Street Lighting in Smart Cities: a Simulation Tool for the Design of Systems based on Narrowband PLC

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***Abstract*—Excessive or improper street lighting is currently responsible for a significant waste of electrical energy in many cities worldwide. In order to improve energy efficiency, the traditional light posts are expected to be gradually replaced by smart systems able to adapt the features of the emitted light to different environmental, traffic, or crowdedness conditions. Power Line Communication (PLC) is the natural choice to support smart light control, since no additional communication infrastructure is needed. However, at the moment not so many simulation tools exist to guide the design and the deployment of smart lighting systems based on PLC. In this paper, we partially address this issue by presenting suitable circuit models that can be used to analyze (through simulations at the physical layer) the behavior of narrowband PLC (NB-PLC) signals transmitted over low-voltage (LV) lines for street light control. The proposed approach is quite simple from the computational point of view, and it is scalable enough to evaluate the quality of PLC signals in large networks with different topologies. The results of several simulations, with signals in the frequency range 95-148.5 kHz, have been compared with the outcomes of some laboratory experiments over a test line.**

***Keywords*—Lighting control, simulation models, cities and towns, Power Line Communication (PLC).**

I. Introduction

The EU policy has defined three strategic objectives to be reached by 2020, i.e. a 20% reduction of greenhouse gas emissions, an increment by 20% of the share of energy produced from renewable resources, and a 20% improvement in terms of energy efficiency. Lighting is a critical source of both greenhouse gas emissions (accounting for up to 70% of the emissions due to road traffic) and electrical energy consumption. In Europe the share of electrical energy used to illuminate the interiors of buildings can be so large as 40% [1], while outdoor lighting may account for about 20% of the city electricity bill [2]. The deployment of smart lighting systems able to adapt automatically light intensity and its features (e.g. luminance, color, flux) not only on the basis of the time of the day, but also as a function of citizens' actual needs, is nowadays considered as a key instrument to reduce energy waste, light pollution and greenhouse gas emissions [3], [4].

Unfortunately, the geographical extension of existing infrastructures as well as the number of street light posts pose serious economic challenges to municipalities, thus hindering the deployment of smart lighting systems on a wide scale. In order to mitigate this problem, the costs for the communication infrastructure have to be minimized. In this respect, Power Line Communication (PLC) technologies are often regarded as the most sensible option to promote a fast transition from classic to smart lighting systems. As known, PLC technologies exploit the existing power lines to transfer commands and data between different devices, thus eliminating the costs due to additional wiring or antennas installation. Both Broadband PLC (BB-PLC) and Narrowband PLC (NB-PLC) technologies have been proposed for smart grid applications [5]. BB-PLC systems operate in the frequency interval 1.8-250 MHz at data rates of hundreds of Mbps. However, they have been developed mainly for local area networks (LANs) (particularly, last-mile links for home networking). So, they can be used just in short-range applications. On the contrary, NB-PLC technologies operate at lower frequencies and at lower data rates (up to 100s of kbps). In Europe NB-PLC relies on four low-frequency bands between 3 kHz and 148.5 kHz, as specified in the CENELEC Standard EN 50065-1 [6]. Originally conceived mainly for remote data acquisition and automatic meter reading, NB-PLC solutions have received an increasing attention for smart grid applications over the last few years because of their low cost and the ability of NB-PLC signals to propagate over longer distances (up to several km) even through transformers [7]. These characteristics make NB-PLC devices suitable for a variety of applications, including smart lighting system control [8].

While new NB-PLC channel models have been recently proposed [9], to the best of our knowledge, just a few studies exist on the propagation of NB-PLC signals over outdoor LV lines, such as those used for street lighting [10]. Therefore, the main goal of this work is to fill this gap. In particular, the purpose of this paper is twofold, i.e.

- To define suitable circuit models in order to understand how the NB-PLC signals are affected by electrical cables, lamps and modems' front ends.
- To implement an easy-to-use simulation framework able to assist technicians in the design of robust PLC-based smart street lighting systems.

Of course, in order to obtain trustworthy simulation results, on one hand the proposed models should be properly validated; on the other the individual model parameters should be extracted from the hardware components deployed on the field.

The rest of this paper is structured as follows: Section II deals with some related work and emphasizes advantages and disadvantages of some existing approaches. In Section III the models of PLC modems, lamps and cables are described. The results of some experiments and simulations in the frequency band 95-148.5 kHz are reported in Section IV. Finally, Section V concludes the paper and outlines future work.

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II. Related Works

The PLC channel modeling techniques can be roughly divided into two groups, i.e. those based on the definition of a radio-like channel model and those based on the bottom-up construction of an network consisting of multiple two-port circuits.

The radio-like channel approach considers the whole power network used for PLC communication as a single channel shared between multiple transmitters and receivers in a multi-path environment. Due to the presence of lines of various length and characterized by different impedances, multiple reflections and echoes may occur in the network. Thus, the linear combination of delayed and attenuated signal replicas at the receiving end can be described by the same mathematical models typically used for wireless communication studies [11]. Unfortunately, this class of techniques is not suitable for analyzing and comparing the behavior at the physical layer of PLC signals used to control a smart street lighting system. Indeed, since the whole power grid is regarded as a single communication channel, adapting the model parameters to different network topologies as a function of the number of nodes and of the length of lines would require a large set of measurements in different conditions. As a result, simulating very different scenarios would be very difficult.

Conversely, the two-port circuit approach is much more suitable for the aim of this paper, as it is intrinsically modular. In this case, the whole PLC network can be split into a graph, whose edges are elementary two-port modules described by independent characteristic matrices [10], [12], [13]. This approach is scalable, efficient and allows an easy representation of different network topologies. Of course, the quality of simulation results depends on the accuracy of the parameter values measured on the field and used in the characteristic matrices. Once all model parameters are known, the computational burden of simulations increases with the complexity and the size of the network considered [14]. In the literature various PLC two-port circuit models exist. However, most of them are focused on BB-PLC systems [12], [15]. A complete two-port component-based simulation tool is described in [16]. However, the underlying model is still mainly conceived for BB-PLC systems in the case of LV outdoor overhead power lines. Also, components characterization heavily relies on measurements.

A quite different model is described in [17], where the power line cables are represented as transmission lines, as proposed in this paper. However, also that solution is focused on BB-PLC systems. On the contrary, the approach described in this paper is different from other models available in the literature for two main reasons. First of all, our work is focused on NB-PLC. Secondly, the proposed model does not consider just point-to-point links, but it includes the possibility to simulate networks where multiple potential receiving nodes are arranged over the same line, as it commonly happens in street lighting systems.

III. System modeling

A smart street lighting system is usually managed by a *concentrator* located at the beginning of a line. Each lamp is controlled by its own PLC modem, which receives messages and data transmitted by the concentrator over an LV power line.

Typically, the height of light posts ranges between 5 m and 7 m. The distance between them depends instead on various factors affecting the ability of the lamp to illuminate the ground. An inter-pole distance of about 20 m is quite common. The actual topology of a street lighting systems depends on local regulations, population and traffic density, street type as well as possible logistic constraints. For design purposes, it would be very useful to rely on a flexible simulation tool able to analyze and to compare a variety of scenarios.

With this idea in mind, in the following the models of the main components of a smart street lighting system (namely the PLC modem, the high-intensity discharge (HID) lamp and the power supply cable) are described.

A. PLC modem model

PLC modems typically have a proprietary architecture. Nevertheless, they also share several common features. First of all, since they have to be connected to a power line, they must be equipped with a coupling network consisting of an electromagnetic interference (EMI) filter and a transformer providing galvanic isolation between the power line and the internal modem circuitry. The EMI filter has the role of protecting the modem from high-frequency disturbances coming from the line. Moreover, it prevents the unwanted transmission of possible interfering signals. Typical values of capacitance and inductance within EMI filters are in the order of hundreds of nF and tens of μH.

A general electrical model of a PLC modem is hard to define. However, according to existing standards, the equivalent input impedance of such modems has to lie within given ranges. Since the total reactance associated with both the transformer and the EMI filter is much larger than the reactance of the modem's internal circuitry, the latter terms can be neglected. As a result, the digital signal processing section of a PLC modem (typically based on a microcontroller unit - MCU) can be roughly modeled as a time-varying resistive load, which changes as a function of the power supply voltage, the computational load, and the specific features of the chosen MCU. The default nominal value of the modem's input impedance is often reported in the data sheet of the device, such as in [18]. As a result, a basic equivalent electrical model of an NB-PLC modem is depicted in Fig. 1.

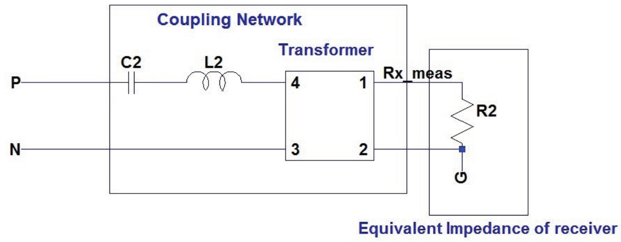
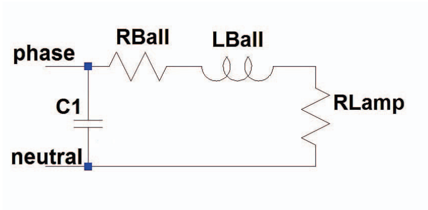
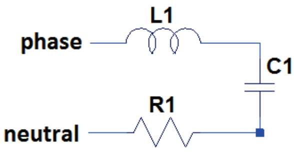


Fig. 1. Equivalent circuit model of a NB-PLC modem.



(a)



(b)

Fig. 2. Equivalent circuits of an electromagnetic (a) and an electronic (b) ballast.

B. High-intensity discharge (HID) lamp model

HID lamps are generally managed through ballasts. Old fluorescent lamps rely on electromagnetic ballasts. The equivalent circuital model of a fluorescent lamp driven by an electromagnetic ballast is shown in Fig. 2(a). Notice that an input shunt capacitor is required to compensate for the phase shift due to the intrinsic inductance of the ballast. However, such a capacitor behaves like a short circuit at RF, thus filtering the PLC signals as well.

Nowadays, most of fluorescent lamps are driven by electronic ballasts which are much more flexible and ensure higher energy efficiency. They typically include safety–oriented capacitors called X-cap. The equivalent circuit of a typical electronic ballast in the NB-PLC frequency band can be modeled by a RLC series resonator, as shown in Fig. 2(b). However, the overall X-cap capacitance (which can be so large as some hundreds of nF) tends to dominate the total equivalent input impedance in the NB-PLC frequency band [19]. For this reason, in the rest of this paper the whole lamp will be simply modeled by a shunt capacitor.

C. Cable model

As known, an LV power line cable consists of three wires, i.e. the phase, the neutral and the ground conductors. Since the PLC signals are transmitted over the phase and neutral conductors only, the PLC communication channel can be modeled as a classic two-wire RLGC transmission line, as shown in Fig. 3, where R, L, C and G are the resistance, inductance, capacitance and conductance, respectively, of the power line per unit of length. The values of such parameters are given by the following expressions [20]:

$$\begin{aligned} R &= \sqrt{\frac{\mu_r \mu_0 f}{\pi \sigma a^2}}\left[\frac{\frac{d}{2a}}{\sqrt{\left(\frac{d}{2a}\right)^2 - 1}}\right] \\ L &= \frac{R}{2\pi f} + \frac{\mu_r \mu_0}{\pi}\cosh^{-1}\left(\frac{d}{2a}\right) \\ C &= \frac{\pi \epsilon_r \epsilon_0}{\cosh^{-1}\left(\frac{d}{2a}\right)} \\ G &= 2\pi C f \tan\delta \end{aligned} \qquad (1)$$

where μ_0 and ϵ_0 are the magnetic permeability and the permittivity in the vacuum; μ_r is the relative magnetic permeability of the chosen conducting materials (i.e. approximately 1 for both copper and aluminium); ϵ_r (typically between 1 and 2) is the relative permittivity of the insulating jacket of the cable; σ is the conductivity of the line ($5.96 \cdot 10^7$ S/m for copper and $3.5 \cdot 10^7$ S/m for aluminium); a is the radius of each conductor; d denotes the distance between the centers of two wires; $\tan\delta$ is the dissipation factor (equal to 10^{-2} for PVC insulation and 10^{-6} for G7-HEPR insulation, respectively) and, finally, f is the signal frequency.

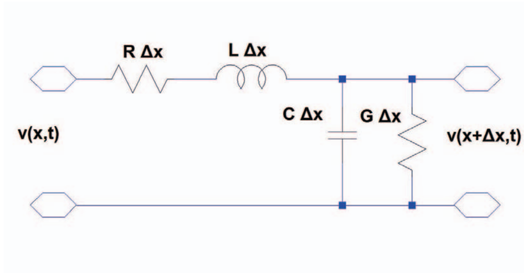


Fig. 3. RLCG circuit model of a power line communication channel.

Depending on the values of R, L, C and G, different cable models can be used to analyze the propagation of NB-PLC signals over the power lines of a smart street lighting system. Of course, the classic RLCG model is the most accurate (provided that the cable parameters are estimated with low uncertainty). However, in some cases the conductance component G can be neglected, thus simplifying the model. Moreover, if the equivalent input capacitance of the PLC modem and the shunt capacitance of the ballast are much larger than the total capacitance of the line (as it typically occurs in practice), then also the value of C can be neglected. Under these conditions, the original model becomes a simpler distributed RL model, which is less demanding from the computational point of view, thus reducing simulation time, especially when large networks are considered.

IV. Results

In this Section, at first a procedure to define the model parameters is briefly described. Then, the results of some validation activities and some simulation examples are reported.

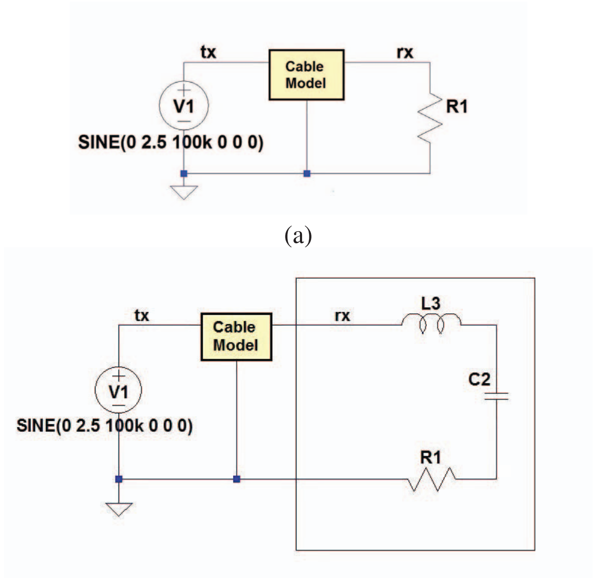
A. Selection of the model parameters

The values of the model parameters of modems, lamps and ballasts have been simply extracted from the data sheets of various devices available in the literature. For the NB-PLC modems, we referred to the specifications of ST7580 and ST7540 by STMicroelectronics.

The electrical parameters of the cables have been measured experimentally and have been compared with the results of of (1) for given values of μ_r, ϵ_r, d, a, $\tan\delta$ and f. An example of such experiments is reported in Table I, which shows the total values of resistance, inductance, capacitance and conductance of three FROR 3G4 cables of different length, when a 100-kHz signal is transmitted over the line. Every power line cable has a cross section area of 4 mm^2 and includes three copper conductors. Conductors are insulated by means of a 0.8-mm PVC jacket with $\epsilon_r = 1.55$.

TABLE I. MEASURED VALUES OF RESISTANCE, INDUCTANCE, CAPACITANCE AND CONDUCTANCE OF THREE FROR 3G4 CABLES.

Cable length [m]	Resistance [mΩ]	Inductance [μH]	Capacitance [nF]	Conductance [μS]
7	200	3.15	0.26	1.62
20	573	8.99	0.74	4.65
30	859	13.5	1.11	7.04



(a)

(b)

Fig. 4. Spice schematic of a 30-m FROR 3G4 cable connected to two different types of load, i.e. a 5-Ω impedance load (a) and a fluorescent lamp driven by an electronic ballast (b).

Note that if the measured values of each electrical parameter are divided by the respective cable lengths, it results that in all cases $R \approx 28.6$ mΩ/m, $L \approx 0.45$ μH/m, $C \approx 0.037$ nF/m and $G \approx 0.23$ μS/m. Such numbers are in good accordance (within a few %) with those given by (1). Consider that the wavelength of NB-PLC signals is about 3 km, while the distance between two consecutive city lamp posts is in the order of a few tens of meters. Therefore, each branch of a street lighting network based on the purely distributed RLCG transmission line shown in Fig. 3 can be replaced by the cascade of a quite limited number of two-port lumped-element RLCG circuits of fixed length, thus reducing substantially both computational complexity and simulation time. As a result, the propagation of NB-PLC signals within a network consisting of hundreds of lamps can be simulated quickly, reliably and with good accuracy. It is worth noticing that the simulation time can be reduced further if the cable model parameters G and C are negligible. This situation is quite common in street lighting networks, for the reasons explained in Section III. In the schematics shown in Figs. 4(a)-(b) three different cable models (i.e. a full RLCG model, an LTRA RLC Spice model and a simplified RL model) are used to analyze and to compare the behavior of a 100-kHz NB-PLC signal transmitted over a 30-m cable. The peak-to-peak signal amplitude is 10-Vpp, since this is the maximum peak-to-peak voltage amplitude allowed by standard EN-50065 [6]. The line is terminated with a simple 5-Ω resistive load [Fig. 4(a)] or with an electronic ballast [Fig. 4(b)]. The ballast model is the same as described

TABLE II. PEAK-TO-PEAK VOLTAGE VALUES AT THE END OF THREE DIFFERENT MODELS OF A $30-m$ POWER LINE CABLE, WHEN TWO TYPES OF LOAD ARE CONSIDERED.

Load type	RL [V]	RLC [V]	RLCG [V]
Resistive load (5 Ω)	4.56	4.56	4.54
Electronic ballast	10.5	10.6	10.6

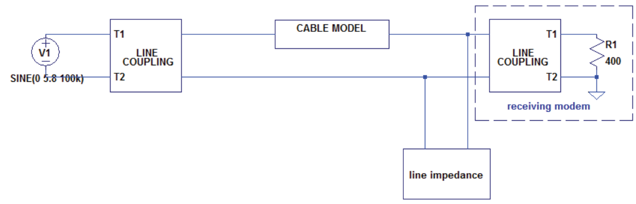


Fig. 5. Schematic of the circuit used to validate the proposed models.

in Section III-B with $R1 = 10$ Ω, $C2 = 220$ nF and $L3 = 1$ μH. The peak-to-peak amplitudes of the voltage signals applied to both loads are shown in Table II. Notice that such amplitudes are almost equal, regardless of the cable model employed.

B. Model validation

The proposed set of models has been validated experimentally in the laboratories of the Department of Industrial Engineering of the University of Trento. For validation purposes, simulation and measurement results have been compared in similar conditions. The schematic of the circuit used for validation is shown in Fig. 5. Two NB-PLC modems ST7580 have been connected to the ends of three FROR 3G4 power line cables with a cross section area of 4 mm^2 and different lengths (i.e. 30 m, 60 m and 90 m, respectively). Modems and cables have been modeled as described in Section III. The lamp instead has been modeled as shown in Fig. 4(a)-(b), i.e. with a 5-Ω load or with an electronic ballast. Both modems can transmit and receive Phase-Shift Keying (PSK) and Frequency-Shift Keying (FSK) signals in the frequency range 95-148.5 kHz. In the specific case considered, a 100-kHz 10-Vpp FSK signal has been transmitted over the lines. The simulations results are based on LTSpice, while the parameters of the received voltage waveforms have been measured with a Digital Storage Oscilloscope (DSO) Agilent 70321. An example of an FSK waveform received by the modem at the end of the 90-m cable and collected by the DSO (after filtering the power line voltage) is shown in Fig. 6. The simulated and measured values of the peak-to-peak voltage values received by the PLC modems at the end of each cable are reported in Table III. The two lines in the table refers to the same load models shown in Fig. 4. Observe that the simulation results are in excellent agreement with the experimental data: the relative differences between pairs of values are indeed in the order of a few percent. Such differences are also generally consistent with the estimated worst-case uncertainty, which is about ± 0.5 V. This value includes not only the intrinsic fluctuations of the waveform and the instrumental uncertainty of the DSO, but also the uncertainty affecting the waveform amplitude at the transmitting end, since this parameter can be just roughly controlled by the modem and it also is partially influenced by the total impedance of the line.

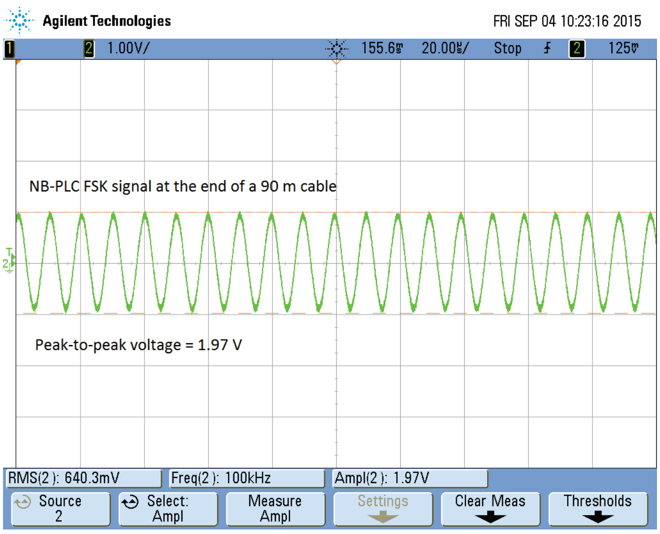


Fig. 6. NB-PLC FSK waveform received at the end of a 90-m FROR 3G4 power line cable. The cross section area of the cable is 4 mm^2. The peak-to-peak amplitude drops from about 10 V down to about 2 V.

TABLE III. SIMULATED AND MEASURED VOLTAGE PEAK-TO-PEAK AMPLITUDES OF A NB-PLC FSK SIGNAL RECEIVED BY A MODEM IN DIFFERENT CONDITIONS.

Distance from TX	Peak-to-peak voltage [V]					
	30 m		60 m		90 m	
	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.
Resistive load (5 Ω)	4.6	4.3	2.9	2.8	2.1	2.0
Electronic ballast	10.5	10.2	7.0	6.4	5	4.6

C. Simulation results on a street lighting network

Some simulation results related to a realistic street lighting system are reported in Table IV. The schematic of the street lighting network is shown in Fig. 7. Each power line consists of an FROR 3G4 cable with a cross-section of 4 mm^2 (like in the experiments). In the example considered, the distance between two consecutive lamp posts is 20 m, and each post is supposed to be 7 m high. As a result, each power line is partitioned into 20-m segments. Such segments are modeled as two-port, lumped-element RL circuits. The corresponding blocks are labeled as *20_RL* in Fig. 7. The power lines of each light post are instead modeled as 7-m lumped-element RL circuits (labeled as *7_RL* in the picture). The network nodes (namely the smart lamps on the top of light posts) include the equivalent circuits of an NB-PLC modem, an electronic ballast and a fluorescent lamp. The values reported in Table IV are the peak-to-peak amplitudes of the FSK signals (with nominal amplitude equal to 10 Vpp) received by modems at various distances from the transmitting node and over lines of different total length (i.e. 200 m, 600 m and 1 km), when no intermediate branches are considered. Observe that the signal amplitude decreases as the line length grows, as expected. However, the reported values are quite different from those shown in Table III. This is due to the presence of multiple and different loads along each line.

Additional simulation results (namely when the side branches of the network in Fig. 7 are considered) are shown in Table V. In this case, the peak-to-peak voltage values at the input of various nodes along the 600-m line are compared with

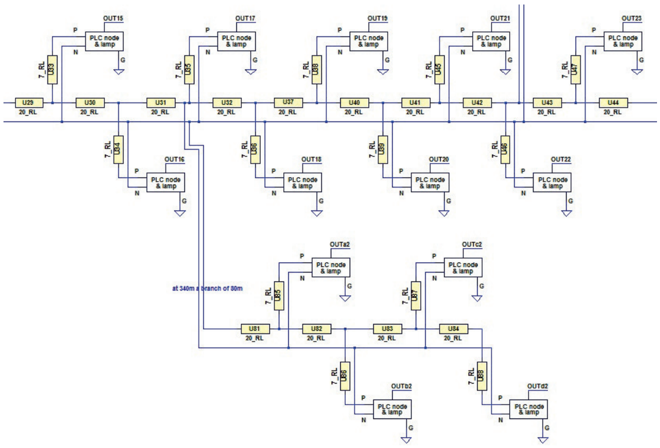


Fig. 7. Schematic of a realistic street lighting network.

TABLE IV. SIMULATED PEAK-TO-PEAK VOLTAGE AMPLITUDES OF A 10-VPP FSK SIGNAL IN DIFFERENT POINTS OF THE STREET LIGHTING NETWORK SHOWN IN FIG. 7.

Line length	1^{st} node	10^{th} node	20^{th} node	30^{th} node	50^{th} node
200 m	8.36	5.28	-	-	-
600 m	8.05	2.94	1.03	0.6	-
1 km	8.05	2.94	0.96	0.31	0.07

those obtained when three branches are inserted at 200 m, 340 m and 440 m from the transmitter. By using the same notation used in Table IV, the dash symbols in Table V denote infeasible configurations. For instance, the eleventh node on the second and on the third branch simply does not exist. Notice that in this example the waveforms amplitude becomes quickly very small over both the main line and the various branches, thus making signal detection quite hard for modems if no repeaters are inserted. Such results confirm the importance of evaluating the electrical features of the adopted NB-PLC signals carefully and at an early design stage, especially if the smart street lighting networks have considerable size and complexity.

V. CONCLUSION

This work presents a set of electrical models to analyze and to simulate the propagation of Narrowband Power Line Communication (NB-PLC) signals in smart street lighting networks. Cables, lamps and PLC modems are modeled as equivalent lumped-element circuits that can be comfortably simulated in Spice. The main advantage of the proposed methodology is the ability to ensure design modularity and scalability, thus greatly reducing simulation time when large street lighting networks are considered. In addition, just a limited amount of tests is needed to estimate the model parameters. The results of a preliminary experimental validation based on FROR 3G4 cables and real NB-PLC modems confirm the validity of the proposed approach. In future, the simulation framework will be enhanced by adding suitable noise and interference models.

ACKNOWLEDGMENT

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TABLE V. SIMULATED PEAK-TO-PEAK VOLTAGE AMPLITUDES OF A 10-VPP FSK SIGNAL ALONG A 600-M LINE OF THE STREET LIGHTING NETWORK SHOWN IN FIG. 7 WHEN THREE BRANCHES ARE ADDED.

	1^{st} node	11^{th} node	17^{th} node	20^{th} node	23^{rd} node	30^{th} node
600 m line	8.05	2.68	1.4	1.03	0.82	0.6
600 m (with branches)	7.92	1.58	0.18	0.13	0.09	0.07
first branch (at 200 m)	-	1.7	1.17	1.09	-	-
second branch (at 340 m)	-	-	0.18	0.17	-	-
third branch (at 440 m)	-	-	-	-	0.09	-

of our models. In addition, the research activity has been supported by the project GreenDataNet (grant n.609000) funded by the EU 7th Framework Programme.

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