MODELING AND ANALYSIS OF A POWER LINE COMMUNICATION NETWORK SUBJECT TO CHANNEL FAILURE

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Abstract: Power line communication (PLC) is a promising technique for information transmission using existing power lines. We analytically model a finite-source PLC network subject to noise/disturbance and evaluate its call-level performance through a queuing theoretic framework. The proposed PLC network model consists of a base station (BS), which is located at a transformer station and connected to the backbone communication networks, and a number of subscriber stations that are interconnected with each other and with the BS via the power line transmission medium. An orthogonal frequency division multiplexing (OFDM) based transmission technique is assumed to be used for providing the transmission channels in a frequency spectrum. The channels are subject to failure during service due to noise/disturbance. When a channel is in failure, its associated call will wait at the channel until the channel is recovered. We model this process and determine the steady-state solution and derive several performance metrics of interest. Numerical and simulation results are presented for the purpose of performance evaluation. The proposed modeling method can be used for evaluation and design of future PLC networks.

1 INTRODUCTION

Power line communication (PLC) is a promising technique for information transmission using existing power lines. PLC technologies can be used in an inside-building low voltage environment, a short-distance medium voltage environment, or a long-distance high voltage environment. Mixed high-voltage, medium-voltage, and low-voltage power supply networks could be bridged to form very large networks for communications, as alternative telecommunication networks.

The great advantage of PLC is that the power lines exist in every home and every room. For example, a computer would need only to plug a BPL "modem" into any outlet in an equipped building to have high-speed Internet access. Therefore, huge cost of running wires such as Ethernet in many buildings can be saved. However, there are still lots of challenges for implementation in reality. Since the power line network has originally been designed for electricity distribution, rather than for data transfer, the power line as communication channel has various noise and disturbance characteristics, resulting in an unreliable channel. Many factors, such as channel attenuation, white noise, RF noise from nearby radio transmitters, impulse noise from electrical machines and relays, may cause the channel unreliability.

In practice the impact of RF noise on a channel can be reduced significantly with OFDM. (Stantcheva, Begain, Hrasnica, and Lehnert, 2000). Based on the measurements reported in (Zimmerman and Dostert, 2002), the noise in the power line communication channels is categorized in five types, where the last type (i.e., asynchronous impulsive noise) is the most unfavorable one and makes more difficulties to the power line channels.

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The power spectral density of this type of noise can reach values of more than 50dB above the background noise.

Much research PLC has been developed in the past a few years. The focused topics include MAC (medium access control) protocols (Hrasnica and Haidine, 2000), noise and channel modeling (Zimmerman and Dostert, 2002), (Katayama, Yamazato, and Okada, 2006), modulation and multiple access techniques (Haring and Vinck, 2000), (Amirshahi, Navidpour, and Kavehrad, 2006), or modem design (Yu, Yu, and Lee, 2003). In (Hrasnica and Haidine, 2000), some reservation MAC protocols were proposed for the PLC network which provides collision free data transmission. A simulation model was developed for the study of the PLC MAC layer that includes different disturbance scenarios. In (Zimmerman and Dostert, 2002), it was examined that the impulsive noise introduces significant time variance into the powerline channel. Spectral analysis and time-domain analysis of impulsive noise were presented in details. In (Katayama, Yamazato, and Okada, 2006), a mathematically tractable model of narrowband power line noise was introduced based on experimental measurements. With the assumption of Gaussian noise with instantaneous variance of a periodic time function, the cyclostationary features of power line noise can be described in close form.

The performance of the OFDM transmission scheme corrupted by impulsive noise was analyzed in (Haring and Vinck, 2000). It showed that the Gaussian noise OFDM receiver in an impulsive noise environment causes strong performance degradation, and proposed an iterative algorithm to mitigate the influence of the impulsive noise. In (Amirshahi, Navidpour, and Kavehrad, 2006), the bit error rate performance of the OFDM system under impulsive noise and frequency selective fading was analyzed and closed form formulas were derived. In (Yu, Yu, and Lee, 2003), a PLC modem applicable to central monitoring and control systems was designed by using a multicarrier CPFSK modulation with adaptive impedance matching.

All the above research was done at the link level or component level. Very little research studied the performance at the system level. In this paper, we study the call-level performance of PLC networks at the system level through through a queuing theoretic framework. The proposed PLC network model consists of a base station (BS), which is located at a transformer station and connected to the backbone communication networks, and a number of subscriber stations (SSs) that are interconnected with each other and with the BS via the power lines. An OFDM based transmission technique is assumed to be used for providing the transmission channels in a frequency spectrum, which is divided into a set of narrowband subcarriers (or subchannels). The subchannels are subject to failure during service due to the noise/disturbance on the power lines.

When a channel is in failure, its associated call will wait at the channel until the channel is recovered (i.e., the noise/disturbance is gone), then the call continues its service. The failure events in different subchannels are independent due to the flat fading characteristic in each divided subchannel.

The remainder of the paper is organized as follows. Section 2 presents the system description. Section 3 develops a two-dimensional Markovian model for performance analysis. Section 4 derives several performance metrics of interest. Section 5 presents numerical and simulation results. Finally, the paper is concluded in Section 6.

2 SYSTEM DESCRIPTION

Consider a PLC access network in the range of a low-voltage power supply network, as shown in Fig. 1. It consists of a BS that is connected to a backbone telecommunication network and a number of SSs that are interconnected with each other and with the BS via the power lines. The transformer station distributes power to the covered low-voltage power supply network and receives power from a medium-voltage or high-voltage power supply network. When an SS is located near the BS, the communication can be organized directly between the SS and the BS. Otherwise, one or more repeaters (RPs) may be required inside the network to compensate for signal attenuation.

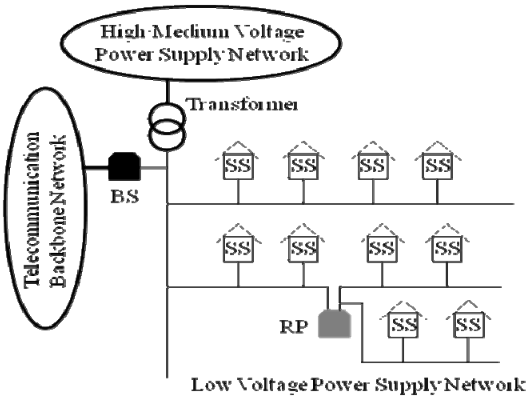

Figure 1: A PLC network architecture.

The BS is an access point for communications between an SS of the PLC network and a user of an external network, and for communications between the SSs inside the PLC network. The signal transmission directions in a PLC network include downlink — from the BS to the SSs and uplink — from an SS to the BS. In the downlink, the BS sends a transmission signal to all the SSs in the PLC network. In the uplink, a signal sent by an SS can not only be received by the BS, but also be received by all other SSs. Hence, the PLC access network holds a logical bus topology, where a set of SSs are connected via a shared communication media — power line, called bus. This type of network may have problems when two or more SSs want to transmit at the same time on the same bus. Hence, some scheme of collision handling or collision avoidance is required for communications, such as carrier sense multiple access (CSMA) or an access control by the BS. The latter is assumed here.

The OFDM is recommended by ITU-T G.hn as the modulation scheme for PLC networks due to the fact that it can cope with frequency selectivity (or time dispersion) — the most distinct property of power line channel, without complex equalization filters. Moreover, OFDM can perform better than single carrier modulation in the presence of impulsive noise, because it spreads the effect of impulsive noise over multiple subcarriers. The available spectrum is divided into a set of narrowband subcarriers (or subchannels), which are overlapping in frequency and orthogonal in time. We assume that these channels are all traffic channels, without including any control channels. The signalling control is assumed to be ideal and is not discussed here.

As mentioned in Section 1, the impulsive noise introduces significant time variance into the power line channel, which indicates a high likelihood of bit or even burst errors for digital communications over power lines. The statistics of the measured interarrival times of impulsive noise above *200ms* follows an exponential distribution. For this sake, in (Hrasnica and Haidine, 2000), the channel was modelled by a Markovian chain with two states, T_{on} and T_{off}, represented by two exponentially distributed random variables, where T_{on} denotes the absence of impulses and the channel is available for utilization, and T_{off} denotes the duration that the channel is disturbed by an impulse and no information transmission is possible.

The BS knows about the occupancy status of the channels. The BS allocates the available channels to the requested calls from the SSs. When a requested call arrives, it will enter the system if there is a channel available; otherwise, it will be rejected.

Note that the channels are subject to failure during service due to the noise/disturbance. The failure events in different channels are independent and identically-distributed (i.i.d.). When a channel is in failure, the associated call will wait at the channel until the channel is recovered. Once the failed channel is recovered, the waiting call will continue its service immediately.

3 PERFORMANCE ANALYSIS

For the above PLC network with N SSs and m traffic channels, we assume that the arrival process of an *individual* idle SS is a Poisson process with rate λ. The channel holding time of a call is exponentially distributed with mean $1/\mu$. We further assume that each call occupies one channel for simplicity.

Due to noise/disturbance, the channel may be subject to failure. We assume that the occurrence of channel failures follows a Poisson process with rate α, i.e., the interarrival time of the failure events follows exponentially distributed with mean $1/\alpha$. In each failure event, it is assumed that the remaining duration (i.e., the recovery time) is exponentially distributed with mean $1/\beta$.

Let $X(t)$ denote the number of failed channels at time t. Similarly, let $Y(t)$ be the number of calls being served at time t. The process $(X(t),Y(t))$ is a two-dimensional Markov process with state diagram shown in Fig. 2 and state space

$$S = \{ (i, j) \mid 0 \le i \le m,\ 0 \le j \le m-i \}.$$

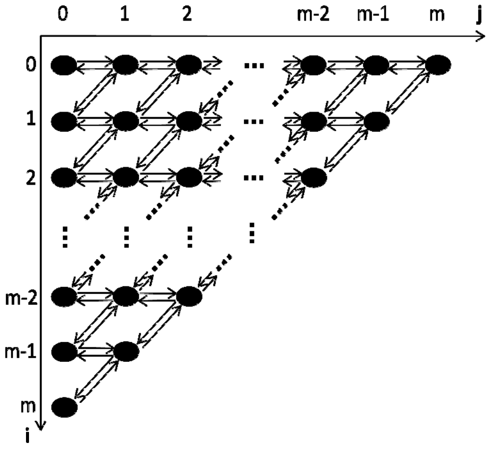

Figure 2: The state diagram of the PLC network.

We denote the transition rate from state (i, j) to (i', j') by $T_{i,j}^{i',j'}$ and specify the different transition rates as follows.

$$T_{i,j}^{i,j+1} = \begin{cases} (N-i-j)\lambda, & 0 \le i \le m-1, 0 \le j < m-i, \\ 0, & otherwise. \end{cases} \quad (1)$$

$$T_{i,j}^{i,j-1} = \begin{cases} j\mu, & 0 \le i \le m-1, 1 \le j \le m-i, \\ 0, & otherwise. \end{cases} \quad (2)$$

$$T_{i,j}^{i+1,j-1} = \begin{cases} j\alpha, & 0 \le i \le m-1, 1 \le j \le m-i, \\ 0, & otherwise. \end{cases} \quad (3)$$

$$T_{i,j}^{i-1,j+1} = \begin{cases} i\beta, & 1 \le i \le m, 0 \le j \le m-i, \\ 0, & otherwise. \end{cases} \quad (4)$$

Let $\pi(i, j)$ denote the steady-state probability that the PLC network is at state (i, j). The global balance equations of the system are given as follows:

$$\begin{aligned} &\pi(i,j)[(N-i-j)\lambda + j(\mu+\alpha) + i\beta] \\ &= \pi(i,j-1)(N-i-j+1)\lambda + \pi(i+1,j-1)(i+1)\beta \\ &\quad + \pi(i,j+1)(j+1)\mu + \pi(i-1,j+1)(j+1)\alpha, \\ &\quad 0 \le i < m, \quad 0 \le j < m-i, \end{aligned} \quad (5)$$

$$\begin{aligned} &\pi(i,j)[j(\mu+\alpha) + i\beta] = \pi(i,j-1)(N-i-j+1)\lambda \\ &\quad + \pi(i-1,j+1)(j+1)\alpha + \pi(i+1,j-1)(i+1)\beta, \\ &\quad 0 \le i \le m, \quad j = m-i, \end{aligned} \quad (6)$$

where $\pi(i,-1) \doteq 0$, $\pi(-1,j) \doteq 0$, and $\pi(i,j) \doteq 0$ if $i + j > m$.

The above equations contain $(m+1)(m+2)/2$ unknowns, i.e., the probabilities $\pi(i, j)$ with $0 \le i \le m$ and $0 \le j \le m-i$. But there are only $m(m+1)/2$ independent equations in the above equations. Thus, $(m+1)$ more equations are required to solve the problem.

Observing the structure of Fig. 2, it is found that only the first row exists if $\alpha = 0$ and $\beta = 0$. Therefore, we can determine a set of particular solutions, $\pi(0, j)$, $j = 1, 2, \ldots, m$, as follows.

$$\pi(0,j) = \binom{N}{j}\left(\frac{\lambda}{\mu}\right)^j \pi(0,0), \quad j = 1, 2, \cdots, m. \quad (7)$$

The final equation is provided by the normalization condition:

$$\sum_{i=0}^{m}\sum_{j=0}^{m-i} \pi(i,j) = 1. \quad (8)$$

Equations (5), (6), (7), and (8) are sufficient to evaluate the state probabilities $\pi(i, j)$, $0 \le i \le m$, $0 \le j \le m - i$.

4 PERFORMANCE METRICS

4.1 The Probability That All Channels Are Not Available

The probability that all channels are not available (either in service or in failure), denoted by P_{ex}, is the sum of the state probabilities with $i + j = m$, $0 \le i \le m$. This event is seen by an external observer.

$$P_{ex} = \sum_{i=0}^{m} \pi(i, m-i). \quad (9)$$

4.2 The Probability That an Arriving Call Sees All Channels Not Available

The probability that an arriving call sees all channels not available (either in service or in failure), denoted by P_{in}, is the probability that the initiating SS finds all channels not available when placing a call request. This metric is similar to P_{ex} except that the observer is an internal source. Note that the proposed model is a finite source system, the PASTA property does not hold. By using the arrival theorem (Kobayashi and Mark, 2009), the P_{in} is obtained by replacing N with N -1 in (9).

$$P_{in} = \sum_{i=0}^{m} \pi_{[N-1]}(i, m-i), \quad (10)$$

where $\pi_{[N-1]}(i, j)$ means the steady state probability at (i, j) when the total number of SSs in the network is N-1. Following this notation, the equation (9) can be re-written as

$$P_{ex} = \sum_{i=0}^{m} \pi_{[N]}(i, m-i).$$

4.3 The Mean System Throughput

The mean system throughput, denoted by T_{sys}, is defined as the mean number of calls being served per unit time. Thus, we have

$$T_{sys} = \sum_{i=0}^{m-1}\sum_{j=1}^{m-i} j\mu\pi_{[N]}(i,j). \quad (11)$$

4.4 The Mean Number of Channels in Failure

The mean number of channels in failure, denoted by N_{cf}, is defined as the mean number of failed channels in steady state. Thus, we have

$$N_{cf} = \sum_{i=1}^{m} \sum_{j=0}^{m-i} i\pi_{[N]}(i,j). \qquad (12)$$

4.5 The Mean Number of Calls Being Served

The mean number of calls being served, denoted by N_{bs}, is defined as the mean number of calls in service in steady state. Thus, we have

$$N_{bs} = \sum_{i=0}^{m-1} \sum_{j=1}^{m-i} j\pi_{[N]}(i,j). \qquad (13)$$

5 NUMERICAL RESULTS

In this section, we present the numerical results in the following configuration: N = 40 or 60, m = 10. The arrival rate λ changes from 1 to 8. The other parameters μ, α, and β are set separately with variable values in each figure. Note that all parameters are given in dimensionless units, which can be mapped to specific units of measurement.

To validate our analysis, we also developed a discrete-event simulator for the proposed model. The simulation was implemented in MATLAB. For convenient illustration, we only show one group of simulation results as a comparison. In the illustrated figures, an excellent match between the analysis and simulation can be observed. Each simulated data point was averaged over 5,000 trials and the associated 95% confidence intervals were computed.

Fig. 3 shows how the probability P_{ex} changes with respect to various parameters. We observe that P_{ex} increases with the increase of call arrival rate λ or the service time $1/\mu$. As λ increases, the system is easier to get full channel occupancy. As the service time increases, the system becomes more difficult to release a channel. In our parameter configuration, we also observe that P_{ex} displays different trends with respect to α and β. The increase of the channel failure rate or the required recovery time delays the channel availability to the initiating call requests.

In Fig. 3, we also observe that P_{ex} increases with the increase of the network population N. When N increases, the total call arrivals to the system per unit time will increase and the system will be easier to get full channel occupancy. The performance of P_{in} is similar to that of P_{ex}. Due to space limitation, we omit the figures here.

Fig. 4 shows how the mean system throughput T_{sys} changes with respect to various parameters. We observe that T_{sys} increases with the increase of λ, μ, or N. As λ, μ, or N increases, the mean number of calls entering the system or the mean number of calls processed per unit time will be increased. We also observe that T_{sys} decreases with the increase of channel failure rate or the required recovery time. A more frequent channel failure event or a longer required recovery time will negatively affect the performance of the system throughput.

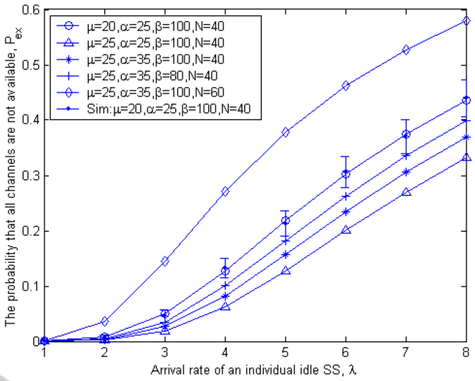

Figure 3: The probability that all channels are not available.

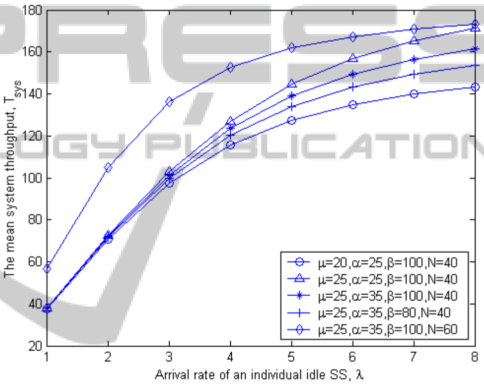

Figure 4: The mean system throughput.

Fig. 5 shows how the mean number of failed channels N_{cf} changes with various parameters. We observe that N_{cf} increases with the increase of λ or N, and decreases with the increase of μ. As λ or N increases, more calls occupy the channels per unit time, leading to more channels subject to failure. Note that in our model, it is assumed that the channels are subject to failure *during service*. We do not consider the failure events for idle channels due to no calls being served (although there is a little impact to an initiating call that happens to access an idle channel being in failure). As μ increases, a call completes its service in shorter duration, reducing the chance for a call to encounter a channel failure event. We also observe that N_{cf} increases with the

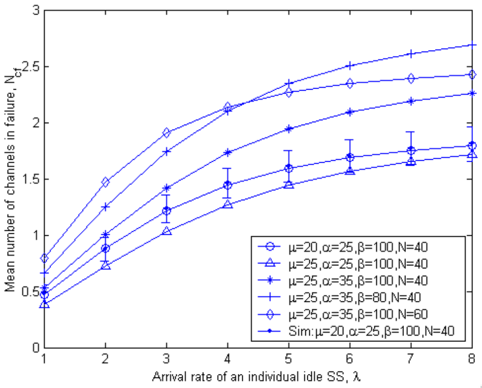

Figure 5: The mean number of channels in failure.

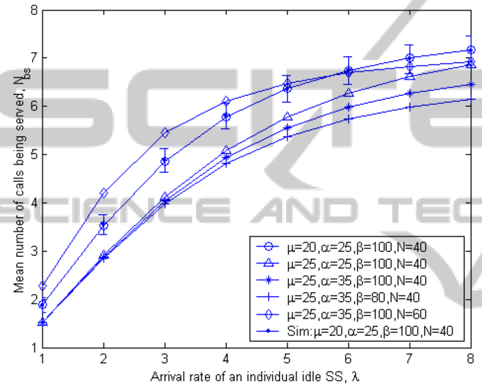

Figure 6: The mean number of calls being served.

increase of channel failure rate or the required recovery time. The reason is obvious.

Fig. 6 shows how the mean number of calls being served N_{bs} changes with various parameters. We observe that N_{bs} increases with the increase of λ or N, and decreases with the increase of μ. This agrees with our intuition. As λ or N increases, a snapshot in steady state will capture more calls being served. On the other hand, the larger μ means the faster processing rate, leading to less calls in service captured by a snapshot. We also observe that N_{bs} decreases with the increase of channel failure rate α or the required recovery time $1/\beta$. As α is increased or β is decreased, a snapshot in steady state will capture less calls being served.

6 CONCLUSIONS

We analytically modeled a PLC network with finite population and evaluate its performance at the call-level through a queuing theoretic framework. The call subject to channel failure holds at the channel until the channel is recovered. The channels obtained from an OFDM based transmission technique are subject to failure during service due to noise/disturbance. We determined the steady-state solution of the proposed model and derived several performance metrics of interest. Numerical and simulation results are presented to show the impact of system parameters on the performance metrics. The proposed modeling method and the derived metrics can be used for evaluation and design of future PLC networks.

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