channel first is

$$\frac{1}{CW_i}\frac{d_i}{CW_i}\frac{CW_i+1}{2CW_i}\sum_{k_1=0}^{d_i-1}\sum_{k_2=0}^{k_1}\sum_{j=0}^{k_2-1}P_j. \quad (35)$$

The number of slots consumed by the station is $k_1 + 1$.

According to this principle and from the above classification, the average number of time slots that the station spends in each backoff phase i is

$$bc_i = \sum_{j=1}^{10} k_{ji}\tau_{ji}. \quad (36)$$

k_{ji} represents the number of time slots spent in different situations, and τ_{ji} represents the transmission probability corresponding to each k_{ji}.

The station has a total of m backoff phases, and the MAC layer delay is defined as the average number of time slots that the station spends from competing channels to successfully transmitting data:

$$E[bc]=\sum_{i=1}^{m-1}p^{i-1}bc_i+p^{m-1}pbc_m+\ldots+p^{m-1}p^n bc_m. \quad (37)$$

Simplified:

$$E[bc]=\sum_{i=1}^{m-1}p^{i-1}bc_i+\frac{p^{m-1}}{1-p}bc_m. \quad (38)$$

VII. SIMULATION ANALYSIS

In this section, we evaluate the performance of the power line/wireless selective communication under different configurations and scenarios, compare the throughput and collision probability under different communication technologies, and analyze the performance of the system by configuring different CW_i, d_i.

We consider the following timing parameters and use the same time slot duration specified in the standard. In the initial stage of simulation analysis, T_c and T_s are calculated using the relevant parameters in wireless communication and power line communication. The T_s and T_c expressions for wireless communication are

TABLE 3. Simulation parameters.

Parameter	*Time(us)*
Slot σ	35.84
Priority slot PRS	35.84
Preamble P	110.48
CIFS	100
RIFS	140
Frame dutation D	2050
ACK	110.48
EIFS	2920.64

$$T_s = H + E[P] + SIFS + ACK + DIFS$$
$$T_c = H + E[P] + DIFS$$

The expressions of T_c and T_s in power line communication are as shown in (39) and (40). Through calculation, we find that although the wireless interface and the power line interface have different time slot parameters, and the expressions of T_s and T_c are different, the values of T_s and T_c of the two interfaces are very close, which has little effect on the simulation results. Therefore, we assume that the two standards use the same time slot parameters. On the other hand, it is also to simplify the analysis process and highlight the ideas of theoretical analysis.

In this paper, we use the slot parameters in power line communication uniformly. (as shown in Table 3) for research.

$$T_s = PRS0 + PRS1 + P + t_L + RIFS + ACK + CIFS. \quad (39)$$
$$T_c = EIFS. \quad (40)$$

Among them, *PRS0*, *PRS1*, *P*, *RIFS*, *CIFS*, and *ACK* respectively indicate the length of priority slots, the preamble, the response inter-frame space, the contention inter-frame space, and the acknowledgement frame.

When collision occurs, the station sets the virtual carrier sense (VCS) timer to *EIFS*, which is the extended inter-frame space used by 1901. After the *EIFS* time, the channel state is idle. Therefore, the duration of the collision $T_c = EIFS$. Finally, we assume that all packets use the same physical rate.

In the simulation environment we built, the nodes in the network are evenly distributed and have equal status. There is no concept of a central node, that is, the network is distributed. Data is transmitted from one node to another without going through the relay forwarding process. The various backoff phases of the nodes are independent of each other, ie the simulation is based on decoupling assumptions. At the same time, we stipulate that each node is saturated, that is, there is always data to be sent, and there is no idle state. The channel conditions are ideal, ie no noise interference, and the data frame transmission failure is only caused by the collision. The network has a stable data transfer rate.

In Figure 3, the throughput performance of different communication modes is evaluated. First, the consistency

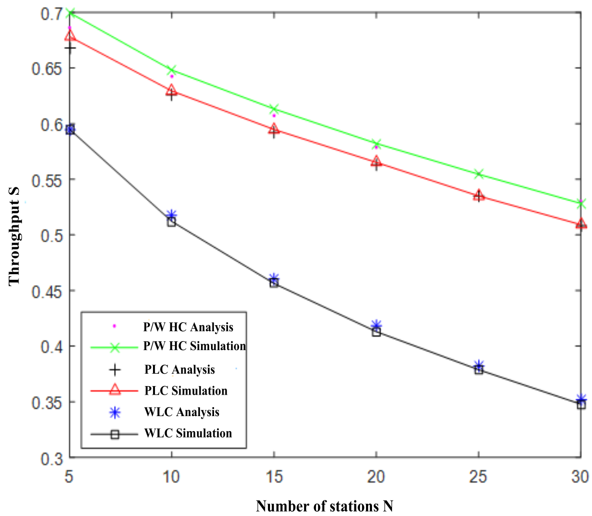


FIGURE 3. Normalized throughput under different communication technologies.

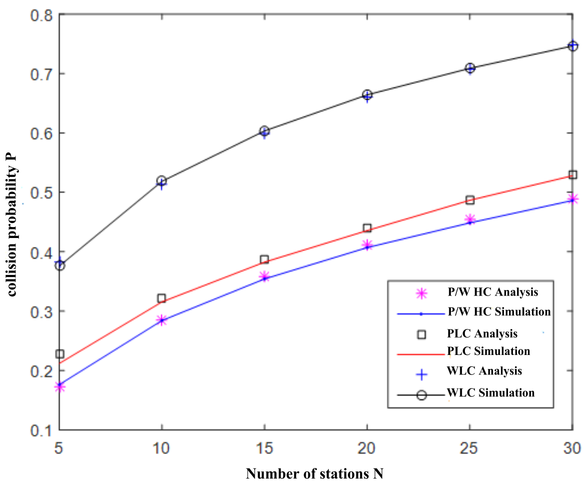


FIGURE 4. Curve of collision probability with the number of stations in different communication technologies.

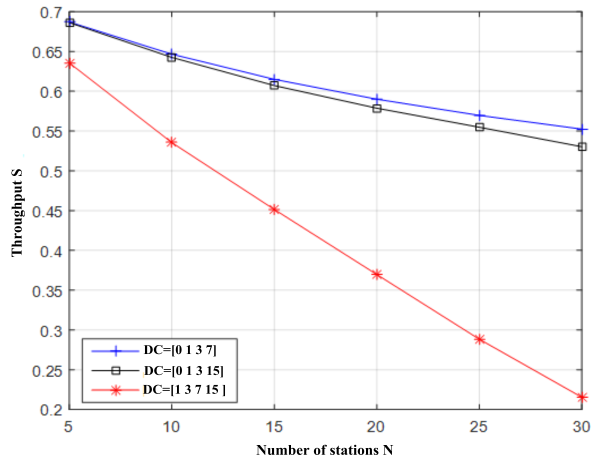


FIGURE 5. Effect of delay counter *DC* on throughput.

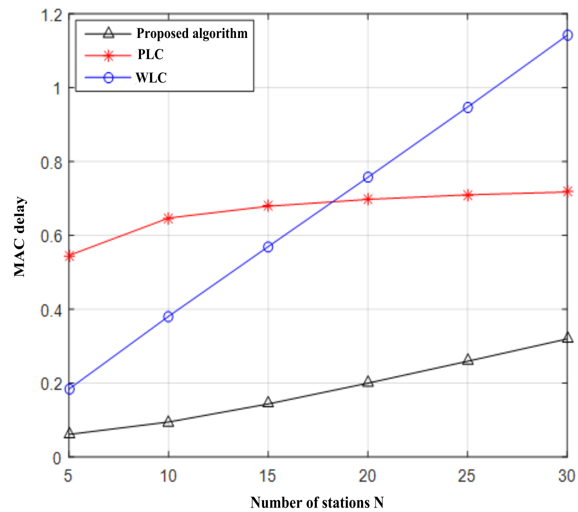


FIGURE 6. Comparison of delays under different communication technologies.

between the theoretical analysis and the simulation results is verified. Second, the figure shows that the throughput performance of the wireless/power line selective communication mode is better than that of the single communication mode because the probability of data transmission success in this mode is higher than that of the power line or wireless individual communication. Finally, the trend of the single curve shows that competition increases with the number of stations, resulting in a decrease in the network throughput.

Figure 4 analyzes the collision probability under different communication modes. The collision probability under the power line/wireless selective communication mode is the lowest. Given that the power line/wireless selective communication uses dual media, when the number of stations increases, different communication requirements can be allocated to the two channels. However, a single medium communication of power lines or wireless is more likely to cause congestion, and thus the probability of collision is large. Meanwhile, a single curve shows that competition increases with the number of stations, and the probability of collision increases.

In Figure 5, the effect on throughput is observed by defining the value of *DC* for different backoff phases (*i*). For different *DC* configurations, we set the minimum contention window to 8. First, as the number of stations increases, the throughput decreases. Second, when *DC* is increased, the probability that the station will directly enter the next backoff stage through the *DC* is reduced. In other words, the probability of network collision increases, resulting in a drop in throughput.

Figure 6 shows that the delay of power line/wireless selective communication is significantly low. Given that the power line/wireless selective communication uses two backoff counters, the station simultaneously detects two channels, and if the value of one of the counters is zero, then the station transmits data. Thus, the station takes less time from

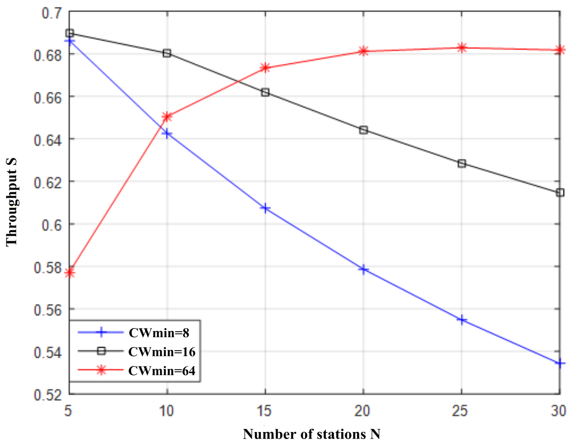


FIGURE 7. Effect of different CW_{min} on throughput.

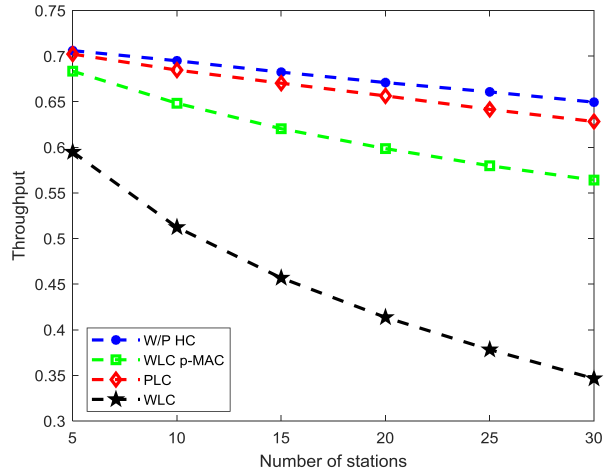


FIGURE 8. Comparison of network throughput under different communication technologies.

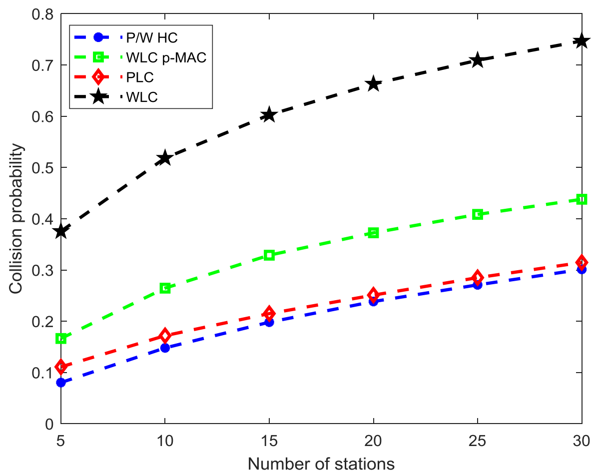


FIGURE 9. Comparison of network reliability under different communication technologies.

competing channels to transmitting data. In addition, when the number of stations is small, the delay of wireless communication is less than that of the PLC. This is because the wireless channel only has one counter, and at this time, the degree of competition in the network is low, enabling the wireless communication method to transmit data faster. As the number of stations increases, the network competition intensifies, and the role of the PLC's delay counter is gradually reflected. The delay counter allows the station to advance to the next backoff phase, avoiding collisions, reducing network latency, and increasing throughput. Therefore, when many stations exist, the power line delay is lower than that of the wireless, and the increase is gradual.

Figure 7 depicts the impact of the minimum contention window on system performance. CW_{min} represents the minimum contention window. When the value of CW_{min} is small, the competition increases with the number of stations, resulting in a decrease in throughput. Given that the backoff counters are randomly selected from $\{0, \ldots, CW_{min}\}$, the counter can take values in a larger range, and the probability of collision of the station is smaller when $CW_{min} = 16$ than when $CW_{min} = 8$. Therefore, the throughput is relatively large. When CW_{min} is increased to a relatively large value, such as $CW_{min} = 64$, the throughput curve begins to increase with the number of stations. This is because the throughput gain from joining a new station outweighs the adverse effects of increased competition. However, the probability of collisions increases with the number of stations, resulting in a relative balance between gain and attenuation, and the curve tends to be flat.

Figure 8 depicts throughput performance under different communication technologies. In order to reflect the impact of the minimum window value on system performance, the CW_{min} of the power line interface is changed to 16, the CW_{min} of the wireless interface is increased to 32, and the p-persistence mechanism is introduced in the wireless communication. From the results, the hybrid communication network has the highest throughput, followed by power line communication. Due to the increase of the minimum window value and the introduction of the p-persistence mechanism, the throughput of wireless communication has been greatly improved. This is because when the minimum window value increases, the probability of collision of data frames sent by the node under the same conditions is reduced, and the transmission success rate is greatly improved. At the same time, the p-persistence mechanism is introduced, that is, when the node can send data, it also needs to select, send it with p probability, or terminate the transmission with a probability of 1-p, continue to wait for a time slot, select again, until the data is sent. As such, the likelihood of collisions within the network is further reduced and throughput is improved.

Figure 9 depicts the reliability performance under different communication technologies and the impact of changes in minimum window values on network reliability is studied. The adjustment of the power line and the wireless minimum window is the same as the simulation shown in Figure 8. Wireless communication introduces a p-persistence mechanism. From the results, the hybrid communication network has the lowest collision probability and the highest reliability. Power line communication is more reliable than wireless communication due to the presence of a delay counter. Because the $CW_{\min}$ of wireless communication is adjusted and the p-persistence mechanism is introduced, the reliability is greatly improved compared with the previous one. At the same time, through horizontal comparison, it can be found that as the number of stations increases, the competition of nodes in each communication system network is intensified, resulting in an increase in collision probability and a decrease in reliability.

VIII. CONCLUSIONS

Although the IEEE 1901 protocol is now adopted by most PLC devices and wireless communication applications are common, power line-wireless cooperative communication research is rarely involved. In this paper, we focus on the performance analysis of the power line-wireless cooperative communication CSMA/CA protocol. The theoretical analysis is based on the decoupling hypothesis between the stations, the theory is verified by MATLAB simulation, and the performance of the proposed system model is evaluated. The results indicate that the performance of collaborative communication is generally better than single media communication, and the performance of throughput can be further improved by configuring optimal parameters. However, the system model proposed in this paper is based on the decoupling hypothesis. In practice, stations are mostly coupled, which is also a consideration for the future research based on MAC layer collaborative communication.

APPENDIX

When k_1 and k_2 have the same value range, the following probability relationships exist:

$$1)\ \mathrm{P}(k_1 = k_2) = 1 - \frac{\binom{CW_i}{1}\binom{CW_i - 1}{1}}{\binom{CW_i}{1}\binom{CW_i}{1}} = 1 - \frac{CW_i - 1}{CW_i} = \frac{1}{CW_i}.$$

$$2)\ \mathrm{P}(k_1 \geq k_2) = \frac{\frac{1}{CW_i}\sum_{J=0}^{CW_i-1}\binom{CW_i}{1}\binom{CW_i - j}{1}}{\binom{CW_i}{1}\binom{CW_i}{1}} = \frac{\frac{1}{CW_i}\left(CW_i + CW_i - 1 + \ldots + 1\right)}{CW_i}. = \frac{\frac{1}{CW_i}\frac{CW_i(CW_i+1)}{2}}{CW_i} = \frac{CW_i + 1}{2CW_i}.$$

$$3)\ \mathrm{P}(k_1 \leq k_2) = \frac{\frac{1}{CW_i}\sum_{J=0}^{CW_i-1}\binom{CW_i}{1}\binom{j+1}{1}}{\binom{CW_i}{1}\binom{CW_i}{1}} = \frac{\frac{1}{CW_i}\left(1 + 2 + \ldots + CW_i\right)}{CW_i} = \frac{\frac{1}{CW_i}\frac{CW_i(CW_i+1)}{2}}{CW_i} = \frac{CW_i + 1}{2CW_i}.$$

$$4)\ \mathrm{P}(k_1 < k_2) = \mathrm{P}(k_1 \leq k_2) - \mathrm{P}(k_1 = k_2) = \frac{CW_i + 1}{2CW_i} - \frac{1}{CW_i} = \frac{CW_i - 1}{2CW_i}.$$

$$5)\ \mathrm{P}(k_1 > k_2) = \mathrm{P}(k_1 \geq k_2) - \mathrm{P}(k_1 = k_2) = \frac{CW_i + 1}{2CW_i} - \frac{1}{CW_i} = \frac{CW_i - 1}{2CW_i}.$$

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