MAC Performance Evaluation in Low Voltage PLC Networks

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***Abstract*—Power line communication (PLC) system refers to the use of power distribution networks for communication purposes. In this paper, we investigate the performance of the low voltage (LV) power lines for smart grid applications involving data transfer in a specific narrow, low frequency band. We propose an analytical approach to obtain the line's transfer function and conduct simulation to determine the performance of the LV PLC system in terms of bit error rate. We then evaluate the performance of the medium access control protocol (MAC) for the LV PLC network taking into account its physical characteristic and performance limitation. We show by simulation that packet loss in this network can be significant even with a light traffic condition due to the noisy channel, and the goodput declines sharply once the individual transmission rate is high enough to congest the network. We also show that the channel errors can be reduced by adjusting the MAC parameters to allow the retransmissions recouping losses.**

Keywords-**Low voltage power line communication; medium access control protocol; performance evaluation; orthogonal frequency division multiplexing**

I. Introduction

The efficiency, safety and reliability of the electricity transmission and distribution system can be much improved by transforming the current electricity grids into an interactive (customers/operators) service network or *smart grid*. Furthermore, smart grid aims to take advantage of the existing power distribution networks to provide value-added services such as network management and control, broadband Internet access or intelligent home where devices are communicating via the electricity wires.

The electrical power system network is comprised of high voltage (HV), medium voltage (MV) and low voltage (LV) transmissions lines. The different transmission lines carry different power levels over different distances using various gauge aluminium conductors steel reinforced cables for electric distribution. The power transmission lines are known to be non-ideal for communication purpose due to noise and unpredictable impedance and attenuation, which vary with time, frequency and location. Despite that fact, power line communication (PLC) has been using in the past to send control signals within the electricity grid [1]. Recent development of more sophisticated modulation (e.g. spread spectrum or multiple carrier modulation) and stronger error correction schemes has overcome earlier obstacles and enabled PLC at speeds comparable to other wired communication mediums. Due to its pervasive nature, PLC now becomes a real contender for an alternative infrastructure in providing services that require data communication.

In particular, advanced metering infrastructure (AMI) is one of the smart grid applications that recently attracts considerable interest from both industry and the research community. It is because AMI provides consumers with the ability to use electricity more efficiently and at the same time enables utilities to monitor and repair their network in real time. Early version of AMI has already been implemented (e.g. in part of Victoria, Australia [2]) using wireless technologies to collect meter readings remotely and automatically. In this paper, we investigate the use of LV transmission line as a medium for data communication between electric meters and the substation as a data concentrator point located on different parts of the distribution network. The recommended frequency band for communication in the AMI application is a narrow, low frequency band between 9 and 490 kHz [3]. Although the choice of LV line for AMI communication is natural as it connects pole-mounted transformers to individual homes associating with the electric meter, its characteristic and network performance from the medium access control point of view are not well understood in the literature. It is because the majority of the work in this area was focusing on indoor PLC network and at the high frequency band applicable for high-speed broadband access [4]. Note that if the PLC is to be extended beyond substation transformers to the MV network, data transmission should then bypass those transformers that have a great impact on PLC in the frequency range of interest.

To this end, our contributions is twofold. We first describe in this paper an analytical model that enables us to obtain the transfer function of the LV PLC lines at the above specified frequency band for generic distribution networks (i.e., including outdoor transmission lines). Based on the obtained transfer function, we then investigate the performance of the LV PLC network as a data communication medium via simulation in terms of bit error rate (BER) versus the signal to noise ratio (SNR). Another major contribution of this paper is the evaluation of a medium access control (MAC) protocol for the LV PLC network based on our understanding of its physical characteristic and performance limitation. Both contributions are useful in designing and optimizing the PLC performance under different load conditions and network configurations.

The rest of the paper is organized as follows. In Section II, we describe the low-voltage power line system and study its physical layer characteristics as well as its communication performance. In Section III, we introduce the MAC protocol for the considered LV PLC system, and conduct simulation experiments to evaluate its performance in Section IV. Finally, some important conclusions are drawn in Section V.

II. LOW-VOLTAGE (LV) POWER LINE

In this section, we first outline our approach to study the characteristic of the LV power lines via its transfer function. We then study the performance of the PLC system in terms of bit error rate (BER) and their resistance to noise using the proposed transfer function and existing known noise models. Results obtained in this section are essential for the design of the medium access control (MAC) protocol of the PLC system. The proposed MAC and its performance will be discussed in later sections.

A. LV line characteristic

Data transmission over power lines suffers from various frequency-dependent reflections and attenuation caused by the cable material and network branching, and is getting worst as the length of the lines increases. There have been several techniques in the literature to model the power lines in attempt to describe the channel behaviour either in time or frequency domains.

Typical time-domain model such as a multipath propagation model is based on superposition of reflected signal on different paths within a PLC network. Model parameters of this multipath propagation approach can be calculated using a so-called echo model [1] that assumes the backward reflection from impedance discontinuity is negligible. Moreover, the model becomes intractable when there are multi branches connecting to the same joint. Alternatively, the parameters can be retrieved from measurements of the network in question, which requires little computation and is easy to implement. The latter, however, is not flexible as measurements must be carried out for every networks and configurations.

In the frequency-domain the transfer function of the PLC system is modeled as a product of simpler transfer functions from several cascading blocks constituting the network. In particular, a so-called transmission matrix or scattering matrix of the building block (e.g. two-wire transmission line block) is computed before its transfer function is determined. The transmission matrix describes the relationship between the voltage (V) and current (I), while the scattering matrix gives that of the incident and reflected waves. As a result, both incident and reflected waves will contribute in the transfer function obtained from transmission matrix. This model is scalable as the network complexity increases and can better describe the network behaviour as a function of physical parameters. The model parameters can again be obtained from the actual measurements, but can also be derived from eigen analysis of network matrices or the lumped-element circuit transmission line model [4]. In this paper, we will utilize the approach of the transmission matrix where the model parameters are determined based on the lumped-element circuit transmission line model. It is because the lumped-element circuit is accurate in the 9-490 kHz frequency range recommended for the AMI application where its length is much smaller than the circuit's operating wavelength [5].

To this end, two line parameters, i.e., the propagation constant γ and the characteristic impedance Z_0 of the lumped-element circuit model, can be given as

$$\gamma = \sqrt{(R + j\varpi L)(G + j\varpi C)}, \tag{1}$$

$$Z_0 = \sqrt{\frac{R + j\varpi L}{G + j\varpi C}}, \tag{2}$$

where ϖ is the angular frequency, R, L, C, G are resistance, inductance, shunt capacitance, and shunt conductance of a unit length (m) of the transmission line. The same method as in [4] can be used to determine R, L, C, G physical parameters.

A typical topology of the residential power lines is shown in Fig. 1, which can be considered as a composition of many suitable simpler networks (building blocks) as depicted in the same figure.

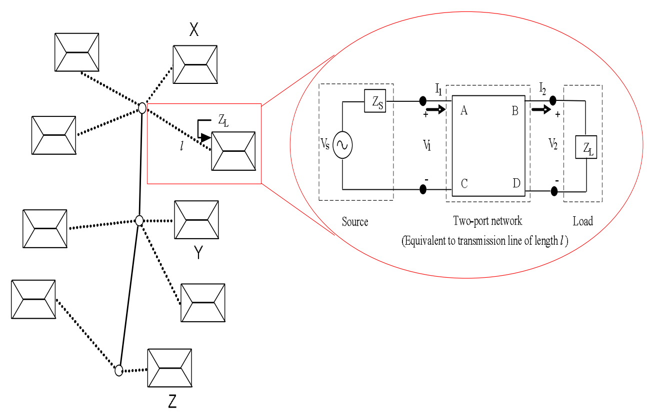

Fig. 1. Illustration of a PLC system.

In Fig. 1, the relation between the sending-end quantities (V_1 and I_1) and receiving-end quantities (V_2 and I_2) is written as

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} cosh(\gamma l) & Z_0 sinh(\gamma l) \\ \frac{1}{Z_0} sinh(\gamma l) & cosh(\gamma l) \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{3}$$

where l is the length of the transmission line. The 2×2 transmission matrix in (3) is called the ABCD matrix from which the transfer function (H) can be derived

$$H = \frac{Z_L}{AZ_L + B + CZ_L Z_S + DZ_S}, \tag{4}$$

where Z_L, Z_S are load and source impedances of the single-branch transmission line, respectively.

The overall ABCD matrix of the network shown in Fig. 1 consisting of multiple single-branch transmission lines, each

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has different cable length and cable type and is described by the i^{th} ABCD matrix, is then given as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_i \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}. \quad (5)$$

The overall transfer function is then obtained as in (4) where Z_L, Z_S are load and source impedances of the PLC network.

Based on a typical single-phase low voltage power line in Australia [2], the solid lines in Fig. 1 represent single-phase bare overhead aluminium conductor steel reinforced (ACSR) cables with the length of approximately 100 meters between two power poles. The dashed lines represent the branch copper cables with PVC insulations. The ACSR cables have a 431.2 mm^2 cross-sectional area and the copper cables have a 10 mm^2 cross-sectional area. As a result, the transfer functions of the power line channel over 9 kHz $\sim$ 490 kHz for the transmission pairs (X to Y and X to Z in Fig. 1) are depicted in Fig. 2. Here we set $Z_s = 50$ Ohm and Z_L is modeled as in [6].

It can be seen that the derived transfer functions do not have significant multipath effects as we expect in this band of frequency. The strong attenuation notches at about 124 kHz are mainly caused by the impedances of the branch loads inside the residential properties.

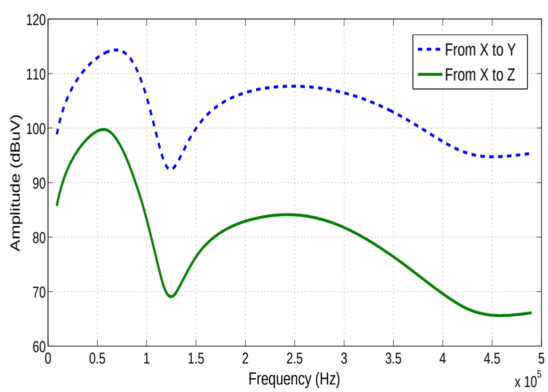

Fig. 2. Transfer function of the LV lines.

B. LV PLC System Performance

Having derived the transfer function, herein we study the performance of the single-phase LV PLC network in terms of BER using multicarrier simulation. In particular, OFDM (orthogonal frequency division multiplexing) modulation scheme is used in our simulation to investigate the BER that can be achieved via this system. Table I shows the parameters used in the simulation. To simulate a realistic PLC network, both white Gaussian noise (AWGN) and impulsive noise [7] are used in the simulation. The impulsive noise is the Middleton's class A and is characterized by the impulsive index α and the ratio Γ between the background noise power and impulsive noise power. In our simulation we chose $\alpha = 0.1$ and $\Gamma = 0.1$. The performance results are shown in Fig. 3 for both AWGN and impulsive noises, respectively.

TABLE I
PLC PHY PARAMETERS

Parameter	Value
Modulations for carriers	DQPSK
Total raw data rate	42.9 kbps
Coding scheme	1/2 rate convolutional code
Number of data subcarriers	96

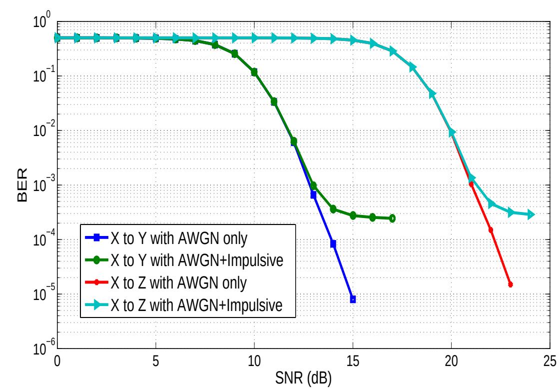

Fig. 3. BER vs. SNR for LV PLC system.

It can be seen in Fig. 3 that the BER is acceptable between point X and Y given the signal to noise ratio (SNR) is above 13 dB as recommended in [8] even in the presence of the AWGN or impulsive noises. For the SNR above the 15 dB, however, the BER is not improved when the impulsive noise is present. More importantly, at the same SNR (i.e. around 13 dB) the BER between point X and Z is very high suggesting that direct communication between them is not feasible.

III. The MAC protocol for LV PLC networks

Given the uniqueness in the physical layer of the LV PLC system, a new data link solution for reliable data exchanges in LV PLC network is necessary. There has been a number of research in the literature dealing with design of a MAC protocol for a PLC system [9]. Majority of the research work focuses on indoor PLC and the carrier sense multiple access with collision avoidance (CSMA/CA) protocol is the most popular choice for networking in the PLC environment. For example, Lee *et al.* in [11] presented an analytical work where the CSMA/CA protocol is used for an indoor PLC home network. Kim *et al.* in [10] later proposed a multihop PLC MAC protocol called Korea Standard power line MAC protocol (KS-MAC). The protocol KS-MAC standard uses the CSMA/CA protocol and considers multihop relaying operation again in an indoor PLC home network.

An outdoor PLC network has obvious differences in physical layer characteristics, and hence it warrants an investigation on the design of a MAC protocol and its performance. A popular solution has been proposed for the outdoor LV PLC environment by the PRIME Alliance Technical Working Group [12]. In this environment, the CSMA/CA protocol is used in the MAC sublayer for the access of the common broadcast channel, and switching nodes are introduced to perform packet forwarding for different subnetworks.

Given the popularity of the CSMA/CA protocol for PLC networks, in this paper, we also consider use of CSMA/CA MAC protocol with layer-2 switching for our proposed LV PLC system. Similar to the common CSMA/CA channel access strategy, whenever an AMI station[1] is ready for transmissions, it first senses the medium to ensure that the channel is idle. If the channel is sensed idle for a guard period known as distributed interframe space (DIFS), then it transmits its packet. Otherwise, it performs a backoff which reschedules the transmission at a later time.

Herein the common binary exponential backoff (BEB) is adopted for our protocol design. During the backoff process, a discrete backoff counter is chosen uniformly in the range $[0, CW-1]$, where CW is called the contention window. The backoff counter is decremented by one for every fixed time period called a slot where the channel remains idle. It is frozen when a packet transmission is detected on the channel, and reactivated after the channel is sensed idle again for a guard period. The guard period is equal to a DIFS if the packet was received error-free, and equal to the extended interframe space (EIFS) if an error occurred. A station performs its transmission when its backoff counter reaches zero.

When a packet transmission is performed, the sender is expected an immediate positive acknowledgement (ACK) replied by the receiver. The sender may wait for a predefined short interframe space (SIFS) time period for the ACK to arrive. If such an ACK is received within the EIFS period, the packet is said to be transmitted successfully. Otherwise, the transmission is unsuccessful and another backoff for this packet transmission is initiated. For each packet the CW is initialized to CW_{min} and doubles after each unsuccessful transmission until it reaches CW_{max}, after which it remains constant until the packet is either successfully received or a retry limit is exceeded and the packet is dropped.

Since we have established in Sec. II that a transmission can only reach its one-hop neighbours in this network, any end-to-end transmission beyond one hop relies on intermediate stations to forward packets. We propose the use of layer-2 switching approach where any end-to-end transmission is performed within the data link layer. In particular, a station whose transmission is addressing to its intended receiver outside of its one hop range must explicitly select one of its neighbours to forward the packet. If there are two or more neighbours that can reach the intended receiver, the sender may randomly select one per packet basis. The one hop transmission for the packet sending/forwarding is performed using the CSMA/CA mechanism with BEB as described above. Given that the targeted communication network is a tree-like topology where the substation is the headend, our packet forwarding solution assumes that each station has knowledge about its neighbours.

[1]In this paper, the AMI station refers to a device consisting of a smart meter and a transceiver that enables communication between stations and with the headend substation.

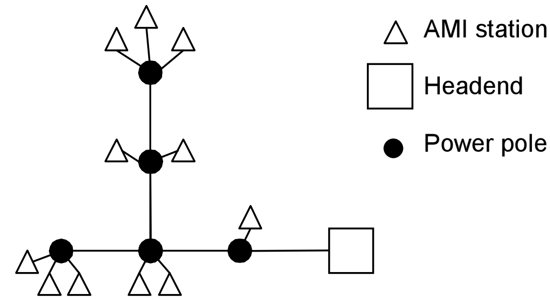

Fig. 4. The considered topology.

This information can be established during a network initialization procedure. For example, a particular broadcast-tree construction may be used for this purpose.

Specifically, in the initialization procedure, the headend first broadcasts an INIT control message to its immediate neighbours. Each neighbour station then rebroadcasts the message after a backoff. Each station also associates the source of the received INIT message as its upstream neighbour and exchange the neighbour list with them. The initialization procedure completes when the INIT messages propagate to the farthest station from the headend. To achieve convergence, neighbour lists are periodically exchanged between neighbours. As the topology change in the PLC network is infrequent, the impact of the time required for the initialization procedure on the overall performance of the operation is negligible. Finally, a similar operation is used for joining of a newly activated station by broadcasting a JOIN message.

IV. MAC Performance Evaluation and Discussion

In this section, we present simulation results of the proposed LV PLC network. For our experiments we use the ns-2 simulator [13] with appropriate modifications to the MAC module enabling the broadcast in PLC networks. Table II presents the system parameters used in the network and Fig. 4 depicts our considered topology. Each AMI station is attached to a power pole, and each power pole is 100 meters away from its neighbouring power pole. We consider a smart grid scenario where sensing data from each AMI station transmits to the headend. The sensing data may include information of the meter reading and projected power usage. The headend may also broadcast some small amount of information such as utility rates to all stations. The BER of the LV PLC channel is set to be 10^{-4} in our simulation. The parameter settings of our proposed MAC protocol are given in Table II.

In our simulation experiments, we consider that each AMI station generates a Poisson traffic with a particular arrival rate where the destination is the headend. The signals generated by each transceiver are broadcast on the common power line. However, these signals have limited traveling range. They can only reach AMI stations connected to the neighbouring power poles. Beyond this range, the signals appear as AWGN noise and cannot be detected properly as indicated in Sec II.

We first focus on the uplink transmission potential of the

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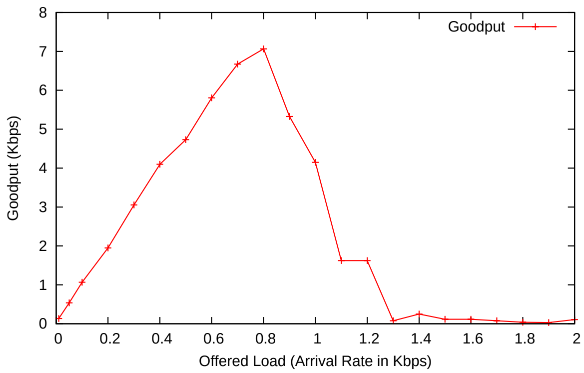

Fig. 5. Illustration of system goodput versus arrival rate.

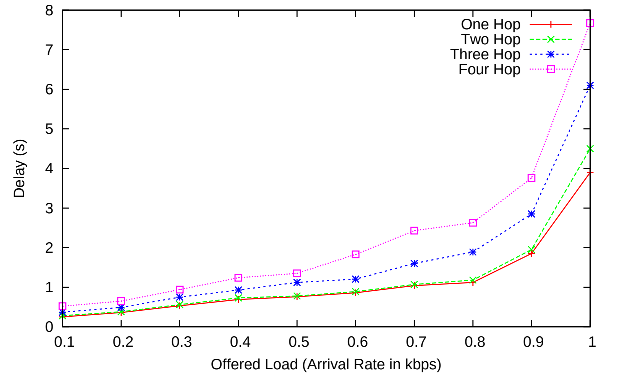

Fig. 6. Illustration of end-to-end transmission delay versus arrival rate for $CW_{min} = 32$.

system. In this setup, all stations except the headend generate a Poisson traffic stream addressing to the headend. We measure the goodput of the system, which describes the rate of useful information successfully received at the headend. We present the goodput performance of the system for a range of source arrival rates. As illustrated in Fig. 4, given a total of 11 AMI stations in the network, the total amount of generated traffic is 11 times the source arrival rates.

In Fig. 5, we present the system goodput for a range of offered load measured by the arrival rates. As observed from the results, the system offers transmission capability up to 7 kbps. This peak performance occurs when each station generates 0.8 kbps of traffic volume. With 11 stations, the total amount of traffic generated is 8.8 kbps and around 1.8 kbps of traffic suffers loss. This represents a delivery ratio of around 79.5%. These packet losses are mainly due to the noisy channel even with a retry limit of 7. When the arrival rate increases beyond 0.8 kbps, network congestion occurs where system goodput declines significantly. This is because with more traffic, transmission collisions intensify which leads to more packet losses.

We further investigate the end-to-end packet transmission delay in this setup. This measure provides critical information for the quality of service (QoS) design of the smart grid application. In Fig. 6, we depict the end-to-end packet transmission delay as a function of the arrival rate representing the load of the network. We show separately the transmission delay for different numbers of hops. As can be seen, the stations that are farther away from the headend incurs relay and thus

TABLE II
PLC MAC PARAMETERS

Parameter	Value
MAC Header size	26 bytes
Payload size	100 bytes
Slot	$20\mu s$
SIFS	$10\mu s$
DIFS	$50\mu s$
Retry Limit	7

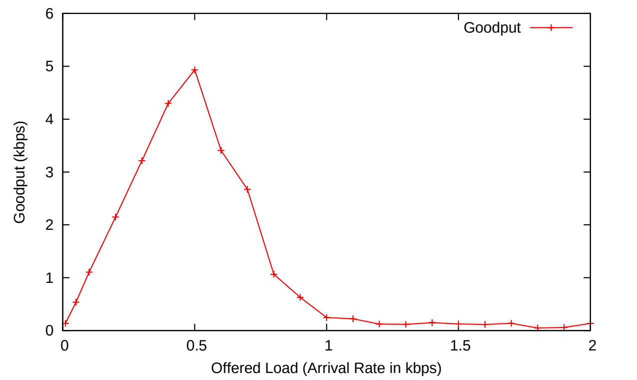

Fig. 7. Illustration of system goodput versus arrival rate with presence of downlink broadcast traffic.

the delay is higher. The transmission delay turns large at around 0.8 kbps of arrival rate indicating reaching of network congestion. Besides, due to the relatively low physical data rate and multihop transmission requirement, the end-to-end transmission delay for stations farther away from the headend exceeds 1 second, which indicates that the system may not be able to support delay sensitive applications.

In the next experiment, we include the downlink transmission and measure the uplink and downlink throughput. In this setup, the headend broadcasts a Poisson traffic stream to all AMI stations in the network. The packet arrival rate of the headend is the same as that of an individual AMI station. For the downlink broadcast traffic, it is considered successful and contributes to the goodput measure when all stations have received the packet. The system goodput results are shown in Fig. 7. We first observe the drop in the maximum goodput from just over 7 kbps to around 5 kbps for the cases without and with downlink broadcast traffic, respectively. With the presence of the downlink traffic, the network congestion appears when each AMI station generates Poisson traffic beyond 0.5 kbps. This indicates the high impact of downlink broadcast traffic.

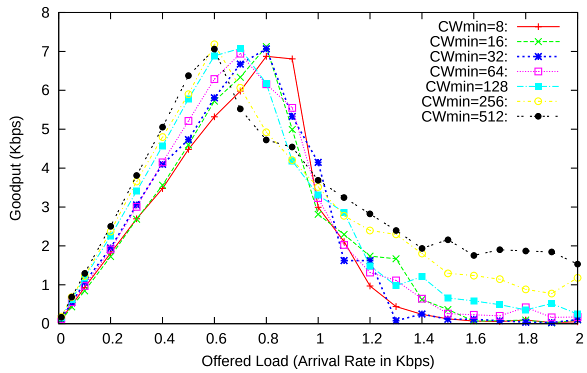

Fig. 8. Illustration of the influence of CW_{min} parameters on the system goodput.

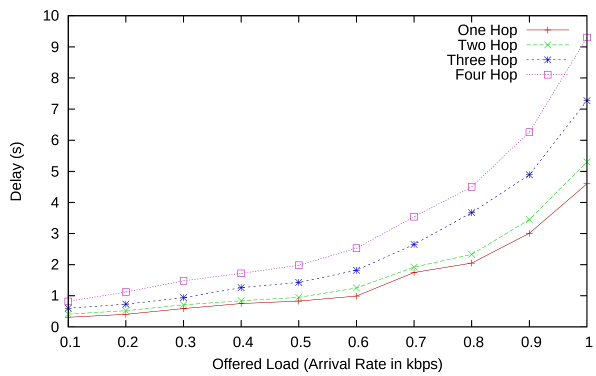

Fig. 9. Illustration of end-to-end transmission delay versus arrival rate for $CW_{min} = 512$.

In the final experiment, we study the influence of CW_{min} parameters on the system goodput. In Fig. 8, we show the system goodput performance versus arrival rate for a range of CW_{min} values while CW_{max} is maintained at 1024. As can be seen, with a larger CW_{min} value which indicates a less aggressive backoff, a lower packet loss rate is observed. This can be determined by slopes of the goodput curves in their increasing region. The extreme setting of $CW_{min} = 512$ achieves 7 kbps when the individual arrival rate is just above 0.6 kbps representing almost 100% of delivery ratio or no packet loss. Conversely, the setting of $CW_{min} = 32$ achieves 7 kbps when the individual arrival rate is 0.8 kbps representing around 79.5% of delivery ratio. However, a large setting of CW_{min} which combats packet loss effectively introduces longer retransmission delay and thus lengthens the end-to-end transmission delay. This is illustrated in Fig. 9 where the end-to-end transmission delay is longer than that reported in Fig. 6 for the setting of $CW_{min} = 32$.

V. CONCLUSION

In this paper, we have proposed an analytical model to obtain the transfer function of a low voltage power line and conducted simulation to determine the performance of the LV PLC system in terms of bit error rate. We found that there is no significant multipath effects in the band of frequency specified for AMI applications. This suggests that the popular multipath propagation model may not be suitable for modeling LV lines. Furthermore, we have observed that the BER is acceptable for communication between adjacent AMI stations as long as the SNR is above 13 dB, but that can not be carried out to stations that are further away in the network.

We have also designed the MAC protocol that is suitable for communication required for the smart grid applications in LV PLC networks such as AMI application. Via simulation, we have shown that packet loss in the LV PLC network can be significant even with a light traffic condition due to the noisy channel, and the goodput declines sharply once the individual transmission rate is high enough to congest the network. We have demonstrated that the channel errors can be reduced by adjusting the MAC parameters (i.e. CW_{min}) to allow the retransmissions recouping losses.

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