Cooperative Communication over a NS-3 PLC Module

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Abstract. Taking advantage of the PLC module developed using NS-3 network simulator, we aim through this work to study a realistic model of a cooperative in-home network based on the MAC switching. To evaluate the QoS of the implemented system, we study the channel behaviour in terms of maximum capacity and bit error rate for the AF and DF relay protocols, in comparison with direct transmission. We also study the throughput obtained by our cooperative system. According to the simulations, and despite the short distances and the minimal variations, the cooperative transmission has proved its out-performance compared to the direct transmission protocol.

Keywords: Power line communication · In-home application
Cooperative communication · MAC layer · NS-3 simulator

1 Introduction

With the advent of renewable energy sources, the power grid is going through a major evolution. To take into consideration these new changes, old electrical equipments need innovative communications systems able to remotely control the intermittent production of renewable energies and optimize consumption. Technological intelligence was introduced in these networks, which led to the concept of Smart Grid (SG).

The Smart Grid is based on making data and power transmissions coexist within the same electrical support, mainly due to the power line communication technology (PLC). The modernization of the grid has used various information technologies in order to meet the communications requirements (reliability, data rates, throughput, security, etc.) in such environments, like the indoor and outdoor systems [1].

Cooperative transmission is one of the solutions to improve the efficiency and performance of the SG network with the presence of disturbing elements characterizing the electrical medium. This relaying technique consists in routing the information from the source to the destination via a relay node, through a

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different path, when the direct link connecting the source and the destination is affected by the fading effects. This cooperation offers flexibility, robustness and coverage to the whole network.

2 State of the Art

Several studies have investigated the application of cooperative communication in different environments. Most of them targeted the physical level, such as the energy consumption side [2], multiplexing/modulation techniques [3] and total capacity [4]. Different relay protocols have been used for this purpose, to which belong the Decode and Forward (DF) and Amplify and Forward (AF) [5]. In [6], a comparison of these two protocols was conducted in an in-home environment, based on a measuring campaign performed in an urban area in Juiz de Fora in Brazil. The results were used to compare the AF and DF protocols in terms of data rates.

Concerning the MAC layer, we found only few works working on it. In [7] the authors show the benefits of the cooperative transmission in terms of packet error ratio through a cooperative protocol for PLC link layer. Using this protocol, the relay sends a Want To Cooperate message to the source that has already received a negative acknowledgement (Nack) from the destination. We note that the simulations for this work were done with Matlab, which is the common evaluation environment used in the cited works. In our work we consider an in-home application based on cooperative communication. We chose to work with NS-3 simulator, which allows to simulate different topologies of the PLC network and offers more flexibility in the channel configuration than the other simulation tools [8]. Simulations in [9–11] were based on this module.

In [9], the authors have studied the characteristics of Linear-Periodic Time-Variant channel which they implement using PLC NS-3 module. Based on this characterization, they introduced an analytical model for MAC scheduler and evaluated its performance through simulations. In [10], a study of the channel transfer function for several PLC topologies was detailed and simulated using the NS-3 PLC module. Simulation results were compared with the output of the MATLAB simulator and the real measurements for broadband and narrowband PLC. Unlike the above-mentioned works which focused mainly on direct transmission schemes, we are treating in our work a cooperative PL communication.

An evaluation of an in-home PLC system was produced in [11] to measure some Quality of Service (QoS) metrics through this network. Based on this home model, we added to the direct communication system studied by the authors, a cooperative communication scheme using the NS-3 PLC module, where the data exchange is done in dual hop via a relay node.

3 Contribution

Our contribution consists on studying the contribution of the cooperative communication in an in-home environment, through the comparison of the AF and

DF protocols with the direct communication. Unlike the previous works, we are based on the PLC module developed using the NS-3 simulator, which is described in [8]. The QoS is evaluated in term of capacity, Bit Error Rate and network throughput. For the latter, we have implemented a new MAC Header facilitating cooperative communication between the different nodes. More details will be provided later.

Our paper will be organized as follows: In the first section we introduce the adopted topology and the NS-3 PLC elements used to build it, followed by a description for the cooperative system. In the second section we use different metrics to evaluate the QoS through the network. Finally, the simulation results are discussed in the third section.

4 Network Topology

The NS-3 simulator is a discrete-event network that includes several modules and features used to simulate network protocols with different topologies. Simulations can be visualized through a graphical interface. The PLC module, not being officially a part of the NS-3 standard distribution, is a module allowing various configuration of PLC networks and the simulation of realistic channels behaviour.

4.1 In-Home Topology

For our in-home application, we adopt the topology model used in [11] to take advantage of the cabling measurements and to compare the given simulations results with the cooperative transmission. More details on the design of this model can be found in the same reference. Figure 1 shows a layout of the network topology with stretching wires. It considers a 60 m^2 home composed of a bedroom, a living room, a kitchen and a bathroom.

The simulation of a communication between two nodes of this network goes through a defined channel configured using the PLC module.

4.2 NS-3 PLC Elements

This module is described in details in [8]. Establishing a communication between two nodes using the PLC module is done in several steps. ***Nodes*** are at first, created and connected through a ***Cable***. The current PLC implementation includes three commonly used power cable types. We are using the NAYY150SE cable in this work.

The ***Channel*** is set up based on a ***Spectral Model***. ***Nodes*** are connected to the channel using methods provided by a ***Net Device*** to enable communication between them.

To facilitate working with the ***Net Device***, a ***Device Helper*** is defined and is usually responsible for creating ***Transmitter*** and ***Receiver Interfaces***. ***Outlets*** are installed on the nodes, and a ***PLC Physical*** is installed on each ***Outlet***.

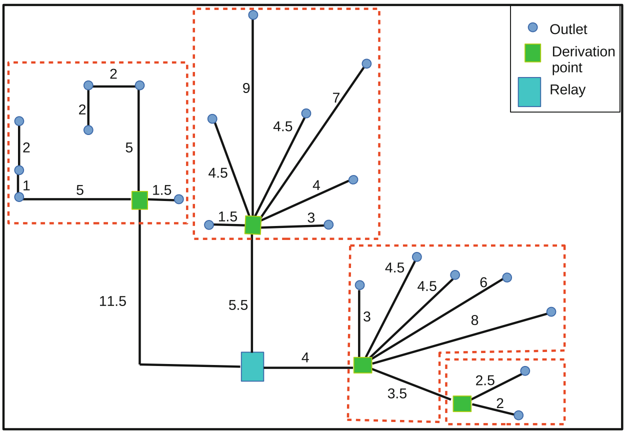

Fig. 1. In-home simulated topology

Once the topology is successfully created, the ***Noise Floor*** is set through ***Interference*** class at each ***Physical Interface*** installed on each ***MAC***. To send a packet from one node to another, the ***CSMA/CA*** MAC protocol is enabled on nodes.

As mentioned in [8], the PLC module supports four ***Impedance*** types, which are fixed, frequency selective, time-selective, and frequency and time selective impedance. Fixed impedance is used in our simulation.

4.3 Cooperative Communication

As cited in [12], cooperative relaying is no longer limited in channel specification and physical layer but also investigated with MAC protocols. In our case, the relayed path is then decided at MAC layer as described in Fig. 2 (usually done based on routing tables).

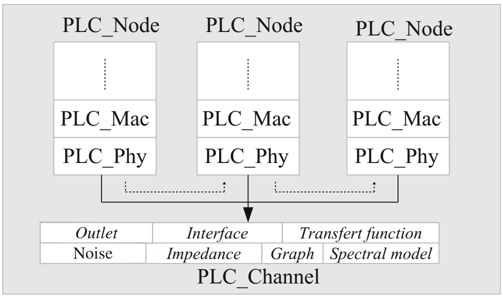

Fig. 2. Cooperative transmission through the MAC and physical layers

The PLC module provides two MAC protocols with different control mechanism which are the ARQ (Automatic Repeat Request) and the Hybrid ARQ. We are using in our network the ARQ MAC where a successful transmission is marked with a positive acknowledgement (Ack).

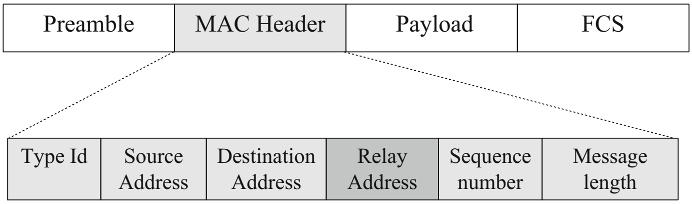

Fig. 3. PLC frame format

To do this, the decided relayed packet is retrieved by the intermediate node due to the new address field added to the MAC header indicating the relay's MAC address (see Fig. 3). The channel access in this module adopts the CSMA/CA mechanism. This mechanism is basically presented as follows: When the channel is free, the sending station executes its Backoff algorithm [14].

It is a counter started at the end of the DIFS (DCF interframe space) that decrements as long as the channel is free. When a collision is detected, this counter is suspended until the channel is released. Once the counter reaches 0, the station starts sending its packet and waits for the reception of an Ack from the destination station. The destination's response is sent after a short interframe space (SIFS). Once the Ack is received, the transmitting station will understand that the transmission was made without collisions. In the opposite case and at the expiration of the Backoff counter, the transmitter resends the same frame.

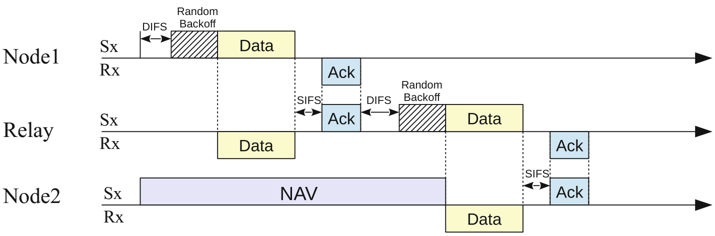

Fig. 4. CSMA/CA scenario for cooperative transmission

In our cooperative network, the CSMA/CA algorithm is performed twice: between the source and the relay, and then between the relay and destination. When the channel is sensed busy, an indicator called Network Allocation Vector (NAV) is maintained at each listening node to inform about the channel reservation status [14]. We have summarized the communication in Fig. 4. In the following sections, we will use this characterization of the network to evaluate its performance.

5 QoS Parameters

The purpose of our work is to evaluate the QoS on this cooperative network, through the quantification of some selected metrics, which are the capacity, the bit error rate and the transmission throughput.

Channel Capacity

Theoretically, the maximum achievable capacity C is given by the known Shannon formula:

$$C = B \log_2(1 + \gamma). \tag{1}$$

B refers to the bandwidth and γ to the received SNR. For a cooperative communication, capacity expression depends on the adopted relaying techniques. Extensive researches focused on the AF and DF protocols in dual or multi-hop communication and several maximization problems were posed. To defend the output of our system, we calculated the capacities of the AF and DF systems in order to compare their achievable rate with that of a direct communication. These capacities are defined by [13]

$$\begin{aligned} C_{AF} = B \log_2(1 + \gamma_{AF}) \quad with \;\; \gamma_{AF} = (\sum_{i=1}^{N} (\gamma_i)^{-1})^{-1} \\ C_{DF} = B \log_2(1 + \gamma_{DF}) = \min_{i=1..N} \{C_i\} \quad with \;\; C_i = B \log_2(1 + \gamma_i) \end{aligned} \tag{2}$$

where γ_i is the received SNR at the i^{th} node.

Bit Error Rate

The Bit Error Rate (BER) is a value usually given in percentage and defines for every transmitted bit sequence the erroneous bit rate. Its expression depends on the adopted modulation scheme. Various forms of digital modulations can be applied in powerline communication. In Narrowband systems, Frequency Shift Keying (FSK), Phase Shift Keying (PSK) and Amplitude Shift Keying (ASK) are used. On the other side, for a transmission of high data rates (above 1 Mbps), M-ary PSK, M-ary QAM and OFDM are adopted for the spectral efficiency they offer [15]. For the BPSK modulation, the BER is given by:

$$BER = \frac{1}{2}\, erfc\left(\frac{E_b}{N_0}\right) \quad with \;\; \frac{E_b}{N_0} = \frac{\gamma.B}{C} \tag{3}$$

We remind that $\frac{E_b}{N_0}$ is by definition the energy per bit to noise power spectral density ratio.

Network Throughput

By definition, the throughput is an average number of flow units per unit of time deducted after successive processing periods. Unlike the theoretical capacity, the throughput T is the output of packets transmission simulation through the network, which explains its lower values. It is calculated using the following formula:

$$T(bit/s) = \frac{8.TotalReceivedBytes}{RoundTripDelay} \tag{4}$$

The Round Trip Delay is defined by the total time spent by a signal to be transmitted from a node to another until the reception of the Ack.

The parametrization of these quantities according to the considered network is specified during the simulation.

6 Simulation Results

The NS-3 PLC module offers specific features to analyse the network and simulated channels behaviour. The installation of this module and basic steps to simulate a PLC system are described on the official website of the developers (see [8]). For the study of the communication channel, some estimations have been taken into account. Table 1 shows the values of the used variables.

Table 1. Numerical values used in simulation

Variable	Value
Nodes number	26
Frequency range	2–30 MHz
Noise Floor	15^{-9} W
Transmit PSD	10^{-6} W
Packet size	1024 Bytes

The channel transfer function is calculated using the method implemented in the PLC module. We first choose to study Shannon capacity C with and without a relay station. Figure 5 shows the variation of this capacity for an AF and DF relay systems versus direct transmission link.

Theoretically, the direct channel can reach a maximum capacity of 70 Mb/s, while DF reaches more than 100 Mb/s, thus exceeding the capacity given by the AF system. This is explained by the low value of the SNR of the direct transmission compared to the cooperative one.

Compared with Figs. 6, 7 and 8, we notice the decline in capacity values using M-QAM modulation with M = 2, 16, 64. It should be reminded that the constellation for M = 2 is the same for BPSK modulation. A higher QAM modulation allows carrying more bits through the channel, Fig. 6, 7 and 8 shows that

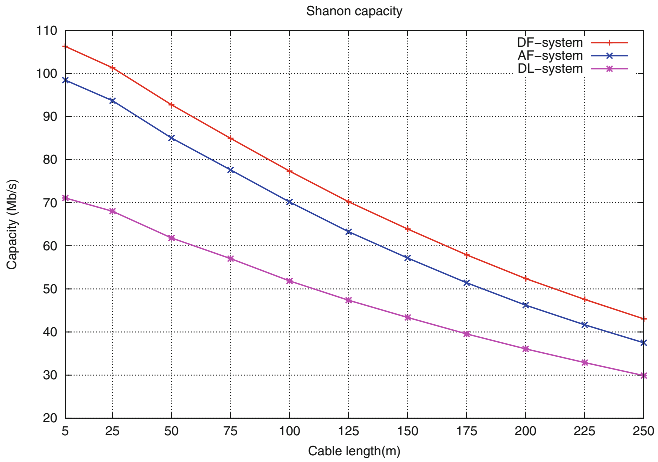

Fig. 5. Shannon capacity variation for cooperative and non cooperative communication

the capacity is proportionally increasing by moving to a higher-order constellation. Also, it is clear that the highest values of capacities are given in short distances. The cooperative communication proves its efficiency in terms of data rate compared to the direct link.

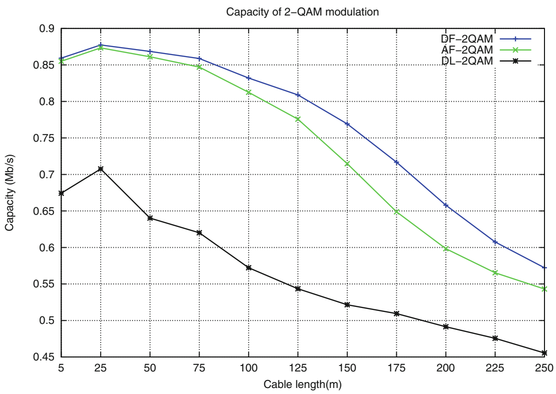

Fig. 6. Capacity for 2-QAM modulation

Concerning the error rate, Fig. 9 gives the BER function progression for the direct channel as well as those relayed. The percentage of error is certainly small in short distances, but the gap between the BER given with the relay compared to the direct transmission is important.

This is due to the better signal quality and the higher spectral efficiency provided by the cooperative transmission.

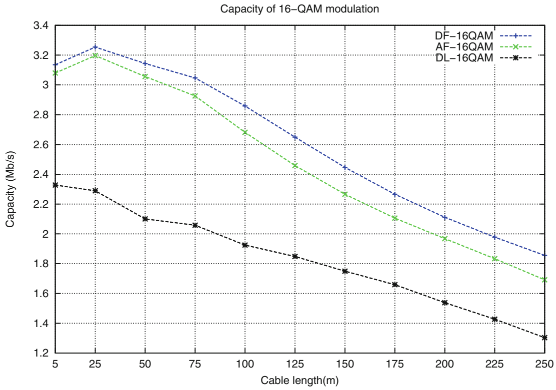

Fig. 7. Capacity for 16-QAM modulation

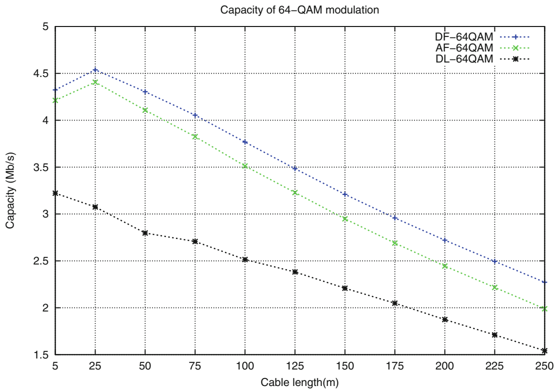

Fig. 8. Capacity for 64-QAM modulation

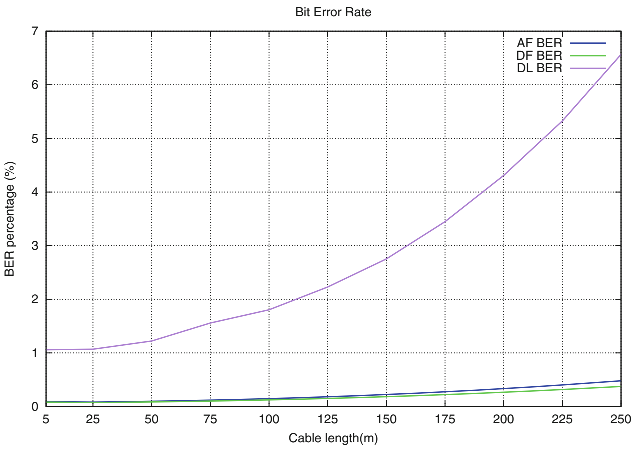

Fig. 9. BER percentage variation with cable length

The cooperative communication technique has been exploited at the MAC level by measuring the throughput value based on MAC forwarding without the use of an Internet stack.

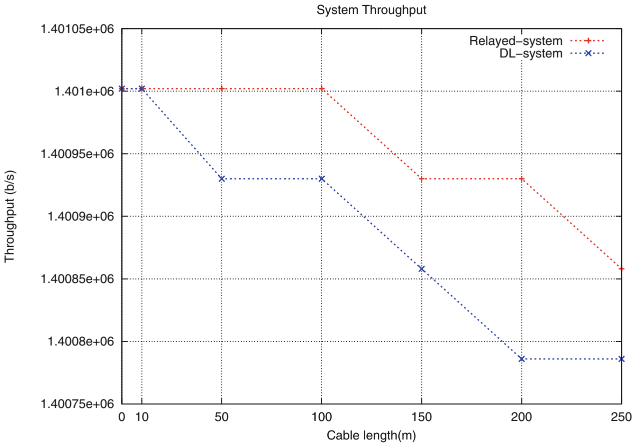

Fig. 10. Measured throughput for cooperative and direct link communications

Finally, Fig. 10 shows the comparison between the three simulated techniques. The improvement of the throughput is clear, although showing the difference between the values has required a precision to 6 digits after the decimal point because of the relatively short wiring adapted for our application. This throughput increasing should be better seen for long distances. Our application focuses on an in-home application where the cable length is limited.

This increase in throughput as well as in capacity has shown the advantage brought by the cooperative communication that we have introduced into this in-home system relative to the concurrent direct link.

7 Conclusion

In this paper, we chose to work on network simulators like the NS-3 simulator whose PLC module was recently developed and put in open source. Based on this module, and focusing on an in-home application, our work consisted in studying a cooperative system based on MAC forwarding by introducing a modification to the predefined MAC header. For the QoS evaluation across our network, we simulated the capacity of a direct channel connecting a source to a destination, as well as the capacities of two relayed channels using the AF and DF protocols while using different QAM modulations. The error percentage (BER) has also been simulated for these channels. The next quantity was the network throughput. The short distances did not prevent us from seeing a clear result on the out performance of cooperative communication compared to direct transmission. It will be interesting to collect these QoS measurements through the set up of a real PLC system and configuring a relay host. This will permit to compare the output of the real system to the results given by the NS-3 simulation.

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