Mitigation of Electromagnetic Radiation in Heterogeneous Home Network Using Routing Algorithm

Hanane El Abdellaouy*†, Alexander Pelov†, Laurent Toutain†, David Bernard*
*Orange Labs, Cesson Sévigné, France
{hanane.elabdellaouy, david.bernard}@orange.com
†Institut Mines-Télécom,Télécom Bretagne-UEB, Cesson-Sévigné, France
{alexander.pelov, laurent.toutain}@telecom-bretagne.eu

***Abstract*—The extension of communication devices and the proliferation of transmission medium in home network contribute to increase the electromagnetic noise in home environment in general and in some area more specifically. To date, no scientific study has yet raised health issues, although public questions still exist. Whereas, lots of actions focus only on base stations of cellular networks. In order to respond to some potential customers concern, we want to minimize such emissions whenever it is possible within home environment. In this regard, we extend Wi-Fi radiation study [1] by considering involuntary emissions from power lines while carrying data in high frequencies. We first propose a PLC radiation model based on antenna theory. We demonstrate then a link-adaptive *radiant exposure* path cost that can fit any shortest path algorithm in order to keep electromagnetic radiation under control within a specific area. The goal of this work is to estimate the radiated power generated jointly from Wi-Fi and PLC links within a heterogeneous network and then reduce it using a routing algorithm.**

***Keywords*—Electromagnetic radiation, heterogeneous home network, power-line communications, routing**

I. INTRODUCTION

Home networks have received in the last few years a lot of attention as a research filed owing to the recent improvement in communication devices and the proliferation of wireless and wired transmission technologies. In many scenarios, the design of home-related solutions is guided by many requirements: higher throughput, energy efficiency, self-management, full automation, etc. However, it is still a significant challenge to consider the electromagnetic radiation awareness as an additional requirement while designing new home network solutions and in particular routing protocols. The electromagnetic emissions cannot only be drawn from Wi-Fi devices, but also involuntarily from power lines. Clearly, the particularity of PLC technology is that power lines were not initially designed to propagate signals at high frequencies. In fact, the HomePlug AV2 technology (an evolution of HomePlug AV technology) uses additional frequency spectrum from $30MHz$ to $86MHz$ beyond frequencies used previously by HomePlug AV from $2MHz$ to $30MHz$ [2]. For both technologies, lower frequencies are preferably used for outdoor, as to higher frequencies are used for indoor communication. Hence, when superimposing a higher frequency signal over the existing $50Hz$ electrical circuit, signal power is lost through electromagnetic radiation [3]. The second loss factor is the resistive losses, which are due to the skin depth that varies with frequency. The second aspect is out of this paper scope. Such involuntary emissions not only result in stronger signal attenuation at the receiver but also lead to Electromagnetic Compatibility (EMC) issues, as the radiated signal may interfere with other existing services, such as amateur radio or Short Wave broadcasting [4]. A number of attempts have been presented in the literature to reduce emissions from PLC networks. They include, for example, the injection of an auxiliary PLC-like signal in order to cancel the resulting electromagnetic field on a specific point in space [5], the reduction of the common mode through adding a passive device between the wall outlet and PLC plug [6], and using time Reversal Technique (TR) to mitigate the Electromagnetic Interference (EMI) [7]. It appears that none of these works has considered joint emissions from heterogeneous PLC and Wi-Fi networks.

In prior work [1], we have addressed the issue of electromagnetic radiation generated by Wi-Fi links within a delimited area while carrying data through this link. To do so, we have assumed that home network is a fully wireless network. Nevertheless, in the present paper, we assume that home network is heterogeneous in the sense that it could accommodate both Wi-Fi and PLC transmission links. The bulk of our proposal is to reduce the electromagnetic emissions caused jointly by Wi-Fi and PLC links within a delimited area. To do so, we demonstrate a link-adaptive radiation-aware routing metric and extend our previous routing algorithm (Electromagnetic Radiation-Aware Routing Algorithm, EMRARA) for heterogeneous networks. This extension is hereinafter called EMRARA-H. The reminder of this paper is organized as follow: in Section II, we demonstrate a radiation model for power lines based on antenna theory, the objective of such model is to provide a single value for each PLC link that can be then used as routing metric. The formulation problem is exhaustively explained in Section III. In Section IV, we conduct a series of simulations to evaluate the performances of our proposed solution. Finally, conclusions are drawn in Section V.

978-3-901882-63-0/2014 - Copyright is with IFIP

II. RADIATION FROM COMMUNICATION SIGNALS OVER POWER LINES

A. *Overview*

The way electromagnetic radiation actually occurs in PLC networks is currently poorly understood, in part due to the vast variety of network types and configurations, which has made it difficult to extract the fundamental influencing factors. Thus, the understanding of PLC-related electromagnetic emissions characterization is a tedious issue given the following reasons:

- Load variation from one home to another and for different times of the day,
- Lack of definition of a suitable method for measuring emissions,
- Lack of consensus on an exact definition of measuring methods.

Several sub-issues underlie the assessment of electromagnetic radiation from power lines:

- PLC regulation affects many sectors: electricity, telecommunication and electromagnetic compatibility.
- Electromagnetic context is closely linked to the existing tools of modeling radiation. Such tools, however, are highly dependent on propagation area: close or far from radiation source.

Several methods have been used to answer such questions. For instance, we mention the Finite Difference or Moments method. These methods are actually implemented in commercial codes such as Feko [8], NEC [9] or CST [10]. However, it turns out that such codes are not suitable to treat expanded geometrical configurations (e.g. power lines). Explicitly, in high frequencies, power line length could likely be much longer than wavelength which complicates radiation estimation using the mentioned codes, either because of the huge amount of data to be treated or because of the excessive computation time. Thus, investigating the power lines radiation could be conventionally carried out by applying three theories:

1) Circuit theory
2) Transmission line theory
3) Antenna theory

Equations of the transmission line theory could be obtained from Maxwell equations or from the equivalent power line circuit. Such equations are leading to roughly determine the induced voltages and currents on power lines. Hence, this theory particularly applies to simple wire structures, while ensuring relatively low calculation time. However, this system resolution mandates the knowledge of impedance and linear admittance matrices for each power line, which is onerous to calculate [11]. Similarly, numerical techniques such as moment's method are not appropriate for long power lines (length is relative to wavelength). Moreover, line transmission theory is ideally suited to the differential-mode current assumption but not necessarily in line with the electromagnetic compatibility simulations because it does not assume common-mode current distribution which is the primary source of radiation. Although the differential mode is responsible for part of the radiation, the common mode can be designated as the main culprit when it comes to emissions from PLC networks [12], [13]. Therefore, for the frequency range from *1.8MHz* to *86MHz*, antenna theory is the most appropriate method to simulate electromagnetic radiation from power line of length of up to ten meters.

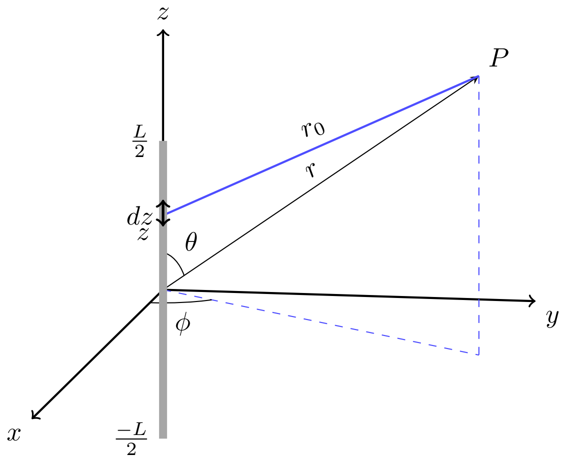


Figure 1. Illustration of antenna theory applied for linear PLC line

We assume first that a power line is thin enough that its radius is much lower than the smallest wavelength in the frequency range. The goal of this theory is to decompose a linear power line of length, L, into N elementary segments and then assume that each section is a radiating source. The electric field can be therefore calculated at any point in the space, by summing up electric field vectors originating from each elementary segment.

B. *Modeling Electromagnetic Radiation from a Power Line*

The premise herein is to design a basic and simple model of electromagnetic emissions radiated from power lines carrying data in high frequencies, in order to formulate a radiation-aware routing metric. The radiated power from an infinitesimal dipole is described in most antenna books [14]. The model presented in this paper sums up the energy radiated from many of these infinitesimal dipoles of length, dz, to make up the whole power line radiation (Figure 1). The electric and magnetic field radiated by a small dipole, dz, in the different space regions depend upon the current in that dipole, $I(z)$, the electric field is given by:

$$\begin{cases} dE_r = \dfrac{I(z)e^{jkr}}{4\pi}(\dfrac{2\eta_0}{r^2} + \dfrac{2}{jw\epsilon})\cos(\theta)e^{jwt}dz \\ dE_\theta = \dfrac{hI(z)e^{jkr}}{4\pi}(\dfrac{jw\mu}{r} + \dfrac{\eta_0}{r^2} + \dfrac{1}{jw\epsilon r^3})\sin(\theta)e^{jwt}dz \\ dE_\varphi = 0 \end{cases}$$

Where $\eta_0 = \sqrt{\frac{\mu}{\epsilon}}$ is the air impedance and $k = \frac{2\pi}{\lambda}$. And regarding magnetic field:

$$dH_\varphi = \frac{I(z)}{4\pi}(jk + \frac{1}{r})\frac{e^{-jkr}}{r}\sin(\theta)e^{jwt}dz$$

For the frequency range $[2MHz, 86MHz]$ used by the technology HomePlugAV2, wavelength varies from $3.48m$ to $150m$. Within a home environment, we would need to estimate radiation for distances far from the power line varying from some centimeters to a dozen meters. Hence, the far zone assumption does not hold for all frequencies. It would then be timely to simplify field expressions according to propagation regions (close and far):

Immediate proximity zone: $r << \lambda$

$$\begin{aligned} \overrightarrow{dE}: \quad dE_r &= \frac{I(z)\eta_0 e^{-jkr}}{2\pi jkr^3}\sin(\theta)dz \\ dE_\theta &= \frac{I(z)\eta_0 e^{-jkr}}{4\pi jkr^3}\sin(\theta)dz \end{aligned} \tag{1}$$

$$\overrightarrow{dH}: \quad dH_\varphi = \frac{I(z)e^{jkr}}{4\pi r^2}\sin(\theta)dz \tag{2}$$

Far zone: $r >> \lambda$

$$\overrightarrow{dE}: dE_\theta = \frac{jk\eta_0 I(z)}{4\pi r^2}e^{jkr}\sin(\theta)dz \tag{3}$$

$$\overrightarrow{dH}: dH_\varphi = \frac{jkI(z)}{4\pi r^2}e^{jkr}\sin(\theta)dz \tag{4}$$

Interestingly, from equations (1) and (2), we note that the electric and the magnetic fields expressions within the close zone are stemmed from electrostatics. In other words, since $\overrightarrow{E}$ and $\overrightarrow{H}$ are in quadrature-phase within the close region, there is no active energy exchange between the doublet and the space (only reactive energy), which means that there is no radiation in the near region; we can therefore assume electromagnetic radiation calculation in the far zone only. From equations (3) and (4), it appears that to calculate the total electric field radiated from a power line, we need the corresponding current distribution that will affects as well the radiated power.

According to the current distribution, waves are either standing or traveling. And according to line transmission theory, electric current distribution can be one or the other of the following distributions:

- Sinusoidal variation of the current amplitude along the power line ⇒ standing waves
- Constant or exponentially decreasing amplitude along the power line ⇒ traveling waves

We assume in the sequel sinusoidal electric current given in the equation (5):

$$I(z) = I_{max}\sin(k(\frac{L}{2} - |z|)) \tag{5}$$

The electric field radiated from a power line of length, L is given by integrating between $\frac{-L}{2}$ and $\frac{L}{2}$ the electric field created by a doublet of length dz in equation (3). The electric field of the power line is then given by the equation (6):

$$E = j\eta_0\frac{I_{max}}{2\pi}\left\{\frac{cos(k\frac{L}{2}\cos\theta) - \cos(k\frac{L}{2})}{\sin\theta}\right\}\frac{e^{jkr}}{r} \tag{6}$$

All parameters are depicted in Figure 1 and summarized in the Table I.

In order to have a single value for each PLC link that can be used as routing metric, we demonstrate a basic radiation model:

The Midpoint Approximate Electric Field Model: By definition, the total radiated power is determined by (7) by integrating the Poynting vector over a closed surface, S, of a sphere of radius r.

$$P_r = \frac{1}{2}Re\left(\oint_S \overrightarrow{E} \wedge \overrightarrow{H}.\overrightarrow{dS}\right) = \frac{1}{2}\oint_S \frac{|E|^2}{\eta_0}dS \tag{7}$$

Then, from equations (6) and (7), we can readily conclude the total radiated power from a linear power line of length L:

$$\begin{aligned} P_r &= \tfrac{1}{2}\left(\int_0^{2\pi}\int_0^{\pi}\frac{|E|^2}{\eta_0}r^2 sin\theta d\theta d\varphi\right) \\ &= 30I_{max}\underbrace{\int_0^{\pi}\frac{\left\{\cos(k\frac{L}{2}cos(\theta)) - \cos(k\frac{L}{2})\right\}^2}{\sin\theta}d\theta}_{\Upsilon} \end{aligned}$$

We choose to approximate the integral Υ using one simple method among interpolating functions methods, namely the midpoint method or rectangle method. It consists, of letting the interpolating function to be a constant function (a polynomial of degree zero) which passes through the point $(\frac{a+b}{2}, \frac{f(a+b)}{2})$. Hence, the integral of a given function can be approximated as follow:

$$\int_a^b f(x)dx \approx (b-a)f\left(\frac{a+b}{2}\right)$$

The integral Υ can therefore be calculated as follow:

$$\Upsilon \approx \pi\left(1 - \cos(k\tfrac{L}{2})\right)^2 \implies P_r = 30\pi I^2{}_{max}\left(1 - \cos(\pi\tfrac{L}{\lambda})\right)^2$$

For this model, it is assumed that the power line radiates equally in all space directions. We can then calculate the power density by dividing the total radiated power by the sphere surface, $4\pi r^2$:

$$\boxed{P_d = \frac{30\pi I^2{}_{max}}{4\pi r^2}\left(1 - \cos(\pi\frac{L}{\lambda})\right)^2} \tag{8}$$

III. RADIANT EXPOSURE METRIC FORMULATION FOR AN HETEROGENEOUS NETWORK

A. Network Model

In our work, a home network is considered as a heterogeneous network hosting four categories of nodes: *Wi-Fi nodes*, *PLC nodes*, *user equipment* (UE) and *routers*. Explicitly, a *PLC node* (e.g. Wi-Fi Powerline Bridge) has both PLC and

Table I. ELECTRIC AND MAGNETIC QUANTITIES AND CORRESPONDING SI UNITS.

Symbol	Unit	Quantity
E	$V.m^{-1}$	Electric field strength
H	$A.m^{-1}$	Magnetic field strength
P_r	W	Radiated power
P_d	$W.m^{-2}$	Power density
$I(z)$	A	Electric current at the point z through the power line
I_{max}	A	Maximum electric current through a power line
k	m^{-1}	Wave number
λ	m	Wave length
w	$rad.s^{-1}$	Angular frequency
ϵ	$F.m^{-1}$	Air permittivity
μ	$H.m^{-1}$	Air magnetic permeability
η_0	Ω	Air impedance
r	m	Distance between the middle of the power line and the investigation point P
L	m	Length of the power line

IEEE 802.11n interfaces but we assume that only one interface could be active at a time. Whereas, a *Wi-Fi node* has only an IEEE 802.11n interface. Regarding routers, they could be seen as relay nodes which can be turned off if necessary. Thus in our network, a node can either be user equipment or router and either *Wi-Fi* or *PLC node*. We assume that all nodes are stationary and their positions are predefined. We model our heterogeneous as a connected and directed graph $G(V_1 \cup V_2, E_1 \cup E_2)$, where V_1 represents the set of *Wi-Fi nodes* and V_2 is the set of *PLC nodes*, as to E_1 and E_2, they are the sets of Wi-Fi and PLC direct links respectively.

It has been proved in [15] that common-mode current, which is the main source of radiation, is a strong function of the wiring topology. Moreover, the electrical topology of a single home is complex because of the multitude of branches of wires, which vary in length, change direction and have different electric load attached to them. The radiation can thus be expected to vary from a house to another, even in the same neighborhood. For the aforementioned reasons, it is necessary to have a low voltage network topology schematic. Authors in [16], [17] propose a random indoor wiring infrastructure model based on analysis of in-home European wiring practices and norms. It has been seen that the number of outlets within a room follows is Poisson variable. For outlets connection, we adopt one of the three most common connection structures, namely, the bus topology with conductors placed along the perimeter [17]. A typical arrangement that we have used in simulations is sketched in Figure 2. We assign to each node a unique identifier $i = 0, 1, |V|$. Moreover, $E_1 \cap E_2 = \emptyset$, it means that $i \to j$ is either a Wi-Fi or PLC link and which has a non-negative edge cost, $w_k(i \to j)$, the index $k \in 1, 2$ is used to designate the radiant exposure value according to the link nature (Wi-Fi or PLC). Note that $k = 1$ if $i \to j \in E_1$ and $k = 2$ if $i \to j \in E_2$.

In the sequel, we rely on the *Radiant Exposure* definition to design our link-adaptive path cost. Explicitly, the radiant exposure is a time integral of the power density $P_d(Wm^{-2})$, and has units of joule per square meters Jm^{-2}. A straightforward radiant exposure, H, formula is given by: $H = P_d.t$, where P_d is the power density usually in Wm^{-2} and t is the exposure time in seconds. The premise behind using such physical quantity is to assess the accumulated amount of radiated energy during data transmission within a given area rather than using instantaneous values. Power line adapter plugs are used to connect *PLC nodes* to the network. These adapters have usually one end into node's Ethernet interface and the other end into an electric wall outlet. In real installation, power lines are usually laid over walls (see Figure 2). Consequently, the virtual link $(i \to j)$, sketched by dashed line in the Figure 2, is more often not straight, it is instead composed of branches of conductors.

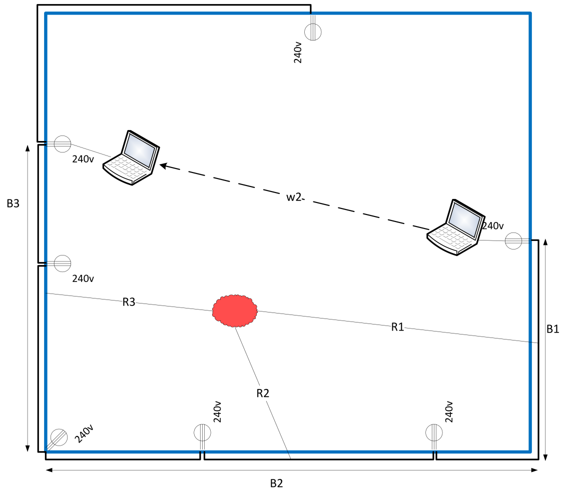


Figure 2. Example of wiring topology: Bus Topology with conductors along the perimeter

In the example depicted in the Figure 2, we define the weight of the link $(i \to j)$, w_2, to be the sum of the radiant exposure values generated from conductor branches of length B_1, B_2 and B_3 respectively. A calculation example is given as follow:

$$w_2(i \to j) = \sum_{k=1}^{3} P_d(B_n) * EPT_{ij}$$

Where $P_d(B_n)$ is the power density generated by the branch of length B_n carrying a sinusoidal current having a maximum value of $T_{max}^{B_n}$. Using the radiation model of a power line, previously demonstrated in section II-B and from the equation (8), we can readily conclude the general expression of the link cost w_2 (Figure 2):

$$w_2((i \to j)) = \sum_{k=1}^{3} \frac{30\pi {I_{max}^{B_n}}^2}{4\pi r_{B_n}^2} \left(1 - \cos(\pi \frac{B_n}{\lambda})\right)^2 * EPT_{ij}$$

B. Radiant Exposure Path Cost

Let denote P_{TX}^{i} and EPT_{ij} the transmit power and the expected packet time to deliver a packet over a direct link $(i \to j)$, respectively. In prior work [1], we have proposed a Wi-Fi link cost to be $\frac{P_{TX}}{4\pi r^2} * EPT$, which is actually the expected radiant exposure of delivering a packet over that link. For a fully wireless multi-hop network, we have used the traditional Dijkstra's algorithm to compute minimum radiant exposure paths.

Radiation pattern is generally complex to be accurately calculated, and it appears that it is inherently dependent on the

Table II. QUANTITIES AND CORRESPONDING SI UNITS OF PARAMETERS IN THE EQUATION 9

Symbol	Unit	Quantity
P_{TX}^{i}	W	Transmit power of the node i
r_i	m	Distance between the transmitter i and the point $\mathcal{P}$
I_{max}	A	Maximum electric current through the PLC link
r_{B_u}	m	Distance between the middle of the branch B_u and the investigation point $\mathcal{P}$
B_u	m	Length of the branch B_u
EPT_{ij}	s	Expected packet time over the link from node i to node j

source nature, in other words, physical features of the transmission medium influence strongly the electric field values. It is therefore important to formulate an extended and adaptive routing metric that takes into consideration electromagnetic radiation from both Wi-Fi and PLC links.

Based on the aforementioned assumptions and Wi-Fi radiation model proposed in [1], we formulate in the equation (9) a link-adaptive path cost to assess the radiant exposure within a radiation-sensitive area caused by a packet transmission through a path $\mathcal{P}_{s,d}$ from a source s to a destination d.

$$\mathcal{C}(\mathcal{P}_{s,d}) = \sum_{i \to j \in \mathcal{P}_{s,d}} (\alpha_{i,j} w_1(i \to j) + \beta_{i,j} w_2(i \to j)) * EPT_{ij} \tag{9}$$

Where

$$w_1(i \to j) = \frac{P_{TX}^{i}}{4\pi r_i^2} \tag{10}$$

$$w_2(i \to j) = \sum_{B_u \in i \to j} \frac{30\pi {I_{max}^{B_u}}^2}{4\pi r_{B_u}^2} \left(1 - \cos(\pi \frac{B_u}{\lambda})\right)^2 \tag{11}$$

$$\alpha_{i,j} = \begin{cases} 1 \quad if \quad i \to j \in E_1 \\ 0 \qquad\qquad otherwise \end{cases} \tag{12}$$

$$\beta_{i,j} = \begin{cases} 1 \quad if \quad i \to j \in E_2 \\ 0 \qquad\qquad otherwise \end{cases} \tag{13}$$

The objective function (9) provides the total cost of the path $\mathcal{P}_{s,d}$ from a source, s, to a destination, d, in terms of radiant exposure. Equations (10) and (11) demonstrate the power density caused by transmitting data through a Wi-Fi and PLC link respectively. As to constraints (12) and (13) ensure that a given link $(i \to j)$ belonging to the optimal path $\mathcal{P}_{s,d}$ is either Wi-Fi or PLC and allow to assign the corresponding power density value to that link.

C. Optimization Problem

With EMRARA-H, we further extend the flexibility of path cost calculation by adaptively determining the values of the radiation-aware metric corresponding to the MAC layer technology. In equation (9), we assume that the constraints (12) and (13) are determined by the transmitter node itself. This enables network nodes to advertise which interface is used for each transmission.

In order to reduce the level of electromagnetic radiation within a given area caused by transmitting data from a source to a destination, we use the well-established Dijkstra's shortest path algorithm and the radiant exposure as pairwise link weight. Unlike most of the metrics used in traditional routing protocols that mainly assess link quality in terms of inherently system-related criteria, such as delay, bandwidth or throughput. Radiant exposure as a routing metric presents the specificity of influencing routing decisions by external environment changes. Furthermore, the link-adaptive cost definition (Equation (9)) assesses the contribution of heterogeneous radiating sources.

IV. EVALUATION RESULTS

In this section, we underline how using the link-adaptive radiation-aware path cost in conjunction with the well-known Dijkstra's algorithm mitigates the radio-frequency emissions drawn from heterogeneous radiating sources.

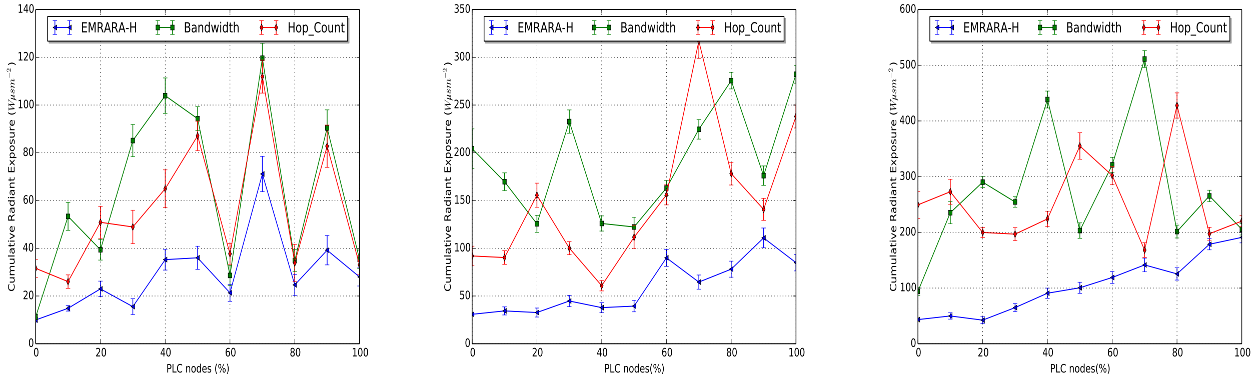
We conduct simulations in our empirical study in order, in one hand, to prove the effectiveness of our link-adaptive path cost, and in the other hand, to answer the following questions. Compared to traditional known schemes, how effectively can our algorithm reduce the radiated energy caused by radio-frequency emissions within a given area? What is the cost in terms of energy consumption? How network parameters influence our algorithm? Network parameters could include:

- Network size: or in other words nodes population.
- User Equipment population: percentage of user equipment among the total number of network nodes.
- PLC nodes population: percentage of PLC nodes among the total number of network nodes.

We vary the aforementioned parameters during simulations in order to analyze their effects on the performance results. Consequently, we have designed a software simulator based on the simulation package NetworkX [18]. NetworkX is a Python package that provides classes and generators to create standard graphs as well as algorithms to treat and analyze resulting networks and obviously many drawing tools.

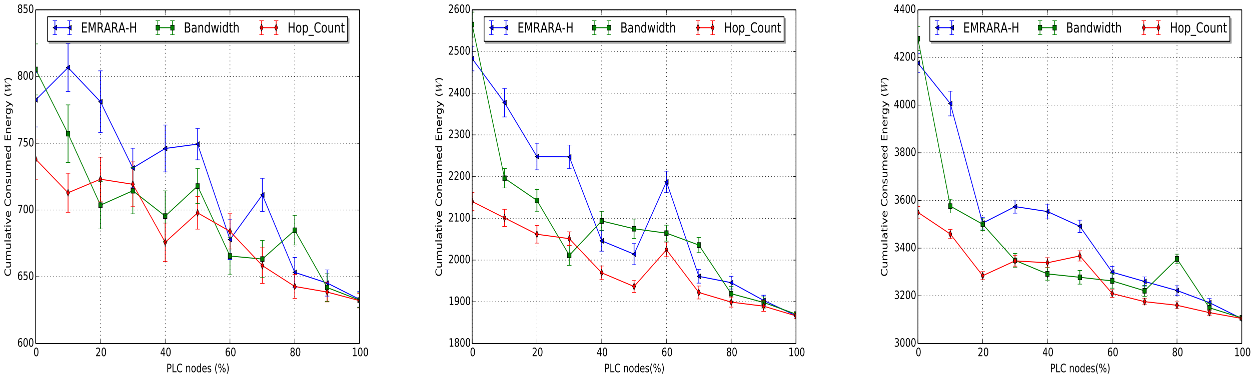
In our simulations, 100 nodes of the same transmission range are randomly distributed into a $200 * 200$ square field. For each parameter setting, 100 trial networks are generated. Since the down-link traffic in home network is till now higher than the up-link traffic, we only assume the down-link traffic sent from the gateway (which is the unique egress to the Internet in our model) to all users. In order to bring out the performance of our algorithm, we use two evaluation metrics: Cumulative Radiant Exposure and Cumulative Energy Consumption. Which are the sums of the radiant exposure and energy consumption costs respectively of shortest paths while transmitting a 1500 bytes packet from the gateway (GW) to all users (UE). For each trial, we randomly pick a set of nodes that have PLC interface in addition to Wi-Fi interface and a set of user equipment (UE), that we could not turn off whichever their position relative to the EM radiation-sensitive area. Then, the averages of cumulative radiant exposure and cumulative energy consumption as well as standard deviation are calculated for individual algorithms.

For more consistency, we assume for each trial 70% of nodes to be user equipment (which is likely the case in a real home network). We conduct simulations for different values



(a) 20 Nodes (b) 60 Nodes (c) 100 Nodes

Figure 3. Cumulative radiant exposure variations with changes in network size. The figures represents 20, 60, 100 nodes, respectively.

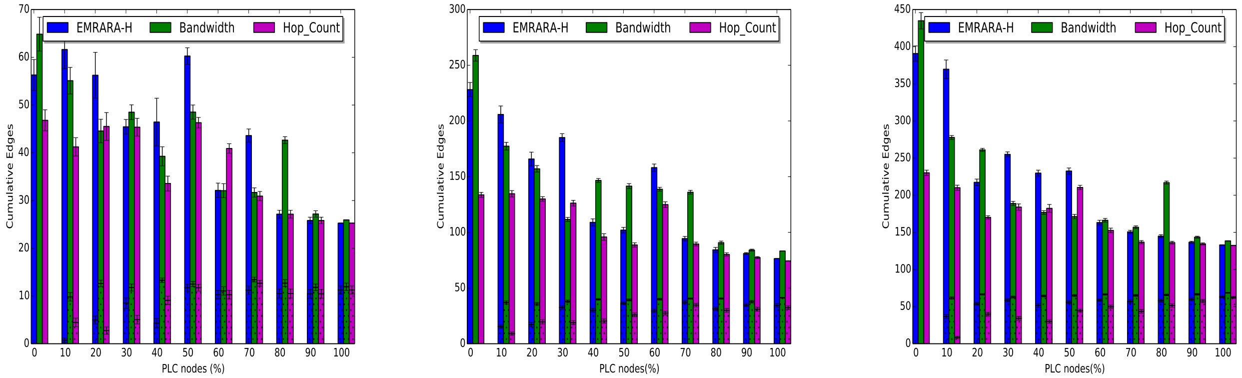


(a) 20 Nodes (b) 60 Nodes (c) 100 Nodes

Figure 4. Cumulative energy consumption variations with changes in network size. The figures represents 20, 60, 100 nodes, respectively.

of network size and PLC nodes population. Figure 3 captures the effectiveness of our algorithm to direct data away from the sensitive area (situated for this examples in the center of the simulation domain) since EMRARA-H outperforms the Dijkstra's algorithm with the link capacity and the hop count as routing metrics, for all network sizes and different PLC nodes population. Meanwhile, it is noticeable from Figure 3, that increasing the network size results in a lower efficiency in terms of radiant exposure of Dijkstra's algorithms with hop count and bandwidth as routing metrics. For example, when we have 20 nodes in the network (Figure 3(a)), *hop-count* and *bandwidth* algorithms generate up to 217% and 447% more cumulative radiant exposure than EMRARA-H, respectively, while when we have 100 nodes (Figure 3(c)), they generate respectively up to 475% and 580% more cumulative radiant exposure than EMRARA-H. Explicitly, since we kept the same simulation domain of $200 * 200$ for different network size, small number of nodes leads to less alternative paths than bigger networks, then the three algorithms may pick the same optimal paths for small networks. Contrariwise, regarding energy consumption, the EMRARA-H algorithm consumes in the worst cases 13% and 17% more than *hop-count* algorithm for networks of 20 and 100 nodes respectively (Figure 4). We can then underline that our algorithm guarantees a good compromise between energy consumption and radio-frequency emissions within a given area. Another clear message from Figure 4, is that the energy consumption decreases remarkably when PLC nodes number increases, it is obvious since a PLC interface consumes less than a Wi-Fi interface while assuming that a PLC interface consumes as much energy as an Ethernet interface.

Bars in Figures 5 are split to two parts, the dashed ones represent the cumulative number of PLC links, and the second ones represent the cumulative number of Wi-Fi links that make up all shortest paths from the GW to 70% of UEs. We point out from the Figures 5 that the energy consumption is closely linked to the cumulative number and the nature (whether it is PLC or Wi-Fi)of links that make up the shortest paths from the GW to all UEs whereas it is not necessarily the case to explain the cumulative radiant exposure variations, purely and simply because RF emission depends upon the distance between the radiating sources and the sensitive area. Concretely, in Figure 5(a) for instance, for a network of 50% of PLC nodes EMRARA-H uses more Wi-Fi links than a network of 70% of PLC nodes, contrariwise the first one generates less



(a) 20 Nodes (b) 60 Nodes (c) 100 Nodes

Figure 5. Cumulative Wi-Fi and PLC (dotted bars) links number variations with changes in network size. The figures represents 20, 60, 100 nodes, respectively.

RF emissions than the second one (see Figure 3(a)).

V. CONCLUSION

In this paper, we studied the problem of minimum radio-frequency radiation for heterogeneous home network in the presence of Wi-Fi and PLC links. To do so, we have pioneered a new link-adaptive radio-frequency radiation-aware path cost for routing uses. We have considered the problem in previous work [1] in fully wireless network. However, home network may host different transmission medium namely power lines which can likely be a source of involuntary RF emissions especially in high frequencies. We have first studied and proposed an electromagnetic radiation model for PLC, and then proceed to study more general mixed model where a path from a source to a destination may be composed of Wi-Fi and PLC links. Hence, we present an extension of our previous algorithm [1], EMRARA-H, that attempts to reduce the RF radiation resulting from data transmission over heterogeneous links, and we show by simulations that it can outperform in different scenarios two other shortest path algorithms. Besides, we plane to strengthen our simulations by considering additional performance metrics in terms of delay, packet error rate, etc...

REFERENCES

[1] H. El Abdellaouy, A. Pelov, L. Toutain, and D. Bernard, “Electromagnetic Radiation-Aware Routing Algorithm,” in *Consumer Communications & Networking Conference (CCNC 2014) , 2014 IEEE*, 2014, pp. 119–126.

[2] HomePlug AV2 Technology, “Raising the bar for sustained high-throughput performance and interoperability for multi-stream networking using existing powerline wiring in the home.” 2013.

[3] M. Ishihara, D. Umehara, and Y. Morihiro, “The correlation between radiated emissions and power line network components on indoor power line communications,” in *Power Line Communications and Its Applications, 2006 IEEE International Symposium on*, 2006, pp. 314–318.

[4] B. Zarikoff and D. Malone, “Experiments with radiated interference from in-home power line communication networks,” in *Communications (ICC), 2012 IEEE International Conference on*, 2012, pp. 3414–3418.

[5] N. Korovkin, E. Marthe, F. Rachidi, and E. Selina, “Mitigation of electromagnetic field radiated by PLC systems in indoor environment,” *International Journal of Communication Systems*, vol. 16, no. 5, pp. 417–426, 2003. [Online]. Available: http://dx.doi.org/10.1002/dac.595

[6] P. Favre, C. Candolfi, and P. Krahenbuehl, “Radiation and disturbance mitigation in plc networks,” in *Electromagnetic Compatibility, 2009 20th International Zurich Symposium on*, 2009, pp. 5–8.

[7] A. Mescco, P. Pagani, M. Ney, and A. Zeddam, “Radiation mitigation for power line communications using time reversal,” in *Journal of Electrical and Computer Engineering*, 2013.

[8] FEKO Comprehensive Electromagnetic Solutions. [Online]. Available: http://www.feko.info/

[9] Numerical Electromagnetics Code (Method of Moments). [Online]. Available: http://www.nec2.org/

[10] Computer Simulation Technology. [Online]. Available: http://www.cst.com/

[11] F. Issa, “Analyse et modélisation du réseau électrique basse tension aux fréquences courants porteurs de la gamme [1 MHz-30 MHz],” Ph.D. dissertation, 2002, Thse de doctorat dirige par Pacaud, Andr Physique Paris 11, Orsay 2002. [Online]. Available: http://www.theses.fr/2002PA112102

[12] C. R. Paul, “A comparison of the contributions of common-mode and differential-mode currents in radiated emissions,” *Electromagnetic Compatibility, IEEE Transactions on*, vol. 31, no. 2, pp. 189–193, 1989.

[13] P. Favre, C. Candolfi, M. Schneider, M. Rubinstein, P. Krahenbuehl, and A. Vukicevic, “Common mode current and radiations mechanisms in plc networks,” in *Power Line Communications and Its Applications, 2007. ISPLC ’07. IEEE International Symposium on*, 2007, pp. 348–354.

[14] A. Balanis, *Antenna Theory: Analysis and Design, 3rd Edition*. John Wiley, 2005.

[15] A. Vukicevic, “Electromagnetic Compatibility of Power Line Communication Systems,” Ph.D. dissertation, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, 2008.

[16] A. Tonello, F. Versolatto, and S. D’Alessandro, “Opportunistic Relaying in In-Home PLC Networks,” in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, 2010, pp. 1–5.

[17] A. Tonello and F. Versolatto, “Bottom-Up Statistical PLC Channel Modeling ;Part I: Random Topology Model and Efficient Transfer Function Computation,” *Power Delivery, IEEE Transactions on*, vol. 26, no. 2, pp. 891–898, 2011.

[18] A. Hagberg, D. Schult, and P. Swart, *NetworkX Reference, Release 1.7*, 2012.