IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 11, 2020, accepted January 31, 2021, date of publication February 12, 2021, date of current version February 24, 2021.

*Digital Object Identifier 10.1109/ACCESS.2021.3059246*

# A Cross-Layered Theoretical Model of IEEE 1901 Power-Line Communication Networks Considering Retransmission Protocols

**SHENG HAO** [1] **AND HU YIN ZHANG** [2]
[1]School of Computer Science, Central China Normal University, Wuhan 430079, China
[2]School of Computer Science, Wuhan University, Wuhan 430079, China

Corresponding author: Hu Yin Zhang (2008301500139@whu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61772386, and in part by the National Key Research and Development Project under Grant 2018YFB1305001.

**ABSTRACT** Power-line communication (PLC) is a promising communication technology of constructing IoT (internet of things) systems, and it employs IEEE 1901 as its medium access control (MAC) protocol. Current studies about IEEE 1901 MAC performance analysis do not consider the influence of physical layer's retransmission protocols, i.e., ARQ (automatic repeat request) and HARQ-CC (hybrid ARQ with chase combining). Moreover, how 1901 protocol affect the energy consumption in PLC networks, and whether 1901 protocol has bound performance are also unsolved in these existing works. Focusing on the above problems, we put forward a cross-layered theoretical model to insightfully analyze 1901 protocol, where the impacts of physical layer's retransmission protocols (ARQ and HARQ-CC), channel fading modes and practical configurations (buffer size, finite traffic load, etc.) are comprehensively taken into consideration in the modeling process. On this basis, we derive the closed-form expressions of 1901 MAC metrics considering retransmission protocols. Furthermore, we construct an energy consumption model, and provide the bound performance analysis for 1901 protocol. Finally, we evaluate the performance of 1901 protocol under different retransmission protocols and system parameters, and verify the proposed cross-layered theoretical model.

**INDEX TERMS** Power-line communication (PLC), retransmission protocols, medium access control, IEEE 1901, cross-layered theoretical model, performance evaluation.

## I. INTRODUCTION

PLC (Power-line communication) network provides an attractive communication medium for home access networks and industrial IoT (internet of things) due to its low cost installations and broad coverage feature [1]–[4]. It also finds applications in diverse domains such as realtime energy management systems, future hybrid networks and cooperative communication systems [5]–[9]. The MAC (medium access control) protocol of PLC networks, IEEE 1901, uses a special CSMA/CA (carrier sense multiple access with collision avoidance) mechanism, having some similarities to that of IEEE 802.11, and it plays a prominent role in the network performance [10]–[13]. The main difference between these two CSMA/CA mechanisms is that the 1901 protocol employs not only a backoff counter but also a so called deferral counter, which provides a novel approach to contention resolution, namely, 1901 can react to contention when it senses the medium busy during a certain number of time slots (determined by its deferral counter), while 802.11 only reacts to contention after detecting a collision [10]. As a consequence, compared with 802.11 protocol, 1901 has larger state space and more complicated state transition.

The associate editor coordinating the review of this manuscript and approving it for publication was Akshay Kumar Saha.

### A. DRAWBACKS AND MOTIVATION

Currently, some valuable studies have paid attention to performance analysis of 1901 protocol for PLC networks [14]–[22]. However, all these works [14]–[22] do not consider the impact of physical layer's retransmission protocols [23]–[30] on 1901's MAC performance. Furthermore, how IEEE 1901 protocol affect the energy consumption in PLC networks, and whether 1901 protocol has bound performance are also neglected in the above works. Therefore, it's still challenging to propose an insightful theoretical framework, which can investigate the MAC performance of IEEE 1901 PLC networks under the influence of retransmission protocols, evaluate the energy consumption and analyze the bound performance of 1901 protocol.

From the viewpoint of engineering application, PLC networks can utilize the entire available bandwidth (1.8–80 MHz). The recent standard of PLC technology can guarantee a high performance communication mechanism by providing data rates of more than 1.5 Gbps [9], [12]. Until now, PLC networks have achieved great commercial success. Based on HomePlug alliance's statistic result, more than 200 million PLC-based devices have been used worldwide. Dozens of companies begin to develop and design embedded PLC-based devices and smart chips (following the standard of IEEE 1901 protocol) [12]. Current PLC-based applications related to IoT (internet of things) have been associated with Smart Grid/Home/Meter [31]–[33], Underground power transmission [34], Intelligent Mining [35], in-vehicle communication [36], photovoltaic system [37], hybrid intelligence communication [7], [38] and Industry 4.0 [39]. As a consequence, thoroughly analyzing IEEE 1901 PLC networks is valuable for practical IoT system construction.

### B. TASKS AND CONTRIBUTIONS

The main objective of the paper is to analyze the MAC performance of 1901 considering retransmission protocols, examine the energy consumption due to 1901 protocol, and make a bound performance analysis for 1901. The core contributions of the paper are:

- We propose a cross-layered theoretical model for IEEE 1901 protocol considering the impact of retransmission protocols. To establish this model, a two-dimension Markov chain (T-D MC) is employed to depict the CSMA/CA mechanism of IEEE 1901. Besides considering the impacts of practical environment configurations (e.g., buffer size, finite traffic load, and deferral counter process (DCP) of 1901), we emphatically analyze the impacts of physical layer's retransmission protocols (ARQ and HARQ-CC) and detailed channel fading modes (containing Rayleigh fading and Nakagami-$u$ fading) on 1901 MAC performance. On the basis, we derive the closed-form expressions of typical MAC metrics of 1901 (containing system throughput, MAC service time, packet drop probability, packet blocking probability and etc) under the influence of retransmission protocols. To the best of our knowledge, this should be the first cross-layered theoretical framework, which can reflect the impact of physical layer's retransmission protocols on IEEE 1901.
- We put forward an energy consumption model to evaluate the consumed power of transmitting one successful bit in IEEE 1901 PLC networks.
- We examine the bound performance of two 1901 MAC metrics (system throughput and successful transmission probability). Through using differential method, we reveal that the bounds of these two MAC metrics depend significantly on the network size.
- We conduct extensive simulation experiments to verify the proposed cross-layered theoretical model, and draw key insights into the MAC performance of 1901 under different retransmission protocols and system parameters.

### C. PAPER OUTLINE

The remainder of our paper is organized as follows. A brief overview of IEEE 1901 and retransmission protocols (containing ARQ and HARQ-CC) is presented in Section 2. Related works are reviewed in Section 3. The system model is proposed in Section 4. We verify our cross-layered theoretical model via simulations in Section 5. Finally, conclusions are summarized in Section 6.

## II. OVERVIEW OF IEEE 1901 AND RETRANSMISSION PROTOCOLS

### A. IEEE 1901 PROTOCOL

The CSMA/CA mechanism of 1901 protocol employs two counters: a backoff counter and a deferral counter. The backoff counter process (BCP) of 1901 is similar to that of 802.11. When the station has a new packet to transmit, the backoff stage $k$ is initialized to 1 and a random backoff counter is uniformly selected among $[1, \ldots, W_1]$, where $W_1$ represents the maximum backoff counter used at backoff stage 1. If the station senses the medium to be idle, the backoff counter is decreased by 1 at each slot time, and it is frozen when the medium is sensed busy. In case the medium is sensed busy, the value of the backoff counter is also decreased by 1 once the medium is sensed idle again [15]. When the value of the backoff counter is decreased to 1, the station attempts to transmit the packet. If suffering a collision, the station jumps to the next backoff stage (backoff stage 2) and repeats the same process as backoff stage 1. When the station is already at the last backoff stage $m$ and the transmission attempt suffers a collision, it re-enters the last backoff stage.

**TABLE 1.** The maximum backoff counter $W_k$ and the value of $d_k$ for 1901 protocol.

| $Priority\ class$: | $CA0$ | $CA1$ | $CA2$ | $CA3$ |
|---|---|---|---|---|
| backoff stage $k$ | $W_k$ | $d_k$ | $W_k$ | $d_k$ |
| 1 | 8 | 0 | 8 | 0 |
| 2 | 16 | 1 | 16 | 1 |
| 3 | 32 | 3 | 16 | 3 |
| 4 | 64 | 15 | 32 | 15 |

The standard 1901 has four priority classes ($CA0 - CA3$), and two priority classes ($CA0/CA1$ or $CA2/CA3$) constitute a priority type [20]. In addition, it has only four backoff stages (i.e., $m = 4$), and the value of maximum backoff counter $W_k$ at stage $k$ depends on its corresponding priority class (shown in Table 1).

Different from 802.11, the additional deferral counter of 1901 allows a station in PLC networks to enter the next

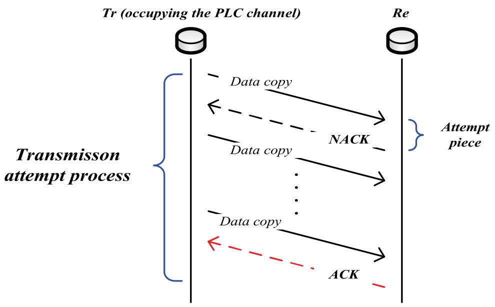


**FIGURE 1.** A successful transmission attempt process (*Tr* denotes the transmitter, *Re* the receiver).

backoff stage even if it does not attempt a transmission. When the station enters backoff stage $k$, the initial value of the deferral counter is set to $d_k + 1$ (the value of $d_k$ is given in Table 1). After sensing that the medium is busy, the station decreases $d_k+1$ by 1 (in addition to executing the BCP). If the medium is sensed busy and the value of the deferral counter is 1 (i.e., sensing the medium busy $d_k+1$ times), and it re-draws the backoff counter without attempting a transmission (if the station is already at the last backoff stage, it re-enters this stage) [20].

### B. RETRANSMISSION PROTOCOLS: ARQ AND HARQ-CC

In practical network scenario, when the station occupies the PLC channel (through 1901's CSMA/CA mechanism) and attempts to transmit its packet, it begins to execute retransmission protocols[1] [23]–[30],[40]–[42]. In the basic ARQ, for decoding, the receiver uses the packet received in the current attempt fragment only, and discards all the erroneously received copies of this packet. In HARQ-CC, the receiver tries to decode the packet received in the current attempt fragment by maximal ratio combining (MRC) it with all the previously received copies of the same packet. In other words, for basic ARQ, we say that the packet is received in outage, if the signal-to-noise ratio (*SNR*) of the packet received in an attempt fragment is less than the minimum *SNR* required for successful decoding (i.e., threshold *SNR*). For HARQ-CC, the packet remains in outage if the accumulated *SNR* (from the first attempt fragment to current attempt fragment) is less than the minimum *SNR* required for successful decoding. For every transmission attempt process, a data packet can be transmitted at most $M$ times (i.e., one transmission attempt process contains no more than $M$ attempt fragments). After each attempt fragment, the transmitter receives an acknowledgment (ACK) if the packet is successfully delivered, or else a negative ACK (NACK). If the packet is not successfully delivered by the deadline, it would be dropped (Fig.1 shows a successful transmission attempt process under the influence of retransmission protocols).

[1]Physical layer's retransmission protocols are used not only for PLC networks, but also for wireless networks following NDMA MAC standard [40]–[42].

## III. RELATED WORK

Up to now, several meaningful works have been proposed to analyze IEEE 1901 protocol.[2] In [14], a semi-Markov based analytical model was established to depict the CSMA/CA mechanism of 1901 protocol in saturated conditions. Vlachou *et al.* designed a series of Renewal theory based analytical models for IEEE 1901 protocol under saturated conditions [15]–[19]. These studies can be summarized as four parts: (1) Constructing the basic analytical model and proving the model admits a unique solution [14], [15]; (2) Examining the performance tradeoff between delay and throughput [17]; (3) Further optimizing 1901 MAC performance on the basic model [18]; (4) Analyzing the performance and stability of 1901 protocol under the coupling condition [19]. Cano *et al.* put forward a theoretical model of IEEE 1901 protocol for saturated PLC networks using renewal process theorem. In [21], Hao *et al.* provided a unified 1901 protocol analysis framework in unsaturated, single-hop environment. Then they continued to construct a theoretical model of 1901 protocol for multi-hop PLC networks [22]. As mentioned previously, these studies do not consider the impact of physical layer's retransmission protocols on MAC performance of 1901, and how to evaluate the energy consumption caused by 1901 protocol. Moreover, they do not make a bound performance analysis for 1901 protocol.

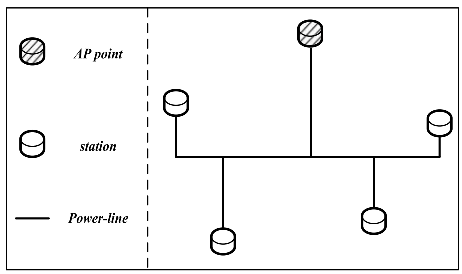


**FIGURE 2.** A simple case of converged PLC network, where stations transmit their packets to the AP.

## IV. SYSTEM MODEL

In this part, we construct the cross-layered theoretical model of IEEE 1901 protocol (the notation of essential results is given in Table 2). The PLC network adopts a converged topology, in which stations delivery their packets to the access point (AP) (shown in Fig.2). The detailed modeling process contains four steps: (1) Establishing the base model to describe the CSMA/CA mechanism of 1901 protocol considering the impact of physical layer's retransmission protocols; (2) Deriving the closed-form expressions of typical MAC metrics under the influence of retransmission protocols; (3) Analyzing the energy consumption of transmitting a successful bit in IEEE 1901 PLC networks; (4) Making the bound performance analysis for 1901.

The cross-layered theoretical model is constructed under the following assumptions:

[2]We only introduce the related works focusing on IEEE 1901 protocol analysis, the studies about 1901 protocol modification are not discussed here.

**TABLE 2.** Notation list relevant to the results derived by the cross-layered theoretical model.

| $Notation$ | $Definition$ |
|---|---|
| $N$ | Number of stations |
| $M$ | Number of attempt fragments |
| $X$ | Transmission distance |
| $X_{k,r}$ | A station at backoff stage $k$ selects the backoff counter $r$ ($W_k \geq r \geq d_k + 1$) and senses the medium busy no more than $d_k$ times |
| $Y_k$ | A station at backoff stage $k$ triggers the DCP |
| $p$ | Conditional collision probability of the station |
| $\tau$ | Probability that a station attempts to transmit its HOL packet in a slot time |
| $p_{tr}$ | Probability that at least one station attempts to transmit its HOL in a slot time |
| $p_{idle}$ | Probability that the medium is idle |
| $N_0$ | Average noise power of white Gaussian noise $\mathcal{N}(0, N_0)$ |
| $\eta$ | Threshold value of $SNR$ |
| $f_{\Xi}(\zeta)\vert\Xi \in [RF, NF]$ | Probability density function of channel gain $\zeta$ under Rayleigh fading (or Nakagami-$u$ fading) channel |
| $F_{\Xi}(\Omega)\vert\Xi \in [RF, NF]$ | Cumulative distribution function of power gain $\Omega$ under Rayleigh fading (or Nakagami-$u$ fading) channel |
| $Pw_t/Pw_r/Pw_o$ | Transmission/receiving/overhearing power |
| $P^{ARQ}_{out,x}$ ($P^{ARQ}_{out}$) | Probability that the $SNR$ of the $x$th attempt fragment is less than $\eta$ when using ARQ protocol |
| $P^{HARQ}_{out,1\to x}$ | Probability that the accumulated $SNR$ up to the $x$th attempt fragment is still less than $\eta$ when using HARQ-CC protocol |
| $p^{\kappa}_s(x)$ | Probability that a successful transmission using $x$ attempt fragements |
| $PDP^{\kappa}$ | Packet dropping probability during transmission attempt process |
| $P_{suc}$ | Successful transmission probability |
| $T_s(x)$ | Time duration that a successful transmission using $x$ attempt fragements |
| $T_c$ | Time duration that the medium is busy due to the collision |
| $T_{drop}$ | Time duration of "dropping packet" |
| $E_{slot}$ | Average size of slot time |
| $S$ | System throughput |
| $\nu$ | Probability that no packet arrives the buffer during a virtual slot time |
| $Ar_a$ | Probability that $a$ packets arrive to the station buffer during the medium service time |
| $\mu_a$ | Probability that there are $a$ packets in the buffer upon a departure |
| $P_a$ | Steady state probability of $a$ packets in the buffer |
| $E[T_{mac}]$ | Average medium service time |
| $E[Q]$ | Average queue length |
| $P_b$ | Packet blocking probability |
| $T_{busy}$ | Total time duration where energy is spent by transmitting, receiving or dropping data packet |
| $EBP$ | Expected total energy cost of transmitting one successful bit |

- Each station has finite buffer size (denoted by $K$), and packets would be rejected because of overflow of the station buffer (denoted by packet blocking probability $P_b$).
- Station attempts to transmit its HOL (head of line) packet with a constant transmission probability $\tau$, and it collides with an independent probability $p$.
- All stations are in the same carrier sensing region, where hidden terminal and exposed terminal problems do not happen. Furthermore, Each station receives packets from the upper layer based on Poisson process with an average arrival rate $\lambda$.
- The PLC channel fading mode follows a typical distribution (Rayleigh or Nakagami-$u$ fading) without considering the interference. The average noise power of white Gaussian noise $\mathcal{N}(0, N_0)$ is $N_0$.

### A. BASE MODEL: CSMA/CA MECHANISM OF 1901 CONSIDERING RETRANSMISSION PROTOCOLS

According to the standard of 1901 protocol, a station at backoff stage $k$ jumps to the next backoff stage $k+1$ by two approaches: (1) attempting an unsuccessful transmission due to collision or (2) sensing the medium busy $(d_k + 1)$ times. Let $r$ be the selected backoff counter at stage $k$, if $r < d_k + 1$ or $r \geq d_k + 1$ and the station senses the medium is busy no more than $d_k$ times, it uses the first approach to jump to the next stage. Otherwise, it adopts the DCP to enter the next backoff stage.

Let $\frac{X_{k,r}}{W_k}$ denotes the probability that a station chooses an initial backoff counter $r$ ($W_k \geq r \geq d_k + 1$) and senses the medium busy no more than $d_k$ times, and $\frac{Y_k}{W_k}$ the probability that a station triggers the DCP at backoff stage $k$. We can express $X_{k,r}$ and $Y_k$ as follows:

$$\begin{cases} X_{k,r} = \sum_{h=0}^{d_k} C_r^h \cdot p^h (1-p)^{r-h};\ r \in [d_k + 1, W_k] \\ Y_k = \sum_{r=d_k+1}^{W_k} (1 - X_{k,r}) \end{cases} \tag{1}$$

Now we can provide the structure of T-D MC for IEEE 1901 protocol (shown in Fig.2). Considering the impacts of buffer size and traffic load, BCP and DCP cannot be triggered when there is no packet in the station buffer. For this purpose, we introduce **E** ($E$) to represent the empty state of the station buffer. The non-empty state is divided into two categories: (1) **BCP** ($d_{k,r}$; $r \in [1, W_k]$) and (2) **DCP** ($d_{k,j}$; $j \in [1, d_k + 1]$). $E$, $b_{k,r}$ and $d_{k,j}$ denote the steady probabilities of the Markov chain, respectively. In addition, we define $F_k$ ($k \in [1, m]$) as the probability that a station jumps from the transient state [43], [44] that it prepares a new HOL packet and begins to execute the CSMA/CA mechanism of 1901 to the backoff stage $k$, and $F_k$ is written as (the detailed derivation process is given in **Appendix A**)

$$\begin{cases} F_1 = 1; \quad k = 1 \\ F_k = \prod_{h=1}^{k-1} (p + \frac{(1-p)Y_h}{W_h}); \quad k \in [2, m-1] \\ F_m = \frac{(p + \frac{(1-p)Y_{m-1}}{W_{m-1}})}{1 - (p + \frac{(1-p)Y_m}{W_m})} \cdot F_{m-1}; \quad k = m \end{cases} \tag{2}$$

We further let $\mu_0$ be the stationary probability that the buffer of station is empty upon a departure, $\nu$ be the transition

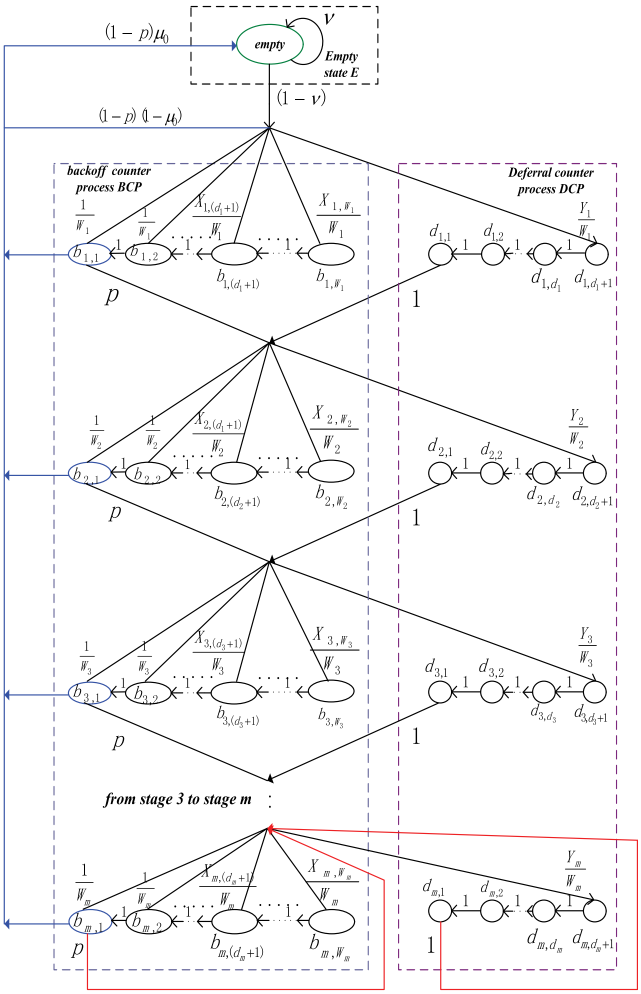


**FIGURE 3.** T-D MC for IEEE 1901 protocol.

probability that no packet arrives at station's buffer during a slot time, thus, based on the above derivation, the transmission attempt probability $\tau$ for a station can be expressed as (see the bottom of the page, the detailed derivation process is given in **Appendix B**)

Hence, the probability that a station fails to transmit its HOL packet due to a collision, i.e., the conditional collision probability $p$ is given by

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

The probability $p_{tr}$ that at least one station tries to accomplish a transmission, and the probability $p_{idle}$ that the medium is sensed to be idle can be expressed respectively as:

$$p_{tr} = 1 - (1-\tau)^N \tag{5}$$

$$p_{idle} = 1 - p_{tr} = (1-\tau)^N \tag{6}$$

Since physical layer's retransmission protocols are considered in our work, the calculation of successful transmission probability $P_{suc}$, system throughput $S$, expected MAC service time $E[T_{mac}]$ and etc would be different from previous works [14]–[22]. We have assumed PLC channel to be Rayleigh fading or Nakagami-$u$ fading, the corresponding PDF (Probability Density Function) $f_{\Xi}(.)|\Xi \in (RF, NF)$[3] of channel gain $\zeta$ can be expressed respectively as:

**For** Rayleigh fading (RF) channel mode

$$f_{RF}(\zeta) = \frac{\zeta}{\sigma_R^2} \cdot exp(-\frac{\zeta^2}{2\sigma_R^2}) \tag{7}$$

**For** Nakagami-$u$ fading (NF) channel mode

$$f_{NF}(\zeta) = \frac{2u^u}{\Gamma(u)} \cdot \zeta^{2u-1} \cdot exp(-u \cdot \zeta^2) \tag{8}$$

where $\sigma_R^2$ represents the scale parameter of Rayleigh distribution, $u$ the Nakagami factor and $\Gamma(.)$ the gamma function, respectively.

Accordingly, the CDF (Cumulative Distribution Function) $F_{\Xi}(.)|\Xi \in (RF, NF)$ of power gain $\Omega$ (note that $\Omega = \zeta^2$)[4] under Rayleigh/Nakagami-$u$ fading mode can be derived as[5]:

$$F_{RF}(\Omega) = 1 - exp(-\frac{\zeta^2}{2\sigma_R^2}) = 1 - exp(-\frac{\Omega}{2\sigma_R^2}) \tag{9}$$

$$\begin{aligned} F_{NF}(\Omega) &= 1 - exp(-u\zeta^2)\sum_{j=1}^{u-1}\frac{(u\zeta^2)^j}{j!} \\ &= \frac{\gamma(u, u\zeta^2)}{\Gamma(u)} = \frac{\gamma(u, u\Omega)}{\Gamma(u)} \end{aligned} \tag{10}$$

where $\gamma(.)$ denotes the lower incomplete gamma function.

Let $Pw_t$ be the transmission power of each attempt fragment, $N_0$ the average noise power of white Gaussian noise

[3] $RF$ denotes the Rayleigh fading, and $NF$ the Nakagami-$u$ fading.

[4] The relationship between channel gain and power gain has been verified in many existing literatures, e.g., [23]–[26].

[5] The detailed derivation process from $f_{\Xi}(\zeta)$ to $F_{\Xi}(\Omega)$ is shown in [45].

$$\begin{aligned} \tau &= \frac{\sum_{k=1}^{m} b_{k,1}}{\sum_{k=1}^{m}(\sum_{g=1}^{W_k} b_{k,g} + \sum_{j=1}^{d_k+1} d_{k,j}) + E} = \frac{A}{B} \quad where: \\ A &= \sum_{k=1}^{m}[\frac{F_k \cdot d_k}{W_k} + \frac{F_k}{W_k}\sum_{r=d_k+1}^{W_k} X_{k,r}]; \\ B &= \sum_{k=1}^{m}[(d_k+1)\frac{Y_k \cdot F_k}{W_k} + \frac{F_k}{W_k}\sum_{r=d_k+1}^{W_k}(r-d_k)X_{k,r} + (\frac{d_k F_k}{W_k}\sum_{r=d_k+1}^{W_k} X_{k,r} + \frac{F_k}{W_k}\frac{d_k(d_k+1)}{2})] + \frac{\mu_0}{1-\nu} \end{aligned} \tag{3}$$

$\mathcal{N}(0, N_0)$, $X$ the transmission distance, $\alpha$ the path loss exponent and $\eta$ the threshold $SNR$ (i.e., the required minimum $SNR$). If using ARQ protocol at the physical layer, we can write the probability $P^{ARQ}_{out,x}$ that the $x$th attempt fragment fails (from physical layer's perspective) as[6]

$$\begin{aligned} &P^{ARQ}_{out,x} \\ &= prb\{SNR \le \eta | x \in [1, M]\} \\ &= prb\{\frac{Pw_t \cdot \Omega \cdot X^{-\alpha}}{N_0} \le \eta\} \\ &\overset{a}{=} prb\{\Omega \le \frac{\eta \cdot N_0}{Pw_t \cdot X^{-\alpha}}\} \\ &\overset{b}{=} \begin{cases} F_{RF}(\frac{\eta \cdot N_0}{Pw_t \cdot X^{-\alpha}}) = 1 - exp[-\frac{\eta \cdot N_0}{Pw_t \cdot X^{-\alpha}}] | RF \\ F_{NF}(\frac{\eta \cdot N_0}{Pw_t \cdot X^{-\alpha}}) = \gamma(u, u\frac{\eta \cdot N_0}{Pw_t \cdot X^{-\alpha}})/\Gamma(u) | NF \end{cases} \end{aligned} \tag{11}$$

*Remark 1:* Since $x$ cannot affect the value of $P^{ARQ}_{out,x}$ (proved by Eq.11), in the following analysis process, we use $P^{ARQ}_{out}$ as the simplified form to replace $P^{ARQ}_{out,x}$. In addition, $Pw_t$ is generally expanded as $Pw_t = C_1 + C_2 \cdot X^{-\alpha}$, where $C_1$ and $C_2$ are two constants.

While using HARQ-CC protocol at the physical layer, we say the packet remains in outage if the accumulated $SNR$, up to and including the $SNR$ of the packet received in the $x$th round (i.e., from the 1st attempt fragment to current attempt fragment) is less than $\eta$. Therefore, the probability that transmission attempt fails until the $x$th attempt fragment $P^{HARQ}_{out,1\to x}$ (from physical layer's perspective) can be given by

$$\begin{aligned} &P^{HARQ}_{out,1\to x} \\ &= prb\{\sum_{\varepsilon=1}^{x} SNR \le \eta | x \in [1, M]\} \\ &= prb\{\frac{\sum_{\varepsilon=1}^{x} Pw_t \cdot \Omega \cdot X^{-\alpha}}{N_0} \le \eta\} \\ &\overset{a}{=} prb\{\Omega \le \frac{\eta \cdot N_0}{x \cdot Pw_t \cdot X^{-\alpha}}\} \\ &\overset{b}{=} \begin{cases} F_{RF}(\frac{\eta \cdot N_0}{x \cdot Pw_t \cdot X^{-\alpha}}) = 1 - exp[-\frac{\eta \cdot N_0}{x \cdot Pw_t \cdot X^{-\alpha}}] | RF \\ F_{NF}(\frac{\eta \cdot N_0}{x \cdot Pw_t \cdot X^{-\alpha}}) = \gamma(u, u\frac{\eta \cdot N_0}{x \cdot Pw_t \cdot X^{-\alpha}})/\Gamma(u) | NF \end{cases} \end{aligned} \tag{12}$$

When a station successfully occupies the channel (through the CSMA/CA mechanism of 1901), and begins to transmit its HOL packet, it initializes the retransmission protocol (ARQ or HARQ-CC). Thus, the probability $p^{\kappa}_s(x)$ ($\kappa \in \{ARQ, HARQ\}$) that a successful transmission using $x | x \in [1, M]$ attempt fragments can be given by

$$p^{ARQ}_s(x) = \binom{N}{1}\tau(1-p)\underbrace{[P^{ARQ}_{out}]^{(x-1)}}_{a1}\underbrace{(1-P^{ARQ}_{out})}_{a2} \tag{13}$$

$$p^{HARQ}_s(x) = \binom{N}{1}\tau(1-p)\underbrace{P^{HARQ}_{out,1\to x-1}}_{b1}\underbrace{(1-P^{HARQ}_{out,1\to x})}_{b2}{}^{7} \tag{14}$$

[6] $prb\{\chi\}$ represents the probability case $\chi$ happens.

*Remark 2:* In Eqs.13-14, part "a1" denotes the case that the transmission attempt process from the 1st time to the $x$th time are all failed (i.e., the SNR of each attempt fragment is less than $\eta$ in previous $x-1$ times), part "a2" the $x$th attempt successes (i.e., the SNR of the $x$th attempt fragment is larger than $\eta$); Part "b1" the case that accumulated $SNR$ from the 1st attempt fragment to the $(x-1)$th attempt fragment is less than $\eta$ (i.e., the packet remains in outage up to the $x-1$the attempt fragment), "b2" the case that accumulated $SNR$ from the 1st attempt fragment to the $x$the attempt fragment is larger than $\eta$. Operator $\binom{N}{1}\tau(1-p)$ denotes there is one station that successfully occupies the channel through executing the CSMA/CA mechanism of 1901.

The successful transmission probability $P^{\kappa}_{suc}$ ($\kappa \in \{ARQ, HARQ\}$) can be accordingly denoted as

$$P^{\kappa}_{suc} = \sum_{x=1}^{M} p^{\kappa}_s(x) \tag{15}$$

A packet is dropped if all attempt fragments fail, therefore, the packet drop probability (caused by retransmission protocols) during one transmission attempt process $PDP^{\kappa}$ ($\kappa \in \{ARQ, HARQ\}$) can be written as:

$$\begin{aligned} PDP^{ARQ} &= \binom{N}{1}\tau \cdot (1-p) - \sum_{x=1}^{M} p^{ARQ}_s(x) \\ &= \binom{N}{1}\tau \cdot (1-p) \cdot [P^{ARQ}_{out}]^M \end{aligned} \tag{16}$$

$$\begin{aligned} PDP^{HARQ} &= \binom{N}{1}\tau \cdot (1-p) - \sum_{x=1}^{M} p^{HARQ}_s(x) \\ &= \binom{N}{1}\tau \cdot (1-p) \cdot P^{HARQ}_{out,1\to M} \end{aligned} \tag{17}$$

If the packet fails to be delivered in an attempt fragment, the receiver replies a NACK frame, else (successfully delivered in an attempt fragment), the receiver replies an ACK frame (the time sequence is shown in Fig.4). Thus, the time duration of a successful transmission $T_s(x)$ can be given by

$$\begin{aligned} T_s(x) = 2PRS + (x-1) \cdot (D + RIFS + NACK) \\ + D + RIFS + ACK + CIFS \quad | x \in [1, M] \end{aligned} \tag{18}$$

where $PRS$, $D$, $RIFS$, $CIFS$, $ACK$ and $NACK$ represent the priority tone slot, duration of data packet, response inter-frame space, contention inter-frame space, acknowledgment frame and negative acknowledgment frame, respectively (defined by the time sequence of IEEE 1901 standard [10]).

The time duration that the packet is dropped $T_{dp}$, and the time duration that medium is sensed busy due to the collision $T_c$ can be respectively expressed as ($EIFS$ is the extended inter-frame space):

$$T_{dp} = 2PRS + M \cdot (D + RIFS + NACK) + CIFS \tag{19}$$

$$T_c = EIFS \tag{20}$$

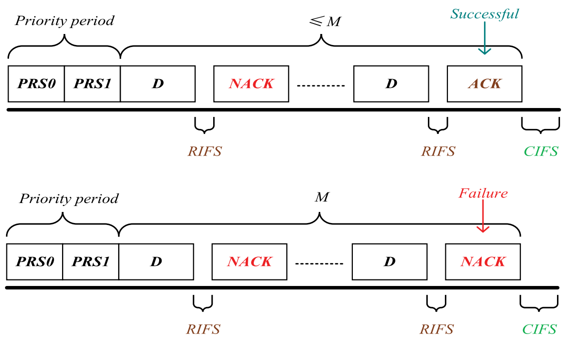


**FIGURE 4.** **The time sequence of 1901 considering retransmission protocols.**

Accordingly, the average size of slot time $E[slot]$ can be written as

$$E[slot] = \sigma \cdot p_{idle} + \sum_{x=1}^{M} T_s(x) \cdot p_s^{\kappa}(x) + T_c \cdot [p_{tr} - (\sum_{x=1}^{M} p_s^{\kappa}(x) + PDP^{\kappa})] + T_{dp} \cdot PDP^{\kappa} \tag{21}$$

where $\sigma$ is the duration of the idle slot time.

Now, the system throughput $S$ for IEEE 1901 PLC networks considering retransmission protocols can be given by

$$S = \frac{E[payload \quad transmitted \quad in \quad a \quad slot \quad time]}{E[slot]} = \frac{\sum_{x=1}^{M} p_s^{\kappa}(x) \cdot L}{E[slot]} \tag{22}$$

where $L$ represents the size of data packet.

*Remark 3:* The value of $S$ is determined by the detailed retransmission protocol and channel fading mode.

Since the station receives packets based on Poisson process, the probability $\nu$ that no packet arrives during a slot time is approximately expressed as

$$\nu \doteq exp\{-\lambda \cdot E[slot]\} \tag{23}$$

### B. THE MAC METRICS OF 1901 CONSIDERING RETRANSMISSION PROTOCOLS

It's easy to find that $\mu_0$ relies on the buffer size and packet arrival process, hence a queue model is established to derive $\mu_0$ and capture the queueing process of the station. We define $P_a$ as the probability of $a$ packets in the station buffer, $\mu_a$ the probability of $a$ packets in the station buffer upon a departure and $Ar_a$ the probability that $a$ packets arrive at the station buffer during the MAC service time $T_{mac}$ [21]. Then, the transition matrix $\boldsymbol{Ar}$ is denoted as

$$\boldsymbol{Ar} = \begin{bmatrix} Ar_0 & Ar_1 & Ar_2 & \cdots & Ar_{K-2} & 1-\sum_{a=0}^{K-2} Ar_a \\ Ar_0 & Ar_1 & Ar_2 & \cdots & Ar_{K-2} & 1-\sum_{a=0}^{K-2} Ar_a \\ 0 & Ar_0 & Ar_1 & \cdots & Ar_{K-3} & 1-\sum_{a=0}^{K-3} Ar_a \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & Ar_0 & 1-Ar_0 \end{bmatrix} \tag{24}$$

where $K$ represents the buffer size of the station.

Let $\boldsymbol{\mu} = \begin{bmatrix} \mu_0 & \mu_1 & \cdots & \mu_{K-1} \end{bmatrix}$, the relationship between $\boldsymbol{\mu}$ and $\boldsymbol{Ar}$ can be represented as following

$$\boldsymbol{\mu} \cdot \boldsymbol{Ar} = \boldsymbol{\mu} \tag{25}$$

Since Poisson arrival is assumed, the expression of $Ar_a$ is written as

$$Ar_a \doteq \sum_{r=0}^{\infty} \frac{exp\{-\lambda[(r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)]\}}{a!} \cdot \frac{\{\lambda[(r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)]\}^a}{a!} \cdot Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \tag{26}$$

where $Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\}$ in Eq.26 can be respectively expanded as follows (please refer to [21] for detailed derivation process):

**For** ($k = 1$), we have

$$\begin{cases} Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \\ = \frac{1}{W_1}; r \in [1, d_1] \\ Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \\ = \frac{X_{1,r}}{W_1}; r \in [d_1+1, W_1] \end{cases} \tag{27}$$

**For** ($k \in [2, m-1]$), we have

$$\begin{cases} Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \\ = \frac{\prod_{t=1}^{k-1} p + [(1-p) \cdot \frac{Y_t}{W_t}]}{W_k}; r \in [1, d_k] \\ Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \\ = \prod_{t=1}^{k-1} p + [(1-p) \cdot \frac{Y_t}{W_t}] \cdot \frac{X_{k,r}}{W_k}; r \in [d_k+1, W_k] \end{cases} \tag{28}$$

**For** ($k = m$), we have

$$\begin{cases} Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \\ = \frac{\prod_{t=1}^{m-1}\{p + [(1-p) \cdot \frac{Y_t}{W_t}]\}}{W_m[1-p-(1-p) \cdot \frac{Y_m}{W_m}]}; r \in [1, d_m] \\ Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \\ = \frac{\prod_{t=1}^{m-1}\{p + [(1-p) \cdot \frac{Y_t}{W_t}]\}}{[1-p-(1-p) \cdot \frac{Y_m}{W_m}]} \\ \cdot \frac{X_{m,r}}{W_m}; r \in [d_m+1, W_m] \end{cases} \tag{29}$$

Accordingly, the expected MAC service time $E[T_{mac}]$ considering retransmission protocols is given by

$$E[T_{mac}] = \sum_{r=0}^{\infty} Prb\{T_{mac} = (r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)\} \cdot [(r-1)E[slot] + \sum_{x=1}^{M} T_s(x)p_s(x)] \tag{30}$$

Based on the knowledge of $M/G/1/K$ queueing system [43], $P_a$ is obtained as

$$\begin{cases} P_a = \dfrac{\mu_a}{\mu_0 + \lambda E[T_{mac}]}; & a \in [0, K-1] \\ P_K = 1 - \dfrac{1}{\mu_0 + \lambda E[T_{mac}]}; & a = K \end{cases} \tag{31}$$

In addition, the average queue length $E[Q]$ and packet blocking probability $P_b$ considering retransmission protocols can be derived as follows:

$$E[Q] = \sum_{a=0}^{K} a \cdot P_a \tag{32}$$

$$P_b = 1 - \frac{1}{\mu_0 + \lambda \cdot E[T_{mac}]} \tag{33}$$

*Remark 4:* In the previous analysis, we provide the T-D MC for 1901 MAC protocol considering retransmission protocols. That is because the following steady states exist in slot time $T$ [44]:

$$\begin{cases} \lim_{T\to\infty} Prob\{empty(T)\} = E \\ \lim_{T\to\infty} Prob\{b_{s(T)=k,b(T)=r}\} = b_{k,r} \\ \lim_{T\to\infty} Prob\{d_{s(T)=k,d(T)=j}\} = d_{k,j} \\ \lim_{T\to\infty} Prob\{\mu_r(T)\} = \mu_r \end{cases} \tag{34}$$

where $s(T)$, $b(T)$ and $d(T)$ represent the values of backoff stage, backoff counter, and deferral counter, respectively.

### C. THE ENERGY CONSUMPTION MODEL FOR IEEE 1901 PROTOCOL

In this section, we propose an energy consumption model to find out the consumed power for successfully delivering one bit of data packet in the IEEE 1901 PLC network considering retransmission protocols. The expected total energy cost of transmitting one successful bit from the station to the destination is called Energy Per Bit (*EPB*), which contains three parts: the energy consumption of transmitting per bit $E_t$, the energy consumption of receiving per bit $E_r$ and the energy consumption of overhearing for other stations (i.e., be in the idle state) $E_{oh}$ [46]. Hence, we have the following equation

$$EPB = E_t + E_r + E_{oh} \tag{35}$$

Let the receiving power and overhearing power be $Pw_r$ and $Pw_{oh}$ (two constants), respectively. Since a data packet may be dropped during executing the retransmission protocol, the average time duration $Avg[T_s]^{\kappa}$ for a specific successful transmission can be given by

$$Avg[T_s]^{\kappa} = \begin{cases} \sum_{x=1}^{M} \dfrac{p_s^{ARQ}(x)}{\tau} \cdot T_s(x) \quad or \\ \sum_{x=1}^{M} \dfrac{p_s^{HARQ}(x)}{\tau} \cdot T_s(x) \end{cases} \tag{36}$$

Similarly, the average time duration $Avg[T_{dp}]^{\kappa}$ for a specific "dropping packet" is expressed as

$$Avg[T_{dp}]^{\kappa} = \begin{cases} \dfrac{PDP_s^{ARQ}}{\tau} \cdot T_{dp} \quad or \\ \dfrac{PDP_s^{HARQ}}{\tau} \cdot T_{dp} \end{cases} \tag{37}$$

Thus, the total time duration $T_{busy}$ where energy is spent by transmitting, receiving or dropping data packet can be written as

$$T_{busy} = Avg[T_s]^{\kappa} + Avg[T_{dp}]^{\kappa} \tag{38}$$

*Remark 5:* A specific successful transmission or dropping packet means that the station having occupied the PLC channel definitely carries out its data transmission attempt process, and other stations do not transmit their packet at the same slot time. That's the reason we have Eqs.36-37.

Accordingly, $E_t$ and $E_r$ can be expressed as follows:

$$E_t = \frac{1}{L} \cdot T_{busy} \cdot Pw_t \tag{39}$$

$$E_r = \frac{1}{L} \cdot T_{busy} \cdot Pw_r \tag{40}$$

A station tries to transmit its HOL packet, the other $N-1$ stations would be overhearing the PLC channel. Therefore, we can obtain $E_{oh}$, and express it as

$$E_{oh} = (N-1) \cdot \frac{1}{L} \cdot T_{busy} \cdot Pw_{oh} \tag{41}$$

### D. BOUND PERFORMANCE ANALYSIS FOR IEEE 1901 PROTOCOL

In this sub-section, we select two metrics, system throughput $S$ and successful transmission probability $P_{suc}^{\kappa}$, to analyze whether the 1901 protocol has bound performance under the influence of retransmission protocols.

Firstly, we consider the bound performance of system throughput $S$.

*Lemma 1:* The bound performance of system throughput $S$ of IEEE 1901 PLC network (considering retransmission protocols) yields the following approximate solution $\tau_{optimal}$, i.e.,

$$\tau_{optimal} \doteq \frac{\sqrt{(N^2\sigma^2 + 2\sigma(T_c - \sigma))N(N-1)} - N\sigma}{N(N-1)(T_c - \sigma)} \tag{42}$$

*Proof 1:* Further extending Eq.22, we can get

$$S = \frac{N \cdot L \cdot A \cdot \tau(1-p)}{\sigma(1-\tau)^{N-1} + B \cdot N\tau(1-p) + T_c(1-(1-\tau)^N)}$$

where $A$ and $B$ are respectively denoted as:

$$A = \begin{cases} \sum_{x=1}^{M} (P_{out}^{ARQ})^{(x-1)}(1 - P_{out}^{ARQ}) \quad or \\ \sum_{x=1}^{M} P_{out,1\to x-1}^{HARQ}(1 - P_{out,1\to x}^{HARQ}) \end{cases} \tag{43}$$

$$B=\begin{cases}[\sum_{x=1}^{M}(P_{out}^{ARQ})^{(x-1)}(1-P_{out}^{ARQ})T_s(x)\\ -\sum_{x=1}^{M}(P_{out}^{ARQ})^{(x-1)}(1-P_{out}^{ARQ})T_c]\\ +(T_{dp}-T_c)(P_{out}^{ARQ})^M \quad or\\ [\sum_{x=1}^{M}P_{out,1\to x-1}^{HARQ}(1-P_{out,1\to x}^{HARQ})T_s(x)\\ -\sum_{x=1}^{M}P_{out,1\to x-1}^{HARQ}(1-P_{out,1\to x}^{HARQ})T_c]\\ +(T_{dp}-T_c)P_{out,1\to M}^{HARQ}\end{cases} \quad (44)$$

Clearly, $P_{out}^{ARQ}$ or $P_{out,1\to x}^{HARQ}$ is determined by the transmission power $Pw_t$, distance $X$, path loss exponent $\alpha$, channel fading mode, and detailed retransmission protocol (recalling Eqs.11-12), hence $A$ and $B$ can be regarded as two constants in the derivation process.

Let $F(\tau)=\frac{\tau(1-p)}{\sigma(1-\tau)^{N-1}+B\cdot N\tau(1-p)+T_c(1-(1-\tau)^N)}$, to get the bound performance of system throughput $S$, we have $F'(\tau)=0$, i.e.,

$$F'(\tau)=0=\frac{\sigma(1-\tau)^{2N-2}+T_c[(1-N\tau)(1-\tau)^{N-2}-(1-\tau)^{2N-2}]}{[\sigma(1-\tau)^{N-1}+B\cdot N\tau(1-p)+T_c(1-(1-\tau)^N)]^2} \quad (45)$$

Simplifying Eq.45, we can derive the following relation expression

$$T_c(1-N\tau)=(T_c-\sigma)(1-\tau)^N \quad (46)$$

Using Taylor formula [45] (i.e., $(1-\tau)^N\approx 1-N\tau+\frac{N(N-1)}{2}\tau^2$), Eq.46 can be simplified as

$$(T_c-\sigma)\frac{N(N-1)}{2}\tau^2+N\sigma\tau-\sigma=0 \quad (47)$$

Solving Eq.47, we have the conclusion of Lemma 1.

For network size $N\to+\infty$, $\tau_{optimal}$ can be further written as

$$\lim_{N\to+\infty}\tau_{optimal}\approx\frac{\sqrt{1+2(T_c/\sigma)}-1}{N(T_c/\sigma)}\approx\frac{1}{N\sqrt{0.5T_c/\sigma}} \quad (48)$$

Let $\rho=\sqrt{0.5T_c/\sigma}$, for $N\to+\infty$, the probability $p_{tr}$, $p_{idle}$ and $p$ can be approximately re-written as:

$$\begin{cases}\lim_{N\to+\infty}p_{tr}=\\ 1-(1-\tau)^N=1-(1-\frac{1}{N\rho})^N\approx 1-exp(-\frac{1}{\rho});\\ \lim_{N\to+\infty}p_{idle}=(1-\tau)^N\approx exp(-\frac{1}{\rho});\\ \lim_{N\to+\infty}p=1-(1-\tau)^{N-1}\approx 1-exp(-\frac{1}{\rho})\end{cases} \quad (49)$$

With this, the upper bound system throughput $S$ of IEEE 1901 PLC network considering retransmission protocols for $N\to+\infty$ can be given by (the two constants $A$ and $B$ have been shown in Eqs.43-44)

$$\lim_{N\to+\infty}S=L\cdot A\cdot\frac{\frac{1}{\rho}\cdot exp(-\frac{1}{\rho})}{\sigma\cdot exp(-\frac{1}{\rho})+B\cdot\frac{1}{\rho}exp(-\frac{1}{\rho})+T_c\cdot[1-exp(-\frac{1}{\rho})]} \quad (50)$$

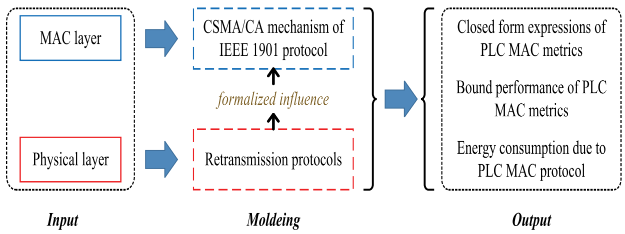


**FIGURE 5. The methodology of the proposed cross-layered theoretical model.**

Secondly, we analyze the bound performance of successful transmission probability $P_{suc}^{\kappa}$.

*Lemma 2:* The bound performance of successful transmission probability $P_{suc}^{\kappa}$ for 1901 protocol (considering retransmission protocols) yields the following solution $\tau'_{optimal}$, i.e.,

$$\tau'_{optimal}=\frac{1}{N} \quad (51)$$

*Proof 2:* Reviewing Eq.15, we can expand $P_{suc}^{\kappa}$ as

$$P_{suc}^{\kappa}=\sum_{x=1}^{M}p_s^{\kappa}(x)=\tau\cdot(1-p)\cdot C_3\cdot N$$

where $C_3$ is expanded as

$$C_3=\begin{cases}\sum_{x=1}^{M}[(P_{out}^{ARQ})^{(x-1)}(1-P_{out}^{ARQ})];\\ \sum_{x=1}^{M}[P_{out,1\to x-1}^{RARQ}(1-P_{out,1\to x}^{RARQ})]\end{cases}$$

Since $C_3$ can be seen as a constant, we denote $H(\tau)=C_3\cdot N\cdot\tau\cdot(1-p)$, and take the derivative of $H(\tau)$

$$\begin{aligned}H'(\tau)&=N\cdot C_3\cdot[\tau(1-p)]^{(1)}=[\tau(1-\tau)^{N-1}]^{(1)}\\ &=N\cdot C_3\cdot(1-N\tau)\cdot(1-\tau)^{N-2}\end{aligned} \quad (52)$$

Let $H'(\tau)=0$, we can derive the optimal solution of Lemma 2, i.e., $\tau'_{optimal}=\frac{1}{N}$ (note that $\tau<1$).

Under the case of $N\to+\infty$, $P_{suc}^{\kappa}$ is expressed as

$$\lim_{N\to+\infty}P_{suc}^{\kappa}=exp(-1)\cdot C_3 \quad (53)$$

Clearly, $\tau_{optimal}$ and $\tau'_{optimal}$ are the functions of $N$, we assert that the bounds of $S$ and $P_{suc}^{\kappa}$ rely significantly on the network size $N$.

Now we use Fig.5 to summarize the methodology of the proposed cross-layered theoretical model.

## V. PERFORMANCE EVALUATION

In this part, we evaluate the performance of IEEE 1901 under the influence of two retransmission protocols (ARQ and HARQ-CC), and verify the proposed cross-layered theoretical model. We developed simulations in Matlab. To realize the CSMA/CA mechanism of 1901 protocol, we add a parallel deferral counter window on the base of using backoff counter window. The parameters used in the simulation are shown in Table 1 and Table 3 (system parameters). In the simulation, a converged topology based PLC network is organized,

**TABLE 3. System parameters.**

| $Generic\quad Parameter$ | $Size$ |
|---|---|
| $Medium\ bit\ rate\ (R)$ | $10Mbps$ |
| $Idle\ slot\ (\sigma)$ | $35.84us$ |
| $Priority\ slot\ (PRS)$ | $35.84us$ |
| $CIFS$ | $100.00us$ |
| $RIFS$ | $140.00us$ |
| $NACK$ | $110.48us$ |
| $ACK$ | $110.48us$ |
| $EIFS$ | $2920.64us$ |
| $L$ (packet size) | $5000.00bits$ |
| $M$ (number of attempt fragments) | 4 |
| $m$ (maximum backoff stage) | 4 |
| $C_1$ | 1w |
| $C_2$ | 0.5w |
| $\alpha$ (path loss exponent) | 2.6 |
| $Pw_r$ | 1w |
| $Pw_{oh}$ | 0.5w |
| $N_0$ (Average noise power) | $10dBm$ |
| $\sigma_R^2$ (Scale parameter of Rayleigh distribution) | 0.5 |
| $u$ (Nakagami factor) | 3 |
| $K$ (buffer size) | 1 |

in which there are $N$ stations and an access point (used to receive packets), and the transmission distance between each station and access point is assumed to be $Xm$. The MAC layer of each station receives packets from the upper layer based on Poisson process with an average arrival rate $\lambda$. Stations transmit data packets to the access point through a PLC channel without considering the interference between stations. The PLC channel is assumed to have a typical fading mode (Rayleigh fading or Nakagami-$u$ fading). All stations have the same priority type ($CA0/CA1$) and the same finite buffer size $K$, in which packets follow FIFO (first in first out) rule. In addition, each simulation experiment is split in 31 batches, and each batch consists of 5000 packets (for per station). The statistics of first batch is discarded to avoid initial distortions, and the considered performance measures are derived from the remaining 20 batches. All simulation results are with 0.95 confidence interval between$[0.91Avg(.), 1.06Avg(.)]$, where $Avg(.)$ represents the average simulation result. The proposed cross-layered theoretical model is solved by using Fixed Point Iteration (FPI) method [47], where the fixed iteration is carried with a precision of $10^{-5}$.

As PLC network's MAC layer introduces some overhead due to priority type, acknowledgment (negative acknowledgment) and inter-frame spaces, in simulations, the data packet transmission is preceded by two priority tone slots $PRS$ and is followed by a response inter-frame space $RIFS$ and an acknowledgment frame $ACK$ (or $NACK$). Finally, the contention inter-frame space $CIFS$ is used. A data packet corresponds to a frame duration $D$ ($D = \frac{L}{R}$). In case of a collision, the stations differ their transmission for an extended inter-frame space $EIFS$ (verified by Eqs.18-20).

We select five significant metrics to measure the performance of IEEE 1901 PLC networks under the influence of different retransmission protocols and channel fading modes, i.e.,

(1) System throughput $S$: the metric can objectively reflect the impact of 1901 protocol on data transmission efficiency.

(2) Expected MAC service time $E[T_{mac}]$: this metric can objectively reflect the service efficiency of using 1901 protocol at MAC layer.

(3) Packet drop probability $PDP^{\kappa}$: this metric can comprehensively reflect the impacts of PLC physical layer's retransmission protocols and channel fading type on the possibility of failure transmission.

(4) Packet blocking probability $P_b$: this metric can objectively reflect the possibility that the finite buffer size is fully-loaded caused by executing 1901 protocol.

(5) Expected total energy cost of transmitting one successful bit $EPB$: this metric can objectively reflect the impact of 1901 protocol on energy consumption for finishing one successful transmission.

The experiments are totally divided into four groups: Firstly, we investigate the relationship between network size and IEEE 1901's performance; Secondly, we test the 1901's performance under different traffic load (i.e., arrival rate); Thirdly, we study the impact of threshold $SNR$ ($\eta$) on 1901's performance; Finally, we examine the impact of transmission distance $Xm$ on 1901's performance.

### A. THE IMPACT OF NETWORK SIZE

In this simulation group, we set the threshold $SNR\ \eta = -4dB$, transmission distance $X = 8m$, average packet arrival rate $\lambda = 50$, and the number of stations $N$ varies in $[2, 20]$. Fig.6 shows the simulation and analysis results including the system throughput $S$, MAC service time $E[T_{mac}]$, packet drop probability $PDP^{\kappa}$, packet blocking probability $P_b$ and total energy cost of transmitting one successful bit $EPB$ for priority type $CA0/CA1$ with different network sizes.

We can see that as the network size $N$ increases, the system throughput increases first, then decreases. The reason is that the system throughput is affected not only by the successful transmission probability but also by the duration of average slot time (verified by Eq.22). The change rule of system throughput also reflects the channel utilization. Namely, with the increase of network size $N$, more stations contend the PLC channel, thus the channel utilization is enhanced (until reaching to the optimal utilization), however as the channel contention continuously intensifies, the channel utilization would be degraded. Since the increasing network size $N$ would enhance the frequency of contention, the data packet has to wait a longer time duration to get the medium service, and the buffer of station is easier to be fully-loaded. Therefore, we can observe that the MAC service time and packet blocking probability increase with the increasing network size $N$. The packet drop probability increases with the increasing network size $N$, since the network size has a positive influence on the performance of packet drop probability (this conclusion can be demonstrated by Eqs.16-17). The total energy cost of transmitting one successful bit $EPB$ increases with network size $N$. That is because with the increase of network size $N$, more stations would overhear the channel state,

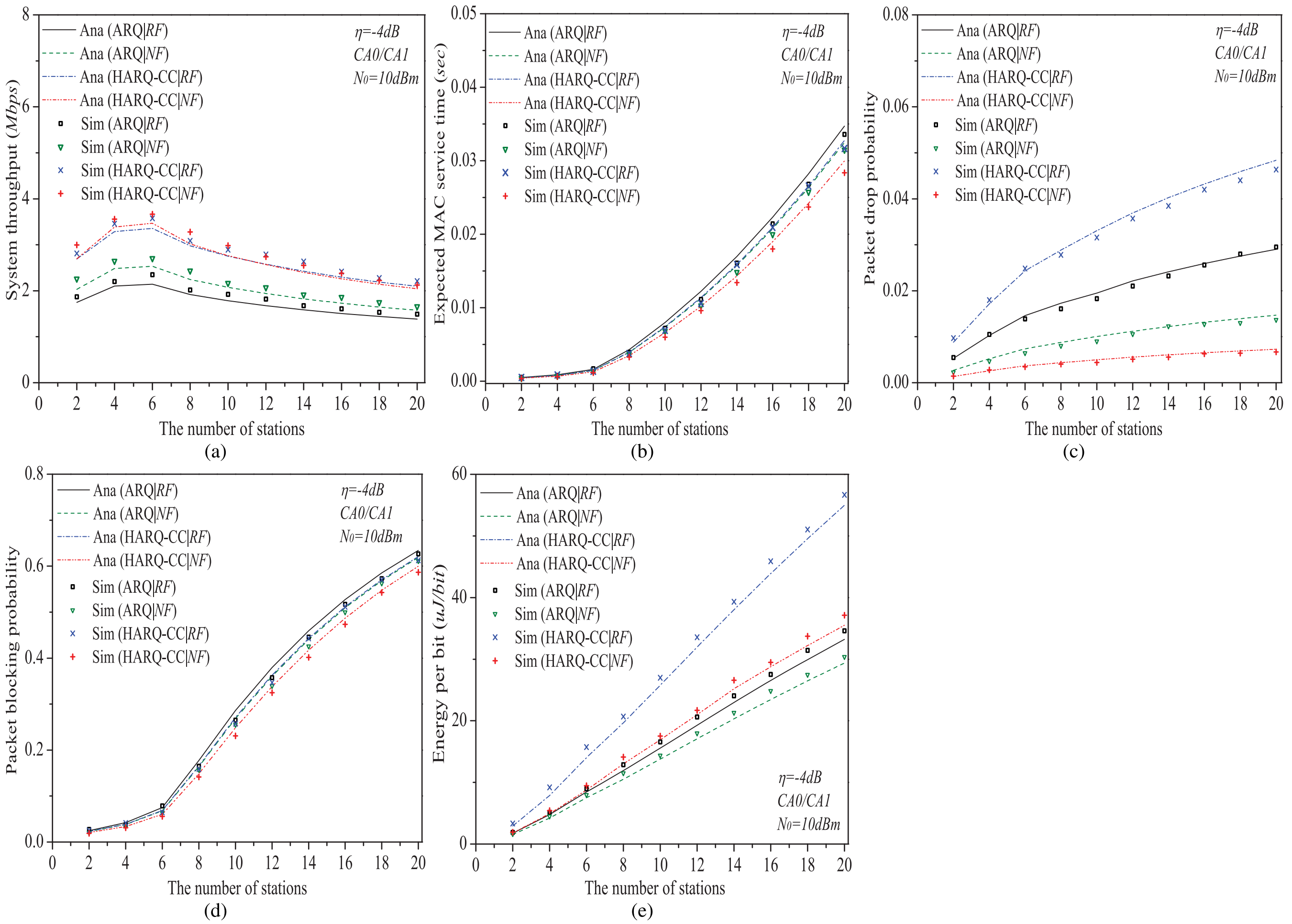


**FIGURE 6.** The MAC performance of 1901 protocol under different network size.

which accordingly enhances the total energy consumption of transmitting one successful bit (verified by Eq.41).

Here is an example of system throughput $S$ ($N \in [2, 20]$). For using ARQ at physical layer, the simulation result of $S$ varies from 1.87$Mbps$ to 2.35$Mbps$, then to 1.49$Mbps$ under $RF$ channel; From 2.26$Mbps$ to 2.71$Mbps$, then to 1.66$Mbps$ under $NF$ channel. The analysis result of $S$ varies from 1.75$Mbps$ to 2.14$Mbps$, then to 1.38$Mbps$ under $RF$ channel; From 2.03$Mbps$ to 2.54$Mbps$, then to 1.58$Mbps$ under $NF$ channel.

For using HARQ-CC, the simulation result of $S$ varies from 2.81$Mbps$ to 3.58$Mbps$, then to 2.21$Mbps$ under $RF$ channel; From 3.00$Mbps$ to 3.67$Mbps$, then to 2.13$Mbps$ under $NF$ channel. The analysis result of $S$ varies from 2.69$Mbps$ to 3.36$Mbps$, then to 2.10$Mbps$ under $RF$ channel; From 2.70$Mbps$ to 3.47$Mbps$, then to 2.05$Mbps$ under $NF$ channel.

### B. THE IMPACT OF TRAFFIC RATE

In this simulation group, we set the threshold $SNR$ $\eta = -3dB$, transmission distance $X = 8m$, number of stations $N = 30$, and the average packet arrival rate $\lambda$ varies in $[0.1, 20]$. Fig.7 shows the simulation and analysis results including the system throughput $S$, expected MAC service time $E[T_{mac}]$, packet drop probability $PDP^{K}$, packet blocking probability $P_b$ and total energy cost of transmitting one successful bit $EPB$ for priority type $CA0/CA1$ with different traffic rates.

We can see that as the packet arrival rate $\lambda$ increases, the system throughput increases first, then slowly decreases. The reason is that as the packet arrival rate increases, the transmission attempt frequency of station increases, so the channel utilization is enhanced (until reaching to the optimal utilization). However, as the transmission attempt frequency continuously intensifies, the collision frequency accordingly increases and the channel utilization would be decreased. Since the increasing $\lambda$ would enhance the channel contention frequency (i.e., increasing the collision probability of stations), the data packet has to wait a longer time duration to get the medium service, and the buffer of station is easier to be fully-loaded. Therefore, as is shown in Fig.7, the MAC service time and packet blocking probability increase with the increasing packet arrival rate. The packet drop probability increases with the increasing $\lambda$. The most possible reason is

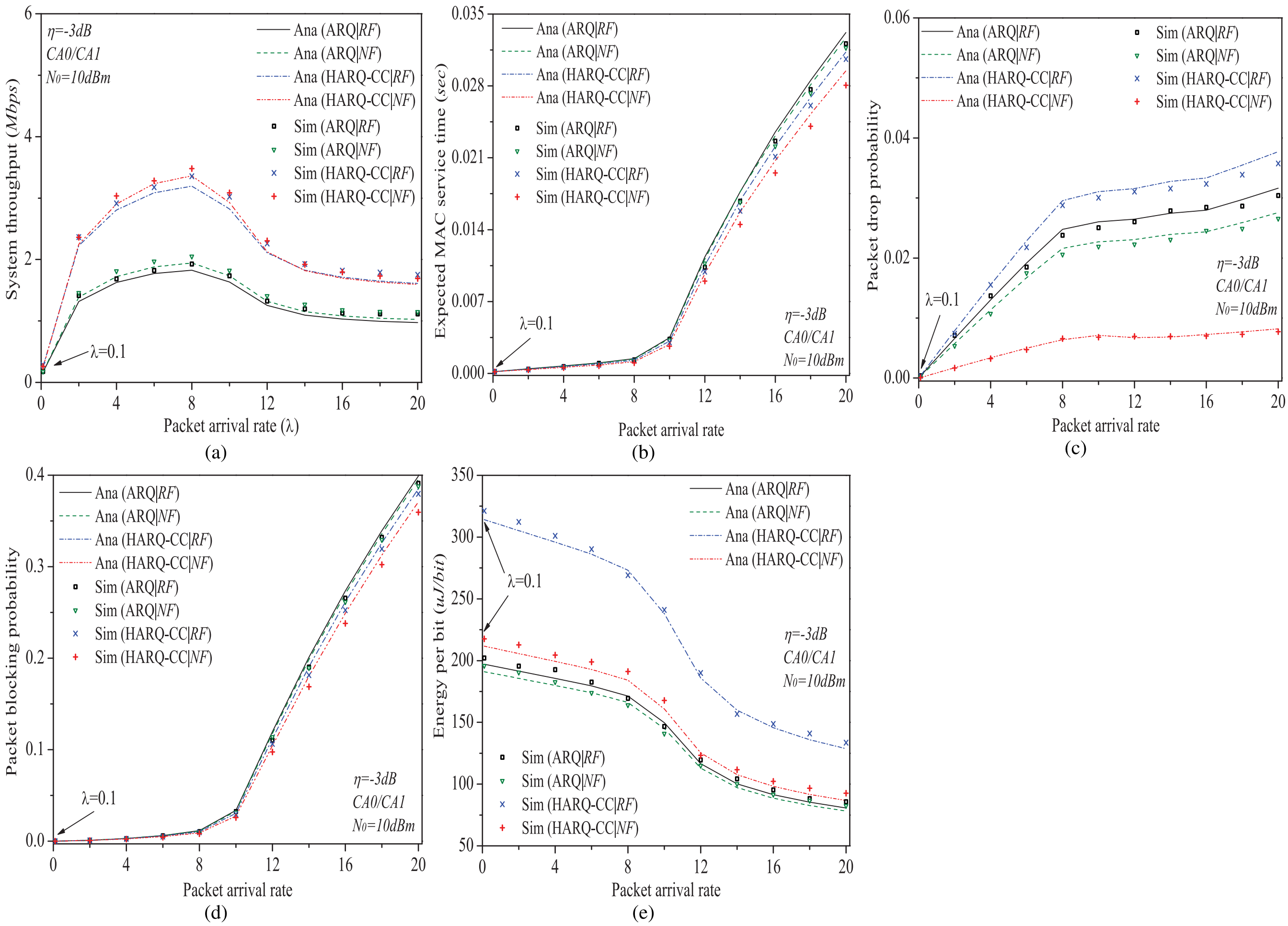


**FIGURE 7.** The MAC performance of 1901 protocol under different traffic rate.

that although the collision probability $p$ and the transmission attempt probability $\tau$ increase with the increasing $\lambda$, nevertheless, the value of $\tau$ is still smaller than $\tau'_{optimal} = \frac{1}{N}$ (reviewing Eqs.52 and **Lemma 2**) under the condition of $\lambda \in [0.1, 20]$. Hence, operator function $\tau(1-p)$ in Eqs.13-14 is still monotone increasing, and it would lead to the change rule of packet drop probability. The total energy cost of transmitting one successful bit *EPB* decreases with the increasing $\lambda$. The most possible reason is that as the packet arrival rate increases, the transmission attempt probability $\tau$ increases, the practical transmission interval is reduced, i.e., a specific successful transmission or dropping packet decreases may need shorter time duration (verified by Eqs.36-37). As a consequence, the time duration $T_{busy}$ is shortened (i.e., the total energy cost of transmitting one successful bit decreases).

Here is an example of packet drop probability $PDP^{\kappa}$ ($\lambda \in [0.1, 20]$). For using ARQ protocol at physical layer, the analysis result of $PDP^{ARQ}$ varies from $3.34 \times 10^{-4}$ to 0.032 under *RF* channel; From $2.92 \times 10^{-4}$ to 0.028 under *NF* channel. The simulation result of $PDP^{ARQ}$ varies from $3.75 \times 10^{-4}$ to 0.030 under *RF* channel; From $2.62 \times 10^{-4}$ to 0.027 under *NF* channel.

For using HARQ-CC, the analysis result of $PDP^{HARQ}$ varies from $3.99 \times 10^{-4}$ to 0.038 under *RF* channel; From $8.65 \times 10^{-4}$ to 0.0082 under *NF* channel. The simulation result of $PDP^{HARQ}$ varies from $3.60 \times 10^{-4}$ to 0.036 under *RF* channel; From $9.24 \times 10^{-4}$ to 0.0077 under *NF* channel.

### C. THE IMPACT OF THRESHOLD SNR

In this simulation group, we set the number of stations $N = 25$, average packet arrival rate $\lambda = 40$, transmission distance $X = 8m$ and the threshold *SNR* $\eta$ varies in $[-5dB, 2dB]$. Fig.8 shows the simulation and analysis results including the system throughput $S$, expected MAC service time $E[T_{mac}]$, packet drop probability $PDP^{\kappa}$, packet blocking probability $P_b$ and total energy cost of transmitting one successful bit *EPB* for priority type $CA0/CA1$ with different threshold *SNR*.

We can see that as the threshold *SNR* $\eta$ increases, the system throughput decreases. The reason is that as the threshold *SNR* $\eta$ increases, the *SNR* of transmission attempt is more possible to be less than $\eta$. As a consequence, the packet

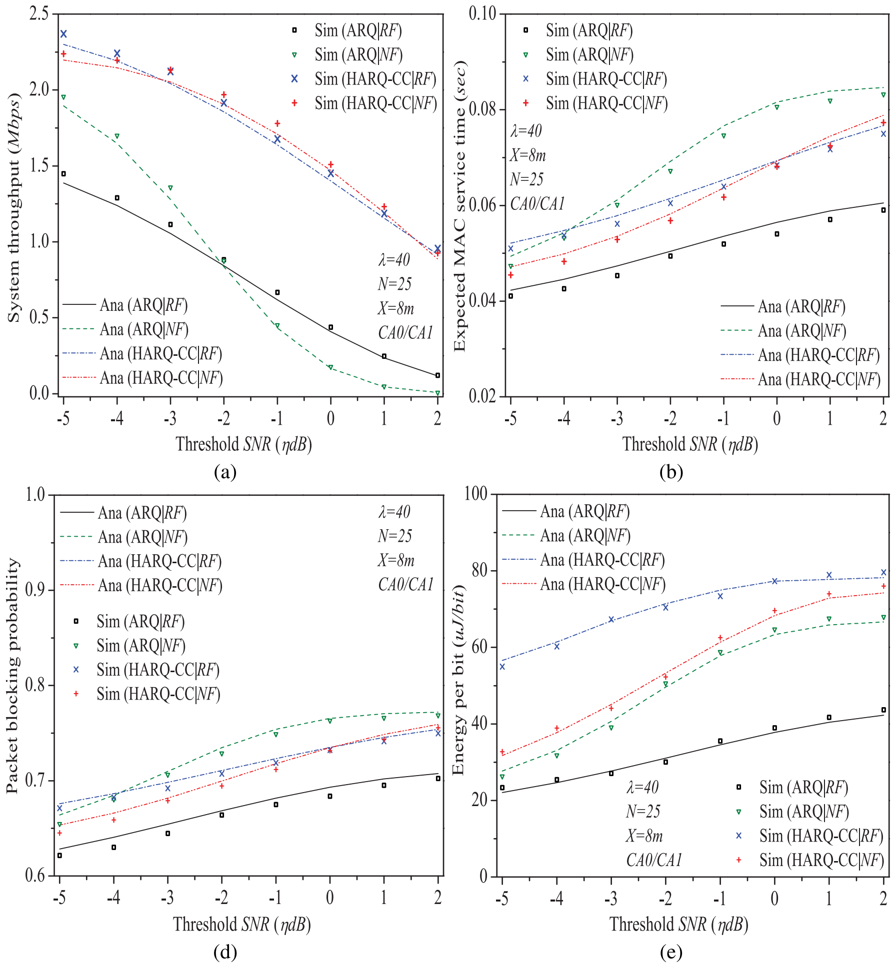

**FIGURE 8.** The MAC performance of 1901 protocol under different threshold *SNR*.

has a higher probability to be received in outage (proved by Eqs.11-12), i.e., the unsuccessful probability of transmission attempt is enhanced (the overall transmission efficiency is reduced). Due to the increase of $\eta$, the station occupying PLC channel may need more attempt fragments to accomplish one successful transmission (i.e., spending more time). The data packet has to wait longer in the station, and the buffer is easier to be fully-loaded. Hence, we can find that the MAC service time and packet blocking probability increases with the increasing $\eta$. The packet drop probability increases with the increasing $\eta$, since the increasing $\eta$ would enlarge the value of $P_{out,x}^{ARQ}/P_{out,1\rightarrow x}^{HARQ}$ that finally causes the increase of $PDP^{\kappa}$ (verified by Eqs.16-17). The total energy cost of transmitting one successful bit $EPB$ increases with the increasing $\eta$. The most possible reason is that with the increase of $\eta$, a station needs more attempt fragments to finish one successful transmission. Therefore, the practical duration of successful transmission is enhanced, which accordingly results the time duration of $T_{busy}$ to be longer (i.e., the total energy consumption of transmitting one successful bit increases).

Here is an example of expected MAC service time $E[T_{mac}]$ ($\eta \in [-5dB, 2dB]$). For using ARQ at physical layer, the analysis result of $E[T_{mac}]$ varies from $0.0422s$ to $0.0605s$ under $RF$ channel; From $0.0494s$ to $0.0846s$ under $NF$ channel. The simulation result of $E[T_{mac}]$ varies from $0.0411s$ to $0.0590s$ under $RF$ channel; From $0.0472s$ to $0.0832s$ under $NF$ channel.

For using HARQ-CC, the analysis result of $E[T_{mac}]$ varies from $0.0521s$ to $0.0767s$ under $RF$ channel; From $0.0472s$ to $0.0788s$ under $NF$ channel. The simulation result of $E[T_{mac}]$ varies from $0.0507s$ to $0.0750s$ under $RF$ channel; From $0.0455s$ to $0.0772s$ under $NF$ channel.

### D. THE IMPACT OF TRANSMISSION DISTANCE

In this simulation group, we set the number of stations $N = 25$, average packet arrival rate $\lambda = 40$, threshold $SNR$ $\eta = 0dB$ and the transmission distance $X$ varies in $[3m, 10m]$. Fig.9 shows the simulation and analysis results including the system throughput $S$, expected MAC service time $E[T_{mac}]$, packet drop probability $PDP^{\kappa}$, packet blocking probability $P_b$ and total energy cost of transmitting one successful bit

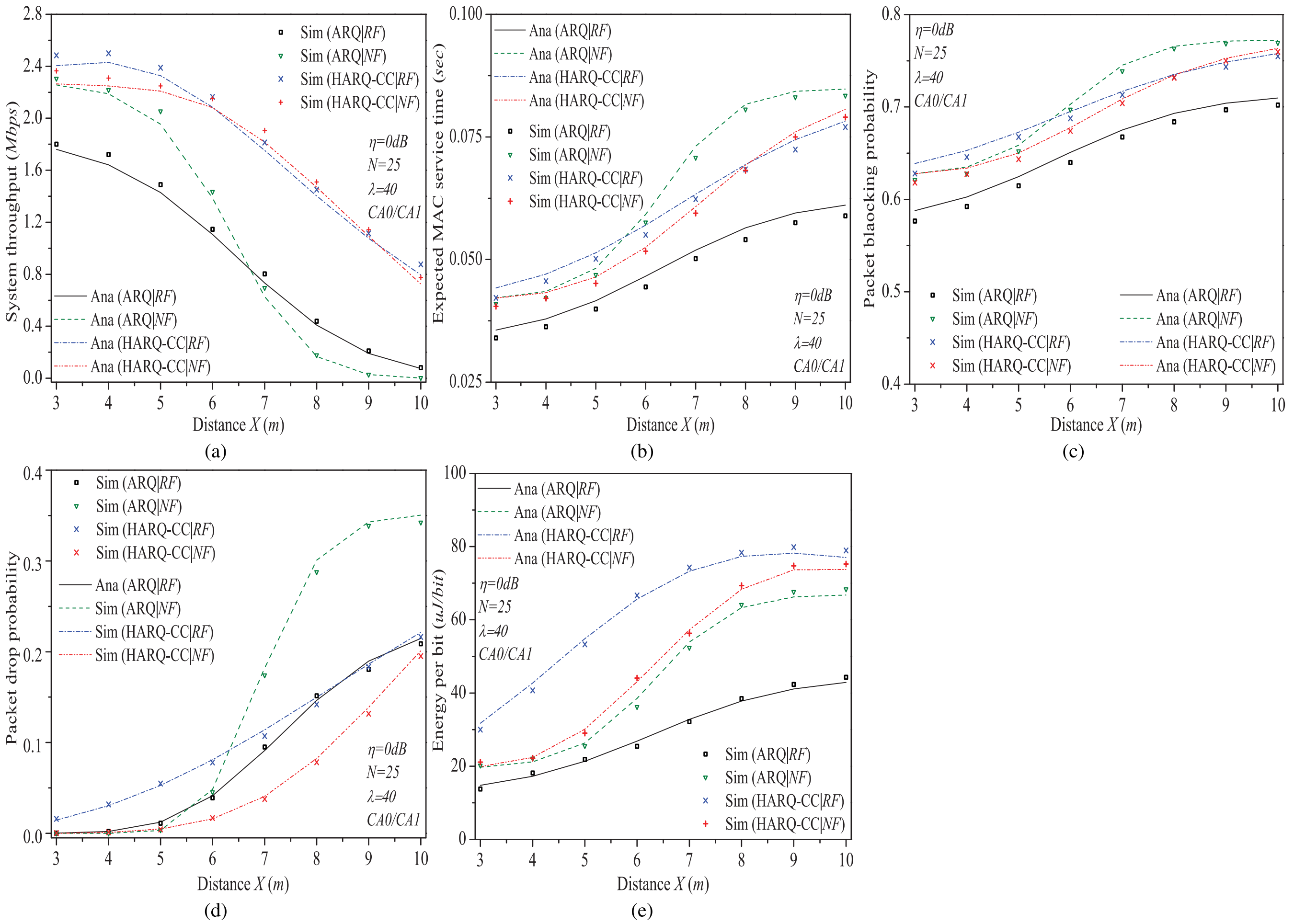


**FIGURE 9.** The MAC performance of 1901 protocol under different Distance $X$.

$EPB$ for priority type $CA0/CA1$ with different transmission distance $X$.

We can see that as the transmission distance $X$ increases, the system throughput decreases. The reason is that as the transmission distance $X$ increases, the $SNR$ of transmission attempt is easier to be less than $\eta$ (this conclusion can be verified by Eqs.11-12). Accordingly, the packet has a higher probability to be received in outage, i.e., the overall transmission efficiency is decreased. The MAC service time and packet blocking probability increase with the increasing $X$. That is because with the increase of $X$, the probability of unsuccessful attempt is enhanced (received in outage), and the station occupying PLC channel may need more attempt fragments to finish a successful transmission (i.e., spending more time). As a result, the data packet has to wait longer in the station, and the buffer is easier to be fully-loaded. The packet drop probability increases with the increasing $X$, since the increasing $X$ would enhance the value of $P_{out,x}^{ARQ}/P_{out,1\to x}^{HARQ}$ that finally causes the increase of $PDP^{\kappa}$ (proved by Eqs.16-17). In overall, the total energy cost of transmitting one successful bit $EPB$ increases with the increasing $X$. The most possible reason is that as $X$ increases, a station needs more attempt fragments to finish one successful transmission. Consequently, the practical duration of successful transmission is enhanced, which accordingly results the time duration of $T_{busy}$ to be longer (i.e., the total energy consumption of transmitting one successful bit increases).

Here is an example of energy cost of transmitting one successful bit $EPB$ ($X \in [3m, 10m]$). For using ARQ protocol at physical layer, the simulation result of $EPB$ varies from $13.77uJ/bit$ to $44.31uJ/bit$ under $RF$ channel; From $20.21uJ/bit$ to $68.37uJ/bit$ under $NF$ channel. The analysis result of $EPB$ varies from $14.80uJ/bit$ to $42.93uJ/bit$ under $RF$ channel; From $19.72uJ/bit$ to $66.78uJ/bit$ under $NF$ channel.

For using HARQ-CC, the simulation result of $EPB$ varies from $30.00uJ/bit$ to $78.95uJ/bit$ under $RF$ channel; From $21.10uJ/bit$ to $75.24uJ/bit$ under $NF$ channel. The analysis result of $EPB$ varies from $31.74uJ/bit$ to $77.10uJ/bit$ under $RF$ channel; From $19.86uJ/bit$ to $73.71uJ/bit$ under $NF$ channel.

As shown in Fig.6-Fig.9, under different retransmission protocols and channel fading modes, there always exists a good fit between analysis and simulation results, which

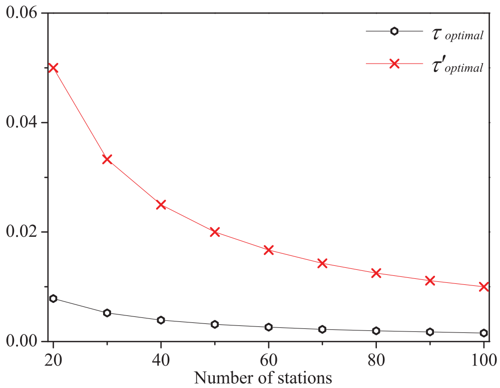


**FIGURE 10.** The values of $\tau_{optimal}$ and $\tau'_{optimal}$.

**TABLE 4.** The theoretical bound performance of $P^{\kappa}_{suc}$.

| $N$ | $RF$ $P^{ARQ}_{suc}$ | $NF$ $P^{HARQ}_{suc}$ | $RF$ $P^{ARQ}_{suc}$ | $NF$ $P^{HARQ}_{suc}$ |
|---|---|---|---|---|
| 20 | 0.3324 | 0.3546 | 0.4758 | 0.4245 |
| 30 | 0.3295 | 0.3516 | 0.4718 | 0.4209 |
| 40 | 0.3282 | 0.3501 | 0.4697 | 0.4191 |
| 50 | 0.3274 | 0.3492 | 0.4686 | 0.4180 |
| 60 | 0.3268 | 0.3486 | 0.4678 | 0.4173 |
| 70 | 0.3264 | 0.3482 | 0.4672 | 0.4168 |
| 80 | 0.3261 | 0.3479 | 0.4668 | 0.4164 |
| 90 | 0.3259 | 0.3476 | 0.4664 | 0.4162 |
| 100 | 0.3257 | 0.3475 | 0.4662 | 0.4159 |

proves that the proposed cross-layered theoretical model is accurate. Here we do not show the results of priority type $CA2/CA3$, since their change rules are similar to that of $CA0/CA1$.

Fig.10 shows the results of $\tau_{optimal}$ and $\tau'_{optimal}$ for $N \in [20, 100]$. We find that as the number of stations $N$ increases, the values of $\tau_{optimal}$ and $\tau'_{optimal}$ decrease (proved by Eq.42 and Eq.51). For computational tractability, we further let $X = 8m$, $\eta = -4dB$, the theoretical bound values of successful transmission probability $P^{\kappa}_{suc}$ under different retransmission protocols $\kappa \in [ARQ, HARQ]$ and channel fading modes $[RF, NF]$ can be calculated in Table 4 ($N \in [20, 100]$).

## VI. CONCLUSION

In this paper, we propose a cross-layered theoretical model of performance analysis for IEEE 1901 PLC networks considering retransmission protocols. In the modeling process, we firstly establish a T-D MC to depict the CSMA/CA mechanism of IEEE 1901, where the impacts of physical layer's retransmission protocols, channel fading modes and general practical environment configurations are comprehensively considered. On the basis, we derive the closed-form expressions of typical MAC metrics of 1901 under the influence of retransmission protocols. Next, we propose an energy consumption model to evaluate the consumed power of transmitting one successful bit. In addition, we make a bound performance analysis for 1901's MAC metrics, i.e., the system throughput and successful transmission probability. We reveal that these two metrics depend significantly on the network size. Extensive simulation experiments verify that our proposed cross-layered theoretical model can accurately evaluate the performance of 1901 protocol under different retransmission protocols and system parameters. Our work can efficiently provide guidance for constructing practical PLC systems, and further optimizing PLC MAC layer.

Our work has numerous extensions. An immediate extension is to study the performance under a network environment with hidden terminals. In addition, how to optimize the MAC performance of IEEE 1901 protocol and reduce the system energy consumption on the basis of this work should be examined in our future study.

## APPENDIX A
## THE DERIVATION PROCESS OF EQ.2

In Section 4, we have defined $F_k$, i.e., the probability that a station jumps from the transient state [43], [44] that it prepares a new HOL packet and begins to execute the CSMA/CA mechanism of 1901 to the backoff stage $k$ ($k \in [1, m]$). Since a station at the above mentioned transient state would definitely enter the backoff stage 1, we have

$$F_1 = 1 \tag{54}$$

Based on the 1901 standard, a station tries to enter the next backoff stage through experiencing the collision or triggering the DCP. Thus, the probability $P_{(k \to k+1)}$ that a station at backoff stage $k$ jumps to backoff stage $k+1$ can be written as

$$P_{(k \to k+1)} = p + [(1-p) \cdot \frac{Y_k}{W_k}];\ 1 \leq k \leq m-1 \tag{55}$$

Hence, the probability $F_k$ for $k \in [2, m-1]$ can be accordingly expressed as

$$\begin{aligned} F_k &= F_1 \cdot \prod_{t=1}^{k-1} P_{(t \to t+1)} \\ &= \prod_{t=1}^{k-1} p + [(1-p) \cdot \frac{Y_t}{W_t}] \quad k \in [2, m-1] \end{aligned} \tag{56}$$

Because of the reentrancy of the last backoff stage $m$ (shown in T-D MC), the probability that the station jumps from the transient state that it prepares new HOL packet and begins to execute the CSMA/CA mechanism of 1901 to the last backoff stage $m$ can be denoted as

$$\begin{aligned} F_m &= F_{m-1} \\ &\quad \cdot [p + (1-p) \cdot \frac{Y_{m-1}}{W_{m-1}}] \cdot \{1 + \sum_{\varrho=1}^{+\infty} [p+(1-p) \cdot \frac{Y_m}{W_m}]^{\varrho}\} \\ &= \prod_{t=1}^{m-1} \{p + [(1-p) \cdot \frac{Y_t}{W_t}]\} \cdot \frac{1}{1-p-(1-p) \cdot \frac{Y_m}{W_m}} \\ &= \{p + [(1-p) \cdot \frac{Y_{m-1}}{W_{m-1}}]\} \cdot \frac{1}{1-p-(1-p) \cdot \frac{Y_m}{W_m}} \cdot F_{m-1} \end{aligned} \tag{57}$$

Gathering the above conclusions (i.e., Eqs.54-57), we derive Eq.2.

## APPENDIX B
## THE DERIVATION PROCESS OF $\tau$ FOR A STATION

We use recursion method to derive the expression of $\tau$. According to the one-step transition probability of T-D MC,[8] we can get the probability of transient state [43], [44] $\Psi$ that a station prepares a new HOL packet and begins to execute the CSMA/CA mechanism of 1901 protocol, i.e.,

$$\Psi = \Sigma_{k=1}^{m} b_{k,1} \cdot (1-p)(1-\mu_0) + E(1-\nu) \tag{58}$$

Combining the definition of $F_k$ (shown in Appendix A), $b_{k,g}$ (or $d_{k,j}$) is determined by the probability that the station at the transient state (i.e., $\Psi$), the probability that the station jumps from the transient state to the backoff stage $k$ ($k \in [1, m]$), i.e., $F_k$, and the probability of entering the state $b_{k,g}$ (or $d_{k,j}$) at backoff stage $k$. Therefore, using the balance equation method [43], the expressions of $b_{k,g}$ and $d_{k,j}$ can be expressed respectively as:

$$\begin{cases} b_{k,W_k} = \Psi \cdot F_k \cdot \dfrac{X_{k,W_k}}{W_k} \\ b_{k,g} = \Psi \cdot F_k \cdot \dfrac{X_{k,g}}{W_k} + 1 \cdot b_{k,g+1}; \quad g \in [d_k+1, W_k-1] \\ b_{k,d_k} = \Psi \cdot F_k \cdot \dfrac{1}{W_k} + 1 \cdot b_{k,d_k+1} \\ b_{k,g} = \Psi \cdot F_k \cdot \dfrac{1}{W_k} + 1 \cdot b_{k,g+1}; \quad g \in [1, d_k-1] \\ d_{k,d_k+1} = \Psi \cdot F_k \cdot \dfrac{Y_k}{W_k} \\ d_{k,j} = 1 \cdot d_{k,j+1}; \quad j \in [1, d_k] \end{cases} \tag{59}$$

Further using recursion strategy, we can derive the expanded expressions for $b_{k,g}$ and $d_{k,j}$

$$\begin{cases} b_{k,g} = \Psi \cdot F_k \\ \cdot [\sum_{h=d_{k+1}}^{W_k} \dfrac{X_{k,h}}{W_k} + \sum_{h=g}^{d_k} \dfrac{1}{W_k}]; \quad g \in [1, d_k] \\ b_{k,g} = \Psi \cdot F_k \cdot \sum_{h=g}^{W_k} \dfrac{X_{k,h}}{W_k}; \quad g \in [d_k+1, W_k] \\ d_{k,j} = \Psi \cdot F_k \cdot \dfrac{Y_k}{W_k}; \quad j \in [1, d_k+1] \end{cases} \tag{60}$$

In addition, the empty state probability $E$ can be written as (using balance equation method)

$$\begin{aligned} E &= E\nu + \sum_{k=1}^{m} b_{k,1}(1-p)(1-\mu_0) \\ &= \frac{\Psi(1-\mu_0)}{1-\nu} \end{aligned} \tag{61}$$

Through the above derivation, we can finally expand $\tau = \frac{\sum_{k=1}^{m} b_{k,1}}{\sum_{k=1}^{m}(b_{k,g}+d_{k,j})+E}$ as Eq.3.

[8]The one-step transition probabilities can be directly derived by T-D MC, thus we do not show them anymore.

## ACKNOWLEDGMENT

The author would like to thank the editor and two reviewers for helpful comments that have improved the quality of the article.

## REFERENCES

[1] C. Cano, A. Pittolo, D. Malone, L. Lampe, A. M. Tonello, and A. G. Dabak, "State of the art in power line communications: From the applications to the medium," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 7, pp. 1935–1952, Jul. 2016.

[2] L. G. da Silva Costa, A. C. M. de Queiroz, B. Adebisi, V. L. R. da Costa, and M. V. Ribeiro, "Coupling for power line communications: A survey," *J. Commun. Inf. Syst.*, vol. 32, no. 1, pp. 8–22, 2017.

[3] D. Righini, F. Passerini, and A. M. Tonello, "Modeling transmission and radiation effects when exploiting power line networks for communication," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 1, pp. 59–67, Feb. 2018.

[4] C. Abou-Rjeily, "Power line communications under Rayleigh fading and Nakagami noise: Novel insights on the MIMO and multi-hop techniques," *IET Commun.*, vol. 12, no. 2, pp. 184–191, Jan. 2018.

[5] G. Artale, A. Cataliotti, V. Cosentino, D. D. Cara, R. Fiorelli, S. Guaiana, N. Panzavecchia, and G. Tinè, "A new low cost power line communication solution for smart grid monitoring and management," *IEEE Instrum. Meas. Mag.*, vol. 21, no. 2, pp. 29–33, Apr. 2018.

[6] L. González-Sotres, P. Frías, and C. Mateo, "Power line communication transfer function computation in real network configurations for performance analysis applications," *IET Commun.*, vol. 11, no. 6, pp. 897–904, Apr. 2017.

[7] V. Fernandes, W. A. Finamore, H. V. Poor, and M. V. Ribeiro, "The low-bit-rate hybrid power line/wireless single-relay channel," *IEEE Syst. J.*, vol. 13, no. 1, pp. 98–109, Mar. 2019.

[8] Y. Huo, G. Prasad, L. Lampe, and V. C. M. Leung, "Efficient access control for broadband power line communications in home area networks," *IEEE Trans. Commun.*, vol. 66, no. 4, pp. 1649–1660, Apr. 2018.

[9] S. Hao and H. Zhang, "An energy harvesting modified MAC protocol for power-line communication systems using RF energy transfer: Design and analysis," *IEICE Trans. Commun.*, vol. E103.B, no. 10, pp. 1086–1100, Oct. 2020, doi: 10.1587/transcom.2019EBP3229.

[10] *IEEE Standard for Broadband Over Power Line Networks: Medium Access Control and Physical Layer Specifications*, IEEE Standard 1901-2010, 2010, vol. 10, no. 2, pp. 1–1589.

[11] *Homeplug Alliance*. Accessed: Jun. 12, 2016. [Online]. Available: https://www.homeplug.org

[12] *IEEE 1901 HD-PLC (High Definition Power Line Communication).* Accessed: Feb. 2018. [Online]. Available: https://www.hd-plc.org

[13] R. M. de Oliveira, A. B. Vieira, H. A. Latchman, and M. V. Ribeiro, "Medium access control protocols for power line communication: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 920–939, 1st Quart., 2019.

[14] M.-H. Jung, M. Y. Chung, and T.-J. Lee, "MAC throughput analysis of HomePlug 1.0," *IEEE Commun. Lett.*, vol. 9, no. 2, pp. 184–186, Feb. 2005.

[15] C. Vlachou, A. Banchs, J. Herzen, and P. Thiran, "Performance analysis of MAC for power-line communications," in *Proc. SIGMETRICS*, Austin, TX, USA, Jun. 2014, pp. 585–586.

[16] C. Vlachou, A. Banchs, J. Herzen, and P. Thiran, "Analyzing and boosting the performance of power-line communication networks," in *Proc. 10th ACM Int. Conf. Emerg. Netw. Exp. Technol. (CoNEXT)*, Sydney, NSW, Australia, Dec. 2014, pp. 1–12.

[17] C. Vlachou, A. Banchs, J. Herzen, and P. Thiran, "On the MAC for power-line communications: Modeling assumptions and performance tradeoffs," *Semiotica*, vol. 2007, no. 166, pp. 97–104, 2014.

[18] C. Vlachou, A. Banchs, P. Salvador, J. Herzen, and P. Thiran, "Analysis and enhancement of CSMA/CA with deferral in power-line communications," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 7, pp. 1978–1991, Jul. 2016.

[19] C. Vlachou, A. Banchs, J. Herzen, and P. Thiran, "How CSMA/CA with deferral affects performance and dynamics in power-line communications," *IEEE/ACM Trans. Netw.*, vol. 25, no. 1, pp. 250–263, Feb. 2017.

[20] C. Cano and D. Malone, "On efficiency and validity of previous homeplug MAC performance analysis," *Comput. Netw.*, vol. 83, pp. 118–135, Jun. 2015.

[21] S. Hao and H. Zhang, "From homogeneous to heterogeneous: An analytical model for IEEE 1901 power line communication networks in unsaturated conditions," *IEICE Trans. Commun.*, vol. E102.B, no. 8, pp. 1636–1648, 2019.

[22] S. Hao and H.-Y. Zhang, "Theoretical modeling for performance analysis of IEEE 1901 power-line communication networks in the multi-hop environment," *J. Supercomput.*, vol. 76, no. 4, pp. 2715–2747, Apr. 2020.

[23] Q. Zhang, F. Yang, J. Song, B. Zhao, and L. Geng, "An effective H-ARQ scheme for LDPC-coded broadband power line communication system," in *Proc. IEEE Int. Symp. Power Line Commun. Appl.*, Beijing, China, Mar. 2012, pp. 165–169.

[24] L. V. Truong, "Performance of Viterbi decoding with and without ARQ on Rician fading channels," *IEEE Trans. Commun.*, vol. 67, no. 2, pp. 903–914, Feb. 2019.

[25] A. Papaioannou, G. D. Papadopoulos, and F.-N. Pavlidou, "Hybrid ARQ combined with distributed packet space-time block coding for multicast power-line communications," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 1911–1917, Oct. 2008.

[26] J. Bilbao, P. M. Crespo, I. Armendariz, and M. Medard, "Network coding in the link layer for reliable narrowband powerline communications," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 7, pp. 1965–1977, Jul. 2016.

[27] B. Makki, A. G. I. Amat, and T. Eriksson, "Green communication via power-optimized HARQ protocols," *IEEE Trans. Veh. Technol.*, vol. 63, no. 1, pp. 161–177, Jan. 2014.

[28] A. Mathur, Y. Ai, M. Cheffena, and M. R. Bhatnagar, "Performance of hybrid ARQ over power line communications channels," in *Proc. IEEE 91st Veh. Technol. Conf.*, Antwerp, Belgium, May 2020, pp. 1–6.

[29] N. Sakunnithimetha and U. Tuntoolavest, "An efficient new ARQ strategy for vector symbol decoding with performance in power line communications," in *Proc. Int. Electr. Eng. Congr.*, Pattaya, Thailand, Mar. 2017, pp. 1–4.

[30] I. Tsokalo, F. Gabriel, S. Pandi, F. H. P. Fitzek, and R. Lehnert, "Reliable feedback mechanisms for routing protocols with network coding," in *Proc. IEEE Int. Symp. Power Line Commun. Appl. (ISPLC)*, Manchester, U.K., Apr. 2018, pp. 1–7.

[31] S. Carcangiu, A. Fanni, and A. Montisci, "Optimization of a power line communication system to manage electric vehicle charging stations in a smart grid," *Energies*, vol. 12, no. 9, p. 1767, May 2019.

[32] H. Zhang, X. Zhao, S. Geng, W. Lu, and Y. Ma, "Selection of indoor relay node positions for a three-hop low-voltage broadband power line communication system," *IET Commun.*, vol. 14, no. 5, pp. 746–751, Mar. 2020.

[33] A. H. K. S. A. Saidi, S. A. Hussain, S. M. Hussain, A. V. Singh, and A. Rana, "Smart water meter using power line communication (PLC) approach for measurements of accurate water consumption and billing process," in *Proc. 8th Int. Conf. Rel., Infocom Technol. Optim. (Trends Future Directions)*, Noida, India, Jun. 2020, pp. 1119–1122.

[34] Y. Li, M. Zhang, W. Zhu, M. Cheng, C. Zhou, and Y. Wu, "Performance evaluation for medium voltage MIMO-OFDM power line communication system," *China Commun.*, vol. 17, no. 1, pp. 151–162, Jan. 2020.

[35] G. Debita, P. Falkowski-Gilski, M. Habrych, G. Wiśniewski, B. Miedziński, P. Jedlikowski, A. Waniewska, J. Wandzio, and B. Polnik, "BPL-PLC voice communication system for the oil and mining industry," *Energies*, vol. 13, no. 18, p. 4763, Sep. 2020.

[36] Z. Sheng, D. Tian, V. C. M. Leung, and G. Bansal, "Delay analysis and time-critical protocol design for in-vehicle power line communication systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 1, pp. 3–16, Jan. 2018.

[37] Y. Zhu, J. Wu, R. Wang, Z. Lin, and X. He, "Embedding power line communication in photovoltaic optimizer by modulating data in power control loop," *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 3948–3958, May 2019.

[38] O. Kolade, A. D. Familua, and L. Cheng, "Indoor amplify-and-forward power-line and visible light communication channel model based on a semi-hidden Markov model," *AEU Int. J. Electron. Commun.*, vol. 124, pp. 1–9, Sep. 2020.

[39] A. G. Merkulov and V. P. Shuvalov, "The perspectives and practice of PLC HomePlug AV modems application in the network devices and industrial tools," in *Proc. 1st Global Power, Energy Commun. Conf. (GPECOM)*, Nevşehir, Turkey, Jun. 2019, pp. 46–49.

[40] R. Samano-Robles, M. Ghogho, and D. C. McLernon, "P-persistent stabilisation for wireless network diversity multiple access protocols," in *Proc. IEEE 7th Workshop Signal Process. Adv. Wireless Commun.*, Cannes, France, Jul. 2006, pp. 1–5.

[41] F. Ganhao, M. Pereira, L. Bernardo, R. Dinis, R. Oliveira, and P. Pinto, "Performance analysis of an hybrid ARQ adaptation of NDMA schemes," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3304–3317, Aug. 2013.

[42] Y.-H. Nam, P. K. Gopala, and H. El-Gamal, "Resolving collisions via incremental redundancy: ARQ diversity," in *Proc. IEEE INFOCOM*, Barcelona, Spain, May 2007, pp. 285–293.

[43] G. Bolch, S. Greiner, H. D. Meer, and K. S. Trivedi, *Queueing Networks and Markov Chains*. Hoboken, NJ, USA: Wiley, 1998.

[44] L. Saloff-Coste, "Lectures on finite Markov Chains," in *Lectures on Probability Theory and Statistics*. Berlin, Germany: Springer, 1997.

[45] I. S. Gradshteyn, I. M. Ryzhikand, and A. Jeffrey, *Table of Integrals, Series, and Products*. New York, NY, USA: Academic, 1980.

[46] C. Aydogdu and E. Karasan, "An analysis of IEEE 802.11 DCF and its application to energy-efficient relaying in multihop wireless networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 10, pp. 1361–1373, Oct. 2011.

[47] R. W. Hamming, *Numerical Methods for Scientists and Engineers*. New York, NY, USA: Dover, 1973.

**SHENG HAO** was born in Lanzhou, China. He received the B.E., M.E., and Ph.D. degrees in computer science from Wuhan University (WHU), in 2012, 2015, and 2020, respectively. He is currently a Lecturer with the School of Computer Science, Central China Normal University, Wuhan, China. His research interests include wireless/optical communication networks, MAC protocols for the IoT, energy harvesting assisted communication systems, and complex network theory.

**HU YIN ZHANG** received the Ph.D. degree from Wuhan University (WHU). He is currently a Professor with WHU. His research interests include high performance computing, network quality of service, and new generation network architecture.