Chapter 5

Radio Access Network Backhauling Using Power Line Communications

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Additional information is available at the end of the chapter

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Abstract

Nowadays, radio access networks (RANs) are moving toward a small cell-based paradigm, where the macro-cell antennas are aided by additional ones with lower coverage capabilities. This paradigm shift brings a new problem into the equation: a backhaul link is needed to carry the traffic from the small cell base stations to the network gateway. Currently, both wired and wireless solutions exist, but none is universally considered optimal. Power line communications (PLC) can be considered as a broadband access solution for this backhaul branch. Recent developments helped to push PLC performances to a point where state-of-the-art solutions can achieve very high-speed data transfers. Aided by traffic generation-based simulations, we will show how the PLC technology can be assessed for the described application. The reader will be guided through the process by discussing small cell networks, the power line infrastructure and basics of traffic generation modeling. The chapter will then discuss a quality-of-service (QoS)-driven analysis and use numerical results to show how requirements can be defined for the backhauling technology. Overall, this chapter will address how PLC and small cell network technologies can be brought together in a unified model to foster future small cell technology.

Keywords: power line communications, small cell networks, backhauling, optimization, broadband access, random channel modeling, stochastic geometry, transmission line theory, traffic generation

1. Introduction

Nowadays, Internet connectivity is a consumer good, and its usage is growing faster and faster. A recent report forecasts that the worldwide mobile data traffic will clock in at 71 exabytes per month in 2022, while in 2016 this figure equalled about 9 EB/month [1]. It also predicts that by 2022 five out of nine billion of mobile subscriptions will be LTE (in 2016 this value was 1.5 out of 7.5), and that video services will generate 75% of the amount of mobile data traffic (in 2016 it was 50%). This growth in the amount of traffic is causing a shift in the way we design networks and the technologies used for their deployment. In fact, other sources predict that new-generation network technologies will see a manifold increase in the strictness of the requirements on capacity, latency, energy consumption, cost and mobility [2, 3].

In the world of mobile communications, connectivity is mainly deployed through what are technically called radio access networks (RANs). A RAN is a part of a system of telecommunications: it is the conceptual intermediary between the mobile end-user, which is the person requesting service through a user device, and the core network, which enables the exchange of data from all the endpoints of the network. A RAN is often implemented through a system of high-powered antennas which partition the geographical territory in areas of a few kilometers of diameter each. These are referenced to as macro-cells, because of their capacity of coverage. RANs are widely spread to enable provision of communication standards as GSM, EDGE, UMTS and LTE. On the other hand, there are also other solutions to provide mobile connectivity.

Small cells are low-power, high-capacity radio access nodes that improve directly the spatial fragmentation and frequency reuse of the network and indirectly local capacity and global coverage. They also bring the network closer to the user, thus helping to save energy and stretching end-device battery life. Small cells can be characterized based on their capacity of coverage, both in terms of distance and number of simultaneous users, into the following broad families: microcells, picocells and femtocells. The latter, which are the smallest and less powerful of the bunch, are used mostly for in-home, private purposes, because of their low cost and high capacity [4], and are the kind of cells that will be considered throughout this work. Small cells are strategically deployed in environments where the network coverage generated by the macro-cell is weak, in order to bring the said network closer to the final user.

This technology introduces the necessity for a backhaul segment to bring data from the small cells to the RAN access points (network gateways) and back further to the core network. Solutions for this link can be wired or not; popular choices are optic fibers, ADSL on twisted pair or radio connections. Furthermore, this additional element in the network's hierarchy needs to be designed properly, taking into account the end-user requirements, and granting easy deployment and no use of end-user spectrum are all necessary action points in network planning [5].

Power line communications (PLC) is a technology that uses the same medium both for power supply and for data connectivity. An immediate advantage of this technology is the fact that there is no need for a new infrastructure, leading to savings in deployment time and costs. Despite the power cables not being designed for data transmission, they are currently employed both for low data rate (e.g., meter reading, alarm signals, emergency communications) and for data-hungry (e.g. in-home HD video streaming) applications [6, 7]. New advancements in the PLC research boosted the communication capacity, even beyond gigabit per second in the in-home environment. While PLC promises easy deployment, its performance for backhauling applications still needs to be thoroughly assessed.

To the best of our knowledge, never-before PLC was regarded as a broadband solution for RAN backhauling. Considering how femtocells are nowadays used inside buildings and how power is fed to this premises through the power line infrastructure, this could be an opportunity to better integrate PLC and provide general connectivity in the small cell environment. To analyze the problem, the contribution in this chapter is organized as follows.

In Section 2 the rationale of the wireless small cell networks, the power line infrastructure paradigm and the traffic generation methods used for the first part of the assessment will be explained.

In Section 3 the overall network structure will be described. A bottom-up transmission line model will be used to simulate the physical PLC channel between network nodes.

Section 4 will explain how, on top of the previous results, an optimization problem can be formulated to perform resource allocation. This also enables smart routing for improved connectivity of far cells.

Section 5 will be dedicated to showing and commenting results from the simulations carried out for several system setups.

Eventually, conclusions will be drawn in Section 6, along with comments on possible future applications and research paths.

2. Setting up the network: the physical layer

The network to investigate comprises small cells and power lines in a joint infrastructure. This section specifically aims at finding out the requirements that a PLC network needs to satisfy to be able to support a small network of private small cells. To do so, the following main aspects have to be addressed: (a) the small cell network deployment on the geographical territory, (b) the power line infrastructure and how it topologically connects the radio base stations (c) the traffic generated by the cells that needs to be backhauled.

Most of the material presented in this section is a synthesis of [8, 9].

2.1. Small cells

Small cells are low-power, high-capacity radio nodes, controlled either by an operator or a private customer. As mentioned before, small cells can be categorized into the following classes:

- Microcells: their coverage can reach up to a few kilometers and is used in large premises such airports or transportation hubs. They enable macro-cell base station controllers to manage the power in the network while optimizing spectrum usage.
- Picocells: these can cover up to a few hundred meters. While being employed for medium-sized venues (malls, train stations and the like), they also enable smoother handoffs of end-users between different macro-cells.

- Femtocells: lowest coverage of all the classes, it clocks in at a few tens of meters. They provide advantages both to operators and end-users, by bringing the network closer to the devices and improving battery life and quality-of-service (QoS). Femtocells can usually support 4, 8 or 16 simultaneous users.

While the first two categories are generally deployed and managed by operators, femtocells are directly controlled by the private user. It is legit to assume that, in a residential neighborhood, connection to the core network is provided in each building through one of these femtocells, meaning that there is a one-to-one relationship between cells and buildings in our model.

The next generation of cellular technology envisions a very different paradigm for networks, where small cells will play a fundamental role in assisting the macro-cells in providing the service in blind spots or where the QoS needs to be improved; in fact, a great increase in the density of small cell is forecasted for the coming years. Our model inquires the possibility of providing the connection to the small cells through simulations where the density of such elements is adjustable, thus allowing the model to relax or tighten the capacity requirement on the PLC technology.

In order to simulate the envisioned network, the first thing needed is a deployment of small cells. To do this, we employ the stochastic geometry tool [10], as to create a random dispersion of small cells, based on their individual coverage and global density, which is indirectly controlled through the portion of geographically territory to be actually covered. Stochastic geometry is a tool that simulates spatial averages and has been recognized as valid and powerful in the wireless communication world; herein, it is applied to generate and study the spatial distribution of PLC nodes (residing in the radio base stations) yielding, when wiring is considered, a random topology model whose idea was already presented in [11].

In our model, base stations are deployed through the following random processes:

- The number of base stations to be deployed is determined through random Poisson's process, whose average depends on the area that each cell covers (it is supposedly constant for every base station) and the quantity of geographical territory to be covered.
- A two-dimensional coordinate plane simulates our geographical territory; each cell's position is determined as a pair of uniform random variables.

A certain degree of overlapping is also allowed between different cells in order to account for neighboring houses or even cells in the same building but located on different floors. **Figure 1** shows a random deployment of cells. The small red circles represent the connected area reached by each base station located in their centers. The served area is the same for all the cells. To implement the specific deployment in **Figure 1**, a 20% value of covered territory was set.

2.2. Power line infrastructure for the small cell network

Once the small cells are deployed, the supporting power line infrastructure is created. Some assumptions are made to develop the model, which is based on the European paradigm

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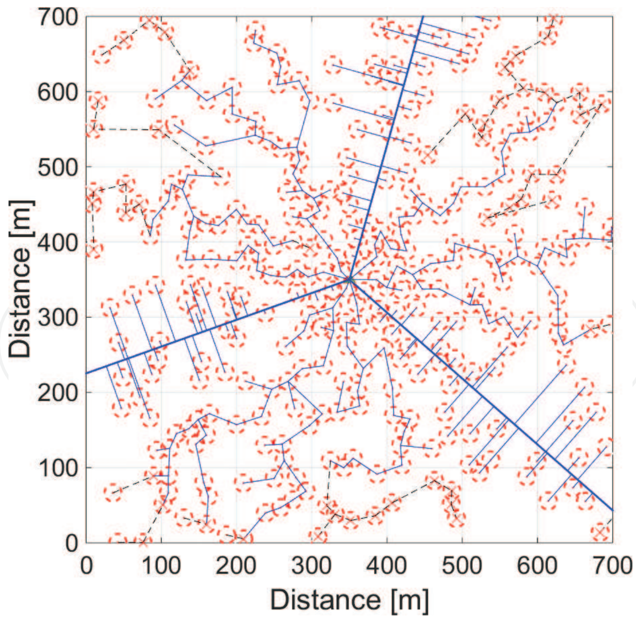

Figure 1. A random network deployment is shown, as produced by the implemented simulation software. The dashed circles represent small cells, while the continuous lines represent power cables from the supply infrastructure.

presented in [6]. This basically means the following things: the network is assumingly structured in a radial architecture, whose branches are all departing from a central concentrator that acts as a front-haul gateway (FHG), which may be located in a medium-voltage (MV) to low-voltage (LV) transformer station. In **Figure 1** the FHG is shown as a triangle in the center of the area. This is where high-speed data links are assumingly realized towards the core network, so the LV network of power lines might enable the backhaul portion of the network, between the private femtocells and the FHG.

On average, from each MV/LV transformer station, a maximum of ten branches are deployed to feed the end-users. Each one of these branches supplies a maximum of 30 to 35 buildings and extends to a maximum distance of 1 km from the FHG, measured in power line cable length. The LV network is the most geometrically complex part of the supply network: the model described in the following stems from observation and real-life cases described in literature [6].

In our model, different topologies for the power line infrastructure are realized to depict different geometrical properties of real networks. The bus topology drives a central backbone through the territory and connects the nearby cells following a minimum policy regarding the global amount of cable used; then, it draws branches to connect the cells to the backbone. The tree and chain topologies connect directly the cells to each other, preferring, respectively, a branching or serial connection policy. The only condition in the creation of these two structures is to avoid intersections of the power line medium between different segments.

While this completes the description of the physical layout of the network, the mobile traffic that is generated needs to be addressed and evaluated to define a requirement on the PLC backhaul technology.

2.3. Traffic generation models

We assume that small cells enable two different types of traffic: voice and data. Based on [4], we assume the probability of each type of call to be 3% for voice and 97% for data. We consider Poisson's distribution for the number of connection requests performed by the population of end-users; this, however, requires to know beforehand the average number of calls per time unit. This parameter is tuned in the model to account for different traffic loads in the considered networks.

Voice traffic is analytically treated as a phone call: 64 kbps are allocated to the user for the whole duration of each call, which follows an exponential distribution. This makes the whole statistic of voice traffic requests Poissonian. On the other hand, data traffic is trickier to model, as amount of data and duration of each communication are variable and co-dependent. This can be modeled through self-similar processes, such as the Pareto and Weibull distributions, which implement the well-known 80/20 rule [12]. Data to model the related probability distribution functions were retrieved from the same paper.

The developed network manages the traffic and resources on the PLC branch under analysis. It is implicitly assumed that resource management of the radio users inside the femtocells is carried out by the cell computational unit itself, and the same goes for the front-haul gateway (FHG) for the traffic to be routed towards the core network.

Results regarding the requirements on the PLC technology are reported in Section 5.1.

3. Transmission line-based bottom-up statistical PLC model

Transmission line theory allows to describe the behavior of a cable used as a telecommunication channel by modeling its medium as a circuit and including effects due to the propagation of short-length waves [6]. This method takes into consideration the nature of the transmission medium by means of:

- Propagation parameters, which allow to describe how signals are attenuated and distorted along the power lines based on the cable type
- Geometry of the cables, meaning how they are actually deployed on the territory based on length and direction
- Topology of the network, how cells are connected to each other and how their presence introduces interference through signal reflection on the channel

Translating this theory into a mathematical model enables bottom-up analysis of the network, as it starts from its lowest layer (physical) and builds models upon it to retrieve typical performances in a deterministic fashion. On the other hand, top-down approaches use real data measurements to infer the possible behavior of the network. As this application for broadband outdoor PLC, to our best knowledge, is not yet described in literature through statistical data, the former type of analysis was preferred.

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While geometry and topology are defined in the first part of the random network generation, propagation parameters are generated afterwards based on the type of cable that is chosen to represent the network.

The method herein employed is the same described in [11]. Basically, the medium whose channel behavior is to be calculated is split into different elementary sections, and for each one of these sections, a transfer function is calculated. Sections of the medium are delimited either by loads (private premises) or discontinuities (change of cable type). Since the power line channel is not symmetrical, it is important to identify the direction of the signal that is being transmitted and whose attenuation profile we want to obtain. This is due to the fact that the transfer function of a certain section depends on all the previous sections passed by the signal. In this phase of the experiment, we consider the cells as transmitting towards the FHG. We consider the MV/LV transformer station to completely separate the channels of different sectors; thus, each one of the main branches departing from the station accounts for its own set of channel responses.

The channel under analysis sweeps the frequency domain between 1 MHz and 30 MHz, as this is the range of current PLC applications, although performances at higher frequencies are being explored [13]. Each private premise is modeled as an impedance whose value is statistically chosen in a uniform interval between 5 and 200 ohms, as the frequencies of the broadband channel impedances tend to drop to very low magnitudes (order of a few ohms). Further information on impedance modeling for broadband PLC channels can be found in [14]. The channel is also assumed to be time invariant for simplicity; in reality the channel in PLC is LPTV (linearly periodic time variant), although mostly at low frequency and only in the presence of strongly time variant loads connected closed to the transmitter or receiver (**Figure 2**).

The channel is evaluated for each cell of the network and each one of the 100 KHz subchannels. The evaluation of the channel is a computation of the chain of transfer functions between the receiving node and the transmitting one, which returns a channel gain as a ratio between the magnitudes of voltages at the ports of the two nodes. When combining this data with the transmitting power of nodes and the power spectral density of the noise, it is possible to retrieve the upper bound of capacity of the physical link through the Shannon formula. By using this method, it is implicitly assumed that inputs and noise behavior are Gaussian, which

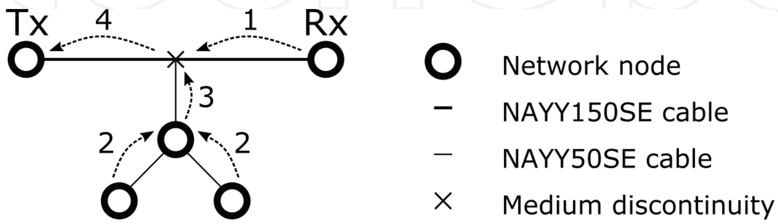

Figure 2. The channel transfer function is computed with the voltage ratio approach method. Starting from the receiving node, each section voltage ratio is used to retrieve the transfer function of that portion of the channel. Whenever a branch is found on the backbone connecting the receiving and the transmitting nodes, it is necessary to compute the transfer function related to this part of the network external to the communication path in order to model the reflections and attenuation it introduces.

is not actually the case of PLC channels, but the results can still be used as a frame of reference to a very well-documented case in literature.

$$C_{TOT} = \sum_{i=1}^{N} B_i \log_2(1 + SNR_i) \tag{1}$$

3.1. Remarks

As mentioned, this transmission line analysis allows to characterize the transfer function of the channel for each cell based on the power line distance of the cell from the FHG, the local density of loads connected to the power line infrastructure and the power spectral density of the noise on the channel.

This transfer function represents the channel gain of the signals transmitted between two points as a chain of voltage ratios, which can be used to compute the Shannon link capacity. The average channel gain (ACG) is the value of channel gain average over the whole spectrum considered for data transmission [15] and is thus strongly correlated to the value of this capacity upper bound calculated with Shannon's formula. By creating a large database of simulations through this model, it is possible to let a node infer the capacity of the medium simply by measuring the intensity of the noise on the cables, thus reducing the computational overhead load needed to map the channel and create an adequate scheduling. This would allow a node (the FHG in a downlink situation, a private cell in the uplink) to infer the capacity between itself and a receiver without sounding the medium.

4. Resource allocation and optimization

Each link between the FHG and a generic cell is characterized by a capacity value. This allows the server of the network, located in the FHG, to allocate the time resource to all the users that in each instant require a certain amount of throughput to connect to the core network.

The MAC protocol is assumed to be a TDMA as the channel is assumed time invariant; nevertheless, the time resource is divided into time frames as the PLC channel displays an LPTV (linear periodically time variant) behavior to simplify the integration of frequency variability in a more advanced stage of the study. The time frame naturally is meant to represent the duration of the mains cycle in an AC power supply network. As a frame of reference, in the European paradigm, this duration equals 20 ms.

Resource allocation schemes are applied to traffic requests that are generated over the network according to the models and metrics discussed in Section 2.3. Whenever one of the small cells generates a connection request, a throughput requirement is created and added for the whole duration of the call to the throughput already required during the said time range. As mentioned before, connection requests can be of two kinds, specifically voice or data. The former kind requires a continuous connection and a fixed throughput of 64 kbps for the whole

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duration of the call, while the latter generates a bigger quantity of traffic not necessarily requiring continuity.

Initially, the network's performance is evaluated by operating a very simple TDMA protocol: during each time frame, the time frame is equally shared between the pools of users requesting access to the medium. If the allocated resource completely covers the required throughput for one or more users, then a smaller chunk is assigned to these users, and the remainder of the resource is shared accordingly.

The TDMA method described above is ideal as it allows a continuous allocation of the time resource, while real communication standards divide the time frame into slots that can be distributed to users. This is due to the fact that the time resource must be split into a finite number of units to respect the packet structure of data transmission. HPAV [16] envisions a duration of the elementary OFDM symbol in the tens of microseconds, which is quantitatively adapted here to divide each frame into 500 elementary symbols. For the optimization problem presented in the following, the time frame is divided into time slots in order to satisfy a system where the number of users and the magnitude of their throughput requests in each time frame are not fixed. Each time slot consists of an integer number of elementary symbols such that the total number of symbols is eventually covered by an integer number of time slots.

The aim of the optimization problem is structured in the following way: first, all the users requesting resource to satisfy calls of the voice kind are assigned enough resource to cover this throughput. When voice calls are satisfied, the rest of the throughput requests are considered, and the rest of the resource is allocated according to the following:

$$\begin{aligned} &\max_{\alpha, N_s} \sum_{k}^{N_U} \sum_{j}^{N_S} \alpha^{(k,j)} C_k(N_S), s.t. \\ &(i) \sum_{k}^{N_U} \alpha^{(k,j)} = 1, j = 1, 2, \dots, N_S \\ &(ii) \max_p \sum_{j}^{N_S} \alpha^{(k,j)} C_k(N_S) \geq \frac{p}{100} C_k, k = 1, 2, \dots, N_U \end{aligned} \tag{2}$$

where N_S and N_U equal, respectively, the number of slots in which the time frame is divided and the number of base stations operating an access request during the current time frame, $\alpha^{(k,j)}$ is the logic operator that equals 1 when the jth time slot is assigned kth base station and C_k is the theoretical capacity of the link between the FHG and the kth base station in case where the whole resource is assigned to the said base station, while $C_k(N_S)$ is the capacity that the kth base station gets from a time slot when the time frame is split into N_S slots. The p parameter allows the equalization of the resource, and it is maximized in order to allow each base station to exploit at least p (%) of the capacity of the link towards the FHG. Condition (i) makes sure that each time slot is assigned to only one user. Condition (ii) on the other hand assures that each user is assigned enough resource to exploit a minimum percentage (p/100) of their actual capacity. The aim of the optimization process is to maximize the aggregated throughput in

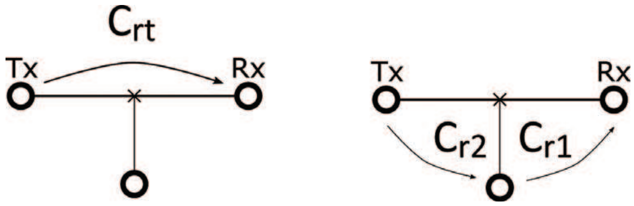

Figure 3. Routing enables a better coverage of the cells far from the FHG by decoding or amplifying the message received from the transmitting node before forwarding it to the receiver. In the network depicted on the left, the central cell is only creating interference and reflections on the PLC medium, while on the right is tentatively considered as a repeater for routing purposes.

each sector under a condition of resource scarcity by changing the overall number of time slots and the number of slots assigned to each user.

4.1. Enabling routing

The optimization problem can also be updated to include routing in it. A node can be chosen to act as a repeater based on the capacity of the channel between the FHG, the repeater and the cells that would be reached by the extended coverage. This also requires to distinguish between uplink and downlink cases because of the asymmetry of the PLC channel.

Simple routing can be enabled by assigning the role of repeater to one of the cells of the network, depending on the typical throughput required by a generic cell and the capacity of the channel between the end-user cell and the FHG with or without the repeater.

Figure 3 shows a case where only one cell is considered for routing-enabled extended coverage. This technique can actually be used to reach multiple cells in the region far from the FHG. Firstly, for each cell to be tentatively covered with routing, it is necessary to consider if the capacities created by a hopped communication give a better performance than the original one:

$$\begin{aligned} C_{DT} &= C_{rt} \\ C_{DF} &= \min\{\tau C_{r2}, \tau C_{rt} + (1-\tau)C_{r1}\} \end{aligned} \tag{3}$$

where C_{DT} and C_{DF} represent, respectively, the power line link capacity in the direct transmission case and the one where Detect-and-Forward strategy is used in the relaying node, as per **Figure 3**. Also, τ represents the fraction of the time frame that is dedicated to a specific connection. It is possible to adapt the problem to a case where the repeater needs to cover multiple cells. Basically, optimization is operated by tuning the aforementioned parameters so that the resource is used at its best. More details about this can be found in [17].

5. Results

In this section, numerical results from the simulations are presented. All the simulated networks consider small cells with a round coverage area whose surface is constant across

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the whole territory, while the simulation area (visible also in **Figure 1**) is square shaped. The length of the side equals the supposed average distance between neighboring FHGs. Cells that are further than a kilometer away (considering power line distance) from the FHG are considered as not connected neither to the communication nor to the supply network. This set of geographical parameters enabled the representation of both sparsely populated areas (as rural environments) and strongly occupied ones (as urban settings) through the tuning of the density parameter. By varying gradually this parameter, it is possible to see how a change in population affects the requirements imposed on the PLC technology and its overall performance. In Section 3 it was mentioned that the type of cable affects the behavior of the network: in our case, two types of cable were used to describe the network, specifically NAYY150SE for the LV lines that depart from the transformer station and NAYY50SE to connect this main bus to the point of connection of private premises. Furthermore, for the resource allocation problem, only cells with a nominal capacity over a certain threshold are considered as covered by service. It is also supposed that the FHG is transmitting with a power spectral density of −50 dBm/Hz and that the channel is characterized by a Gaussian noise with a power spectral density having a floor of −140 dBm/Hz. To evaluate the performance of the network, the grade of service (GoS) will be used. This is defined as the ratio between the throughput supported (ST) by the technology and the one required (RT) by the aggregated users across all the base stations:

$$GoS = \begin{cases} 1, RT \geq ST \\ \dfrac{ST}{RT}, otherwise \end{cases} \tag{4}$$

With the model described in Section 2, it was possible to assess preliminarily how the cells generate traffic and how they define a requirement for the PLC technology to enable broadband access. It was found that, when generated traffic resembled models of real cellular networks, the magnitude of this traffic was compatible with the highest capacity found on the PLC medium in outdoor applications. For a more detailed report, please refer to [18].

As mentioned before, transmission line theory enables bottom-up analysis of the network performance. In **Figures 4** and **5**, it is possible to see how the channel varies its behavior based on frequency and the power line distance between the communicating nodes; this behavior changes for different densities of cells deployed on the geographical territory.

Figure 4 shows how the channel gain behaves at different frequencies and power line lengths of analyzed links for a fixed density. In this specific case, the density was tuned in order to obtain an average of 35 cells for each one of the main branches departing from the FHG: this is reportedly [6] the maximum number of private premises fed by one main LV bus in the European paradigm. As in the Japanese/American paradigm, this number is much lower; it made sense to consider the European one as it sets the strictest conditions on the capacity of the channel. The underlying scatter plot shows the actual real channel gain of cells at different frequencies and distances; from the clear pattern these data create, a second-order interpolation was extracted in order to easily describe the behavior.

Figure 5, on the other hand, shows how the capacity of a generic link between a cell and the FHG can be correlated to the ACG of the same link. As seen in **Figure 4**, it is possible to infer the ACG of a link by knowing the distance of a cell from the FHG and the density of cells in the territory. Furthermore, it is easily possible to see how the ACG strongly depends on the length

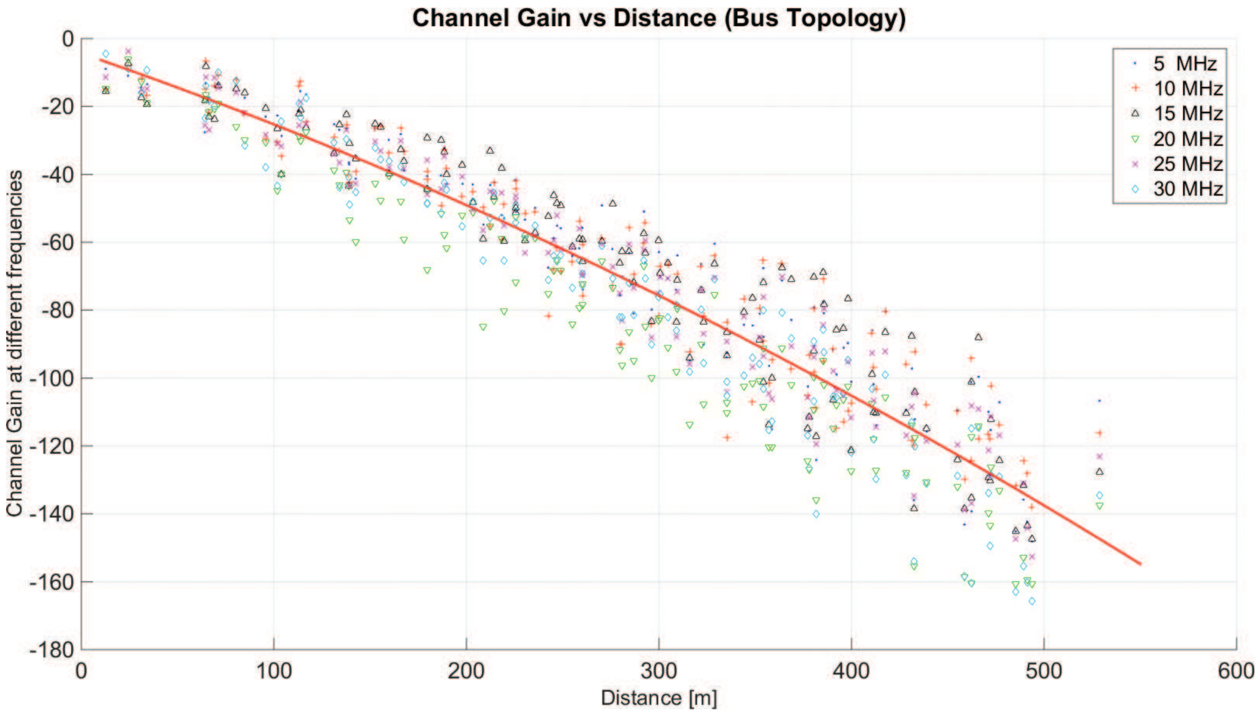

Figure 4. The scatter plot shows the channel gain computed with Shannon's formula and transmission line-based techniques in relation to the power line distance of the considered cells. A pattern is very clear; thus, a second-order interpolation was driven to retrieve the central red curve, which represents the ACG. This depends on the density of cells on the territory.

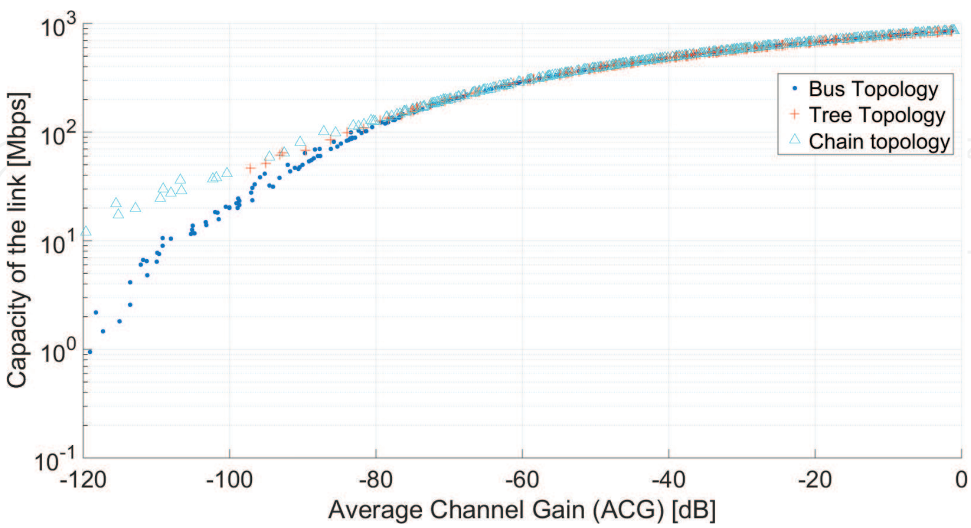

Figure 5. This semilogarithmic scatter plot shows the relation between the capacity of a link and the ACG attributed to the same. This relation does not depend on the distance; thus, it is possible to use it to infer a cell's capacity towards the FHG by measuring the ACG of the link.

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of medium a signal must go through to enable communication. In **Figure 6**, the FHG (represented with a triangle in the center of the network) is always considered the transmitting node, thus enabling a downlink kind of communication. As mentioned in Section 3, it is possible to correlate this value with the capacity of the link between the FHG and the generic cell, when a few parameters of the network are known, such as distance of the communicating cell, density of the cells and power spectral density of the noise on the medium. Analysis from further simulations revealed that capacity correlated to the ACG neither depend on distance nor density of cells in the network. With reference also to **Figures 4** and **5**, it is possible to see that for a high-density network, coverage can reach almost 400 meters of power line length. In situations of lower cell density, cells that are further from the FHG can be covered by the PLC connection service. It follows that PLC coverage depends on distance also in relation to the density of base stations in the territory and their average coverage, i.e., the number of loads connected to the same shared medium.

Figures 7 and **8** report the grade of service (GoS) and the average aggregated throughput on the main buses departing from the FHG for the evaluation of the time resource assignment. The first one represents the network's performance when a simple TDMA protocol is employed, namely, each transmitting user gets a time slot whose duration is inversely proportional to the total number of transmitting users, while the second one shows the same values when the optimization process is operated. The average aggregated throughput is calculated as the sum of the effective throughput carried on the medium. Each user contributes to this figure either with the minimum value chosen between the throughput assigned by the FHG and the throughput required to satisfy the users in the cell. On the other hand, the grade of service is how much the throughput required by the users in the cell is actually satisfied: 1

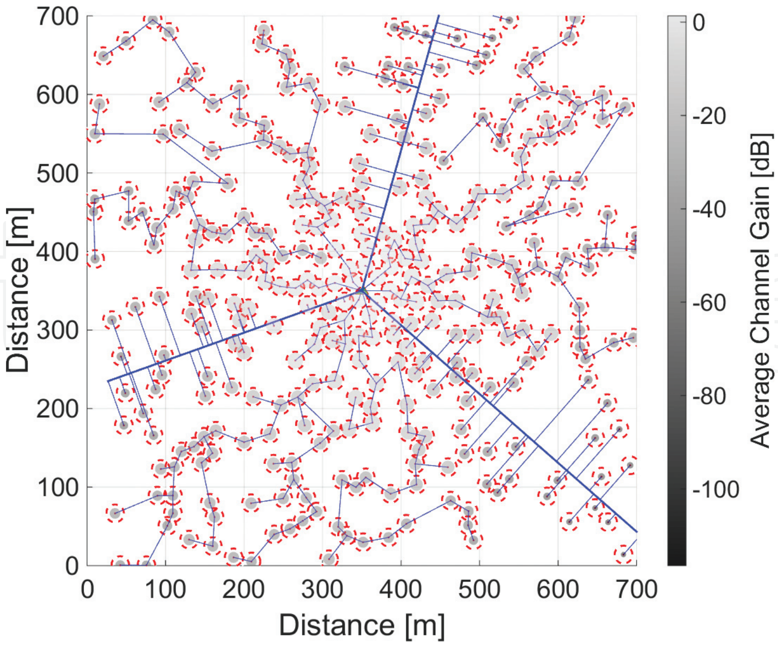

Figure 6. In this randomly generated network, a map of colors is used to show how the ACG fares in comparison with topology and distance of the cells from the FHG. As mentioned in section 5, cells whose ACG is circa −120 dB or higher can achieve a capacity of about 1 mbps or more.

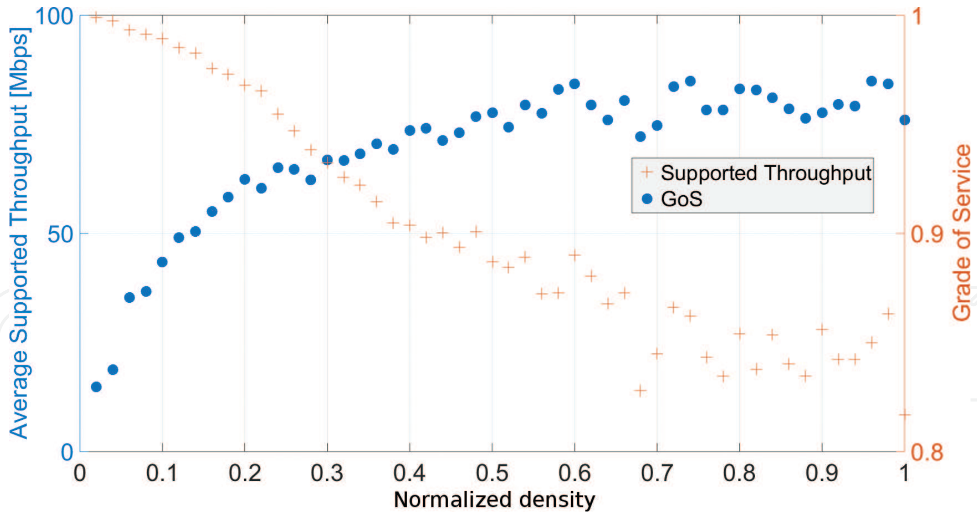

Figure 7. This graph shows the average supported throughput on each main bus departing from the FHG and the grade of service in relation to the normalized density of cells in a network where a simple TDMA protocol is applied.

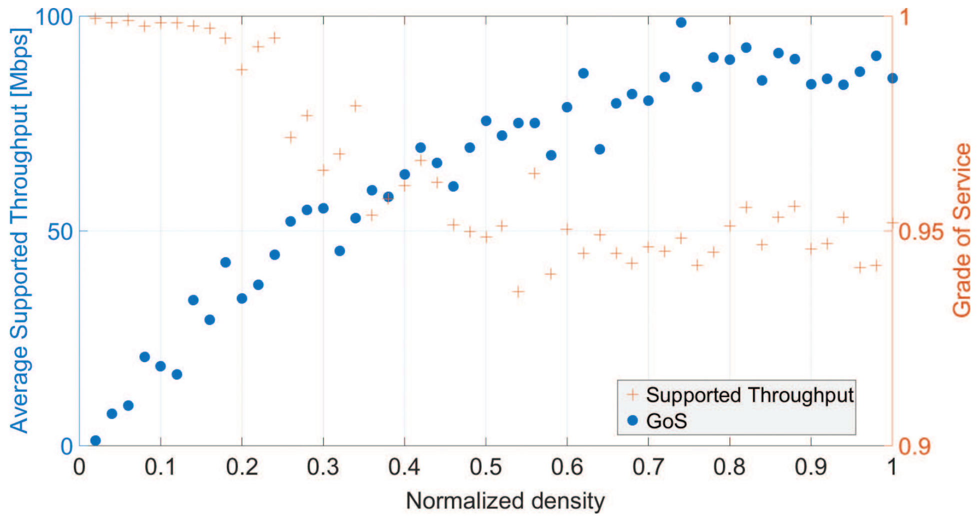

Figure 8. This graph shows the average supported throughput on each main bus departing from the FHG and the grade of service in relation to the normalized density of cells in a network where the optimization of the resource is carried out.

accounts for a network where all the users are satisfied, whereas 0 represents the opposite condition.

Also, for each density step considered for the simulations, the p factor mentioned in the definition of the optimization problem is reported to show how much resource is on average assigned to the requesting users to satisfy the generated calls. Its trend can be observed in **Figure 9**. This value is higher for low-density values because of the low number of users that request connections to the FHG.

From **Figures 7** and **8**, it is possible to see that the GoS is behaving better for the cases where the optimization is carried out. On the other hand, for lower densities, optimization seems to decrease the average supported throughput, probably due to the granular nature of the time

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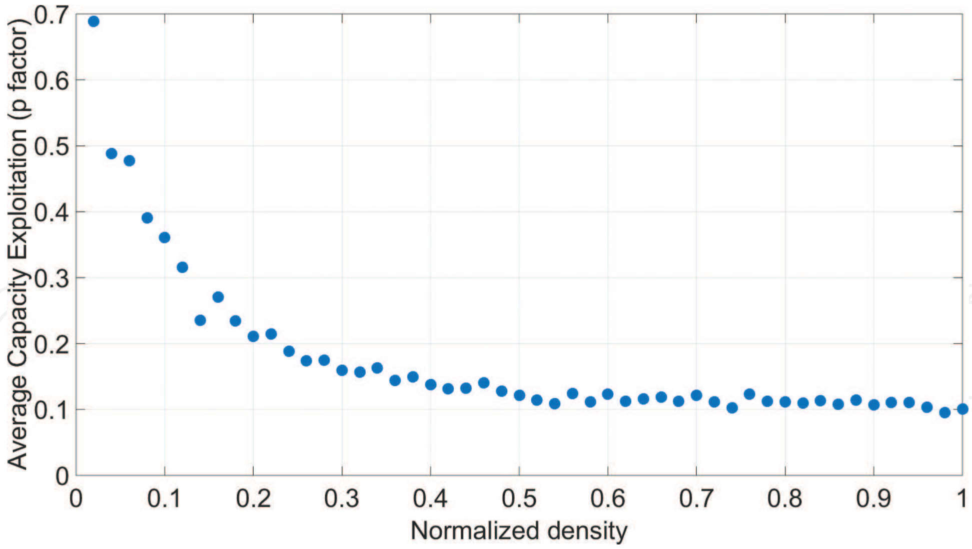

Figure 9. When the optimization is carried out on the time resource in a network, the p factor actualizes how much of the nominal capacity of the link towards the FHG each cell is able to exploit, based on how much time resource is assigned to each user.

resource in the optimization case versus the continuous one assumed in the simple TDMA case used for the former graph.

6. Conclusions

PLC is regarded nowadays as an enabling technology for IoT, smart grid and smart home applications. This study explores the possibility of using PLC as a broadband access solution for radio access networks by exploiting traffic generation models, transmission line theory and an optimization process to show how a TDMA protocol can be improved upon to let a central coordinator element schedule the time resource in an appropriate manner.

The experiments carried out on the simulation level showed how it is possible to employ PLC as a technology for broadband access in radio access networks. Studies carried out in the past showed which requirements were put on the shared medium, whereas here a general model for PLC performance was developed to infer which performance the technology is fit to provide. Specifically, herein it was shown that the technology is able to support connectivity for a small network of private femtocells covered by a LV power supply network, ranking as an adequate last mile solution. It was also shown how this performance can be enhanced for high-density networks by employing an optimization method, aiming at maximizing the supported throughput.

Moreover, it is mentioned in additional remarks (Sections 3.1 and 4.1) how the techniques used in the study will be exploited more in the future to gain a deeper insight into how hybrid broadband PLC-radio access networks can be designed to offer a better connection service to the end-users that populate them, namely:

- The transmission line theory model will be employed in conjunction with the topological and geometrical information to develop a system to infer the capacity of the link based on these information, which do not require a sounding of the channel, thus decreasing overhead and enhancing data speed.
- By using the method above, it will also be possible to consider different methods of routing inside the network to extend the coverage provided by the FHG. This will involve considering the combined capacities of the links that are created by partitioning the network. This will also depend on the type of link enabled, be it uplink or downlink.

A more realistic model could be developed by including different cell coverage sizes while also considering a more realistic behavior of users in the base stations via a traffic generator based on inferred statistics. Future endeavors will be devoted to experimentation in the field.

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