Interference Predictions for In-Home Power Line Communication Systems

Ming Zhang and Wilfred Lauber
Communications Research Centre Canada,
3701 Carling Avenue
Ottawa, Ontario, K2H 8S2, Canada
ming.zhang@crc.ca

***Abstract*—**This paper investigates the nature and extent of the unavoidable RF emissions from in-home power line communication systems (PLC). Numerical models for these systems provide a good perception of the unintentional emissions and the effectiveness of the measures employed to reduce the harmful impact of these leakage emissions on radio reception. A specific wiring/ load configuration within a bungalow was chosen to characterize typical in-home PLC environments. The signal power spectral density of a HomePlug device was used in the numerical model.

***Index Terms*—** In-home power line communication, numerical simulation, EMC.

I. Introduction

Power Line Communications (PLC), also known as Broadband Power Line Access (BPL), is the latest technology to provide broadband Internet access through existing house wiring. With the power line serving as the in-home PLC network backbone, every outlet in the home becomes a high-speed Internet access point. Access from the in-home network to long-haul networks can be established with other devices or facilities, such as wireless (WiFi) and digital subscriber loop (DSL).This technology has the potential to offer benefits relative to regular cable, DSL or wireless connections [1].

However, the development of in-home PLC has a number of complex issues. Primarily, the use of this medium for communications at the higher frequencies is technically challenging. Power line networks are not designed for radio-communication services, as evidenced by a variety of conductor types, connections and load impedances. With such an ill-defined system from the RF standpoint, PLC systems can cause harmful interference to licensed operations in the frequency range of use, 3-30 MHz. This frequency band has been used for decades by amateur radio operators, as well as international shortwave broadcasters and a variety of communications systems (military, aeronautical, etc.).

In 2004, the FCC released its Report and Order [2] to facilitate the development of Access BPL—that is, the use of BPL to deliver broadband service to both in-home and external systems. In July 2005, Industry Canada (IC) issued a Consultation Paper on Broadband over Power Line Communication Systems [3], to solicit comments from various parties on the development and regulation of PLC systems and to take steps to facilitate the deployment of the technology in Canada. FCC rules allow PLC to be operated on an unlicensed basis, subject to certain technical and administrative restrictions intended to protect existing radio-communication services.

However, the PLC interference issue is contentious, and remains under discussion within North America and elsewhere. A range of radiated limits has been proposed by users of various sectors of the spectrum, either for system compliance or for the purposes for adjudication in cases of reported interference [4-6]. However, at present none of these proposals can satisfy the dual objective of protecting existing users while, at the same time, allowing the PLC to operate in a commercially viable manner.

Some measurement and numerical analyses of the physical mechanisms have been carried out [4-6]. However, most of the simulations used over–simplified wiring configurations, with CW signals rather than actual wideband data signals. This has given rise to debate as to the accuracy and reliability of the analyses. The main contribution of this work is to overcome these two deficiencies.

Research at the CRC has been in two parts, namely 2-45 MHz medium-voltage (MV) overhead PLC systems [7, 8] and 4-24 MHz in-home PLC systems. Reference [9] briefly presented some results for in-home PLC systems, with further details of results and discussion in this present paper.

The work is organized as follows. Section II presents the electromagnetic characterization of an in-home system, with a broadband Gaussian excitation source modeling wideband data signals. In Section III, far-field

Manuscript received September 11, 2008; revised February 10, 2009; accepted March 18, 2009.

This paper is based on "Evaluation of Interference Potential of In-Home Power Line Communication System" ,by M. Zhang and W. Lauber, which appeared in the Proceedings of the 12th IEEE Int. Symposium on Power Line Communications and Its Applications (ISPLC), Jeju Island, Korea, April 2008. ©2008 IEEE.

radiation patterns are calculated at a number of frequencies, to examine radiation from the service wires.

In Section IV, radiated levels in the near-field (within a few tens of metres from the house wiring) have been calculated for single, and simultaneous access to the in-home PLC network. Two cases, single house and a community of four houses, are considered. In each case, the highest radiated emissions are examined for compliance with FCC rules [2].

In Section V, a brief summary of the results, together with a discussion on the reduction of interference from in-home PLC systems, are presented.

II. SIMULATION SETUP

A. House Wiring

In North America, it is common for a distribution transformer to service several homes via underground cables. Normally the cables contain three wires (2 phase and 1 neutral). Figure 1 shows a typical connection. The secondary winding of the transformer is centre-tapped and connected to neutral. At the service entrance, the neutral conductor is grounded. In this 3-wire system, branch circuits supply 110V from between this grounded conductor and one of the ungrounded conductors, and 220V between the two ungrounded conductors.

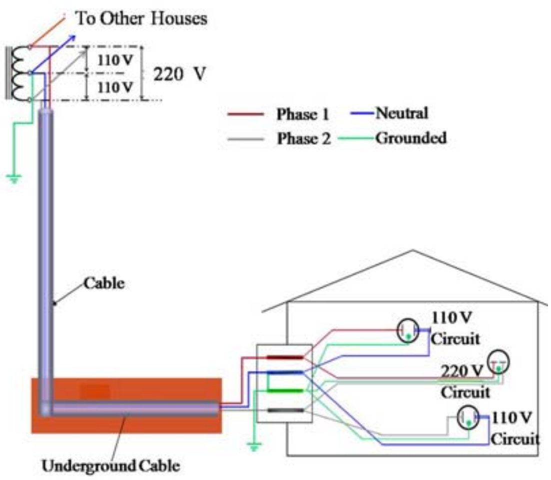


Figure 1: Transformer/ House wiring topology.

The wiring geometry and environment are very complex. As a basis for modeling, a bungalow has been considered with building materials commonly used in Canada and the northern part of the USA. The structure and dimensions are shown in Figs. 2 and 3.

B. Characterization of the PLC System

The electrical wiring configuration considered here, consists of one main and two branch (ceiling) circuits, Fig. 4. The main circuit has four wires: two phase, a neutral and a ground; each branch circuit has a phase and a neutral wire. Because of the small loss (a few tenths of a dB per km at 20 MHz in the wire), they may be modeled as 0.5 cm x 0.5 cm cross section perfect conductors. Deviations from the parallel (1.4 cm spacing) are much less than the wavelength λ (15 metres at 20 MHz) and may be ignored. The underground cable from the distribution transformer to the house entrance is shielded and buried in lossy soil, and radiation from this length may be neglected. The wires are embedded in the house wall insulation layer (Fibre-Glass), with outlets mounted in the interior wall. A total of five duplex receptacles and two types of loads terminate this wiring. These receptacles, No.1 to No.5 receptacles (lower sockets) are used to connect to loads or plug in-home PLC devices. All four ceiling lights are kept on. Though this configuration is simplified compared to the real world, it is believed to capture the nature of in-home power distribution networks.

The house model sits on a 20 cm-thick concrete ‘pad’ foundation. Under this foundation is a 2.5 m thick good-soil (ε_r = 15, σ= 15*mS*) layer, with an area of 33.9 x 31.4 metre^2, as shown in Fig. 5.

C. Numerical Simulation

Unlike telephone wires with very low emission from their differential line, power wiring is highly unbalanced, and potentially very leaky. Placing limits on common-mode current at the point of injection is unlikely to control the interference level, even if the PLC excitation signal is in a differential mode. A HomePlug device is modeled as a voltage source, with a 50 Ω resistor as the series source impedance, as shown in Fig. 4. A Gaussian pulse centred at 15 MHz with a 15 MHz bandwidth was used as the voltage excitation. The central level of the pulse was initially set to 1 volt in the z-axis polarization direction.

TrendNet, one of the HomePlug certified products [1], implements Intellon’s INT51X1 OFDM-base technology chip, operating from 4.3 to 20.9 MHz with data rates of up to 14 Mbps. This is a second generation device with a pre-notching capability to protect four radio amateur bands, as shown in Fig. 6. The power levels vary with RF signal frequencies, with a maximum level of around –50 dBmW /Hz. This maximum level and notches have been used in the numerical modeling.

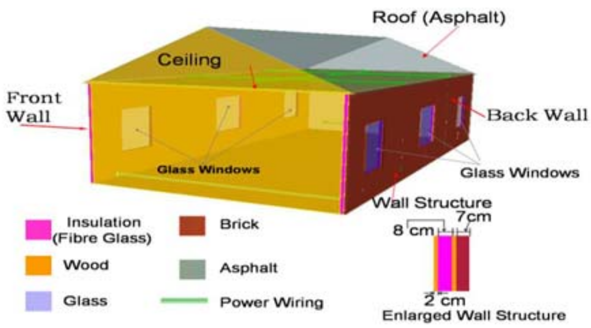


Fig. 2: Structure of the one-storey house considered in the numerical model.

Numerical simulations have been carried out using Empire software, which is based on the finite difference time domain (FDTD) method [10]. Certain results, such as input impedance and reflection coefficient, are independent of the applied source level, whereas other results such as electric field strength and radiated power are, of course, directly proportional to the source level. Source levels vary with frequency as the Gaussian distribution. With an excitation normalization feature in the software, this variation with frequency caused by the applied Gaussian pulse itself, can be automatically removed. The field strength must then be scaled to the power spectral density (PSD) level of -50 dBmW/Hz (or 10 dBmW/MHz), using the scaling algorithm described in [7]. In each scaling evaluation, the frequency span was set to 150 kHz and the resolution bandwidth to 3.5 kHz.

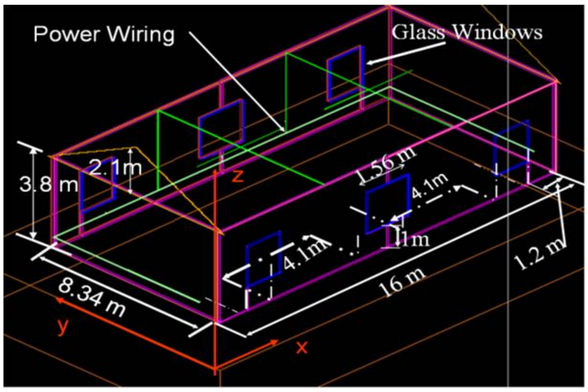
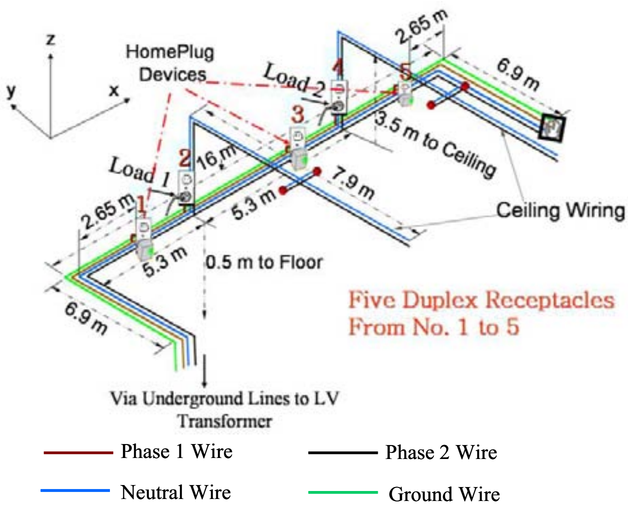


Fig. 3: Dimensions of the one-storey house considered in the numerical model.



Symbols		Equivalent Circuit	
	Light Bulb		114 Ω Resistor
	Home Plug (PLC Modem)		A voltage source with a series 50 Ω resistor
	Load No.1		A 12 kΩ Resistor with an 0.6 mH inductor in series
	Load No. 2		A 1 kΩ Resistor

Fig. 4: Electrical wiring configuration and loads considered in the numerical model.

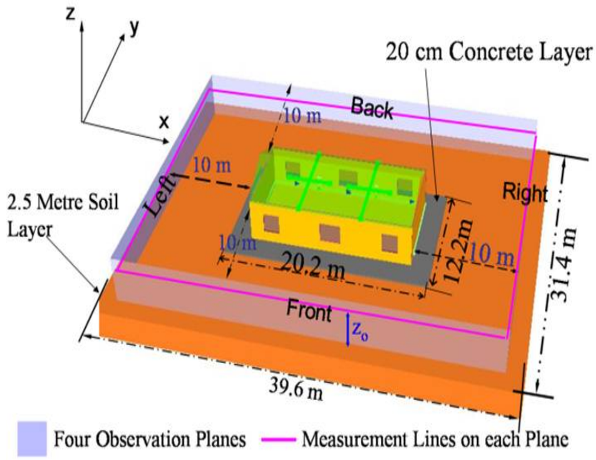


Fig. 5: Numerical simulation setup, showing the house concrete 'pad' foundation, the 2.5 metre soil ground and the four observation planes placed 10 metres away from each side.

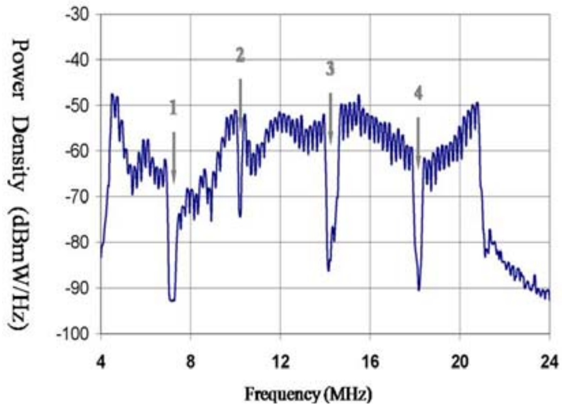


Fig. 6: Spectrum of TrendNet TPL-102E (HomePlug certified product), showing four frequency notches for Amateur Bands. 1): 7-7.3 MHz, 2): 10.1-10.15 MHz 3): 14.0-14.25 MHz and 4): 18.068-18.168 MHz.

III. Results in Far field

A. Reflection Coefficient

The RF signals launched into home power lines do not simply travel point to point along the service wires; they also escape as undesired radiated emissions. This radiation can be studied in the context of a "wire transmitting antenna", whose reflection coefficient and input impedance at the injection point are two key characteristics.

In the following calculations, the HomePlug device was connected in turn, to three receptacles (see Fig. 4). Each connection is associated with different wire and load patterns. Reflection coefficients for these three ports have been calculated with a 3.5 kHz frequency resolution, and are shown in Figs. 7 and 8. These Figures indicate that the behaviour of the reflection coefficient obtained at one outlet is quite different from that at another.

The probability of the wiring acting as an efficient radiator is shown to be very small. In Fig.7, for three injection locations, impedance mismatch exists at each injection point for most of the operating frequencies, resulting in very large reflection coefficient values.

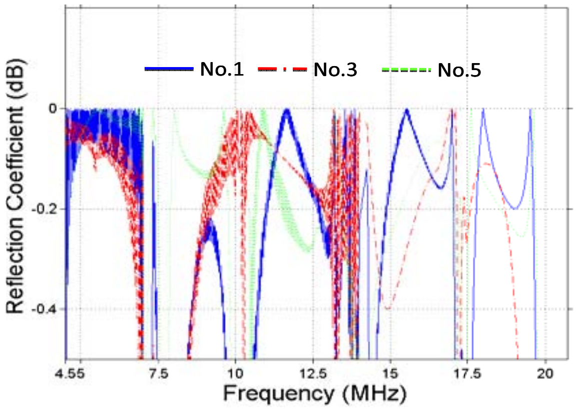


Fig. 7: Reflection Coefficient values around 0 (dB) versus frequency for the three signal ports, where the HomePlug device was plugged into No.1, No.3 and No.5 outlet. This shows impedance mismatch at the injection points for most of the operating frequency range.

However at isolated frequencies, the house wiring can act as a resonant antenna (reactive components tuned out or impedance matched with the excitation source). That is, at certain frequencies, the reflection coefficients can be very small (< –10 dB). This is undesirable because of the potential interference to other radio services in the far-field.

Fig. 8 indicates that the deepest resonant band (with reflection coefficient -32 dB), is located around 7.05 MHz for the No.1 injection outlet. This location is coincidently within one of the four amateur bands, with radiation from this resonant band notched by the HomePlug device itself (Fig. 6). Other cases studied show that the resonance behaviour of a particular power line varies greatly with wiring topology and impedance loadings.

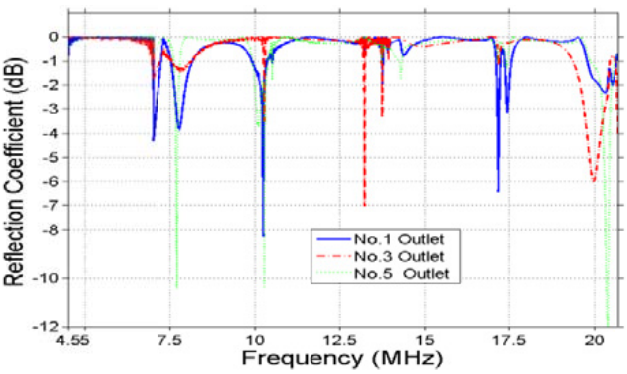


Fig. 8: Reflection Coefficient values (dB) versus frequency for the three signal ports, where the device was plugged, in turn, into No.1, No.3 and No.5 outlet. At some frequencies, the reflection coefficients are very small.

B. Radiation Pattern

Radiation patterns have been calculated at a series of resonant and non resonant frequencies, as well as at 'quasi-resonant' frequencies (with small reflection coefficients but larger than -10 dB). These patterns show how closely a PLC wiring configuration can act as a good radiator, and its relationship with reflection coefficient values. Two pairs of radiation patterns with the HomePlug device terminated at No.1 and No.5 outlets are presented here. In these examples, radiation patterns at the azimuth angles of φ=0° and 90° are calculated at two frequencies, one resonant or quasi-resonant frequency (less than -8 dB), and the other non-resonant, but close to the resonant or quasi-resonant frequency. It is seen from Figs. 9 (a) and 9(b) that the two patterns in each pair are almost the same in shape, but the main beam levels at the resonant frequency are about 10-13 dB higher than those at the non-resonant frequency.

A scenario of a region or city with full-scale deployment of in-home PLC service, is considered. For such a large population of PLC systems, it is expected that almost all possible configurations of wiring, appliances and other loads will be present within the population. Cumulatively, it is thus highly probable for those resonant and 'quasi-resonant' frequencies to appear at any location of the spectral range of 4.49-20.7 MHz. As mentioned, these in-home wirings would be very efficient radiators.

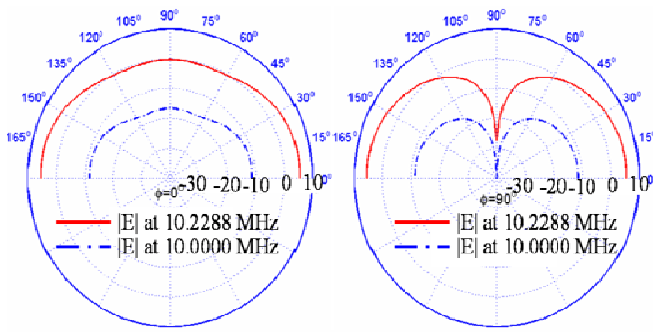


Fig. 9(a):Elevation patterns at azimuth angles of φ=0° and 90°, at frequencies of 10.2288 and 10.000 MHz, for No.1 outlet injection. At 10.2288 MHz the in-home system is quasi-resonant with a reflection coefficient less than -8 dB.

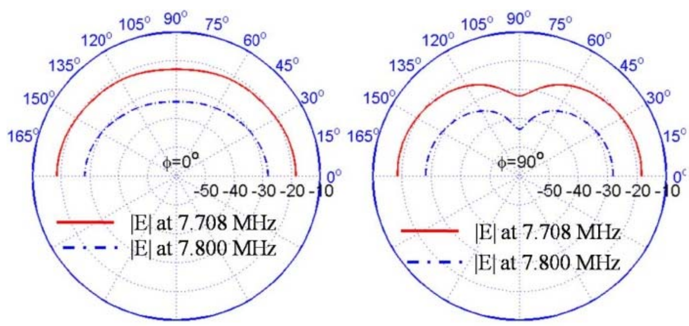


Fig. 9(b): Elevation patterns at azimuth angles of φ=0° and 90°, at frequencies of 7.7080 and 7.8000 MHz, for No.5 outlet injection. At 7.7080 MHz the in-home system is resonant with a reflection coefficient less than -10.4 dB.

IV. CASE STUDIES IN NEAR FIELD AND FCC COMPLIANCE

A. FCC Limit

Once the home power lines are energized with RF signals, the resulting electromagnetic fields can be classified as either radiated or guided. Radiated characteristics in the far-field have been examined in the context of a "wire antenna" in the previous section. Guided fields carry the RF signals along the line. Power wiring is inherently unbalanced, compounded by the appliance extension lead or Homeplug device plugged into it. These characteristics cause impedance discontinuities, multiple reflections and radiated emissions in the vicinity of wiring.

In this study, electromagnetic compatibility (EMC) was examined by consideration of near field distributions. Following FCC measurement procedures, the electric field strengths in both horizontal and vertical polarizations for each case, were calculated over the frequency range of 4.49-20.7 MHz, at a total of 104 frequency points. For in-home systems operating below 30 MHz, field strengths must not exceed:

$$E_{\lim}(in\ dB\mu V/m) = 29.5 + 40\log_{10}(30/d) \qquad (1),$$

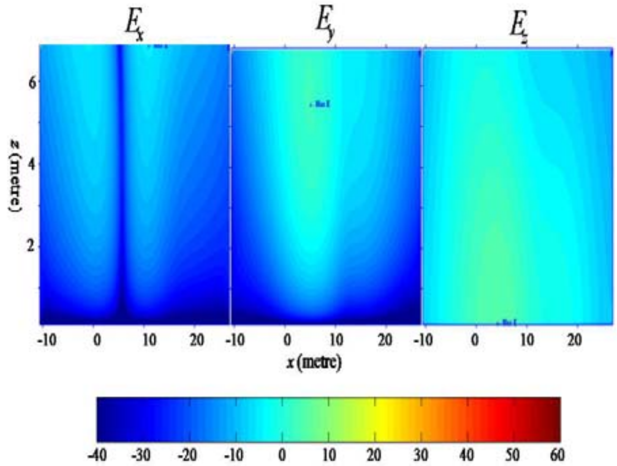
If measurement distance d is 10 metres, and 3 dB is added to compensate for the difference between quasi-peak detector (FCC) and peak values (simulation) [2], Equation (1) gives an FCC limit of 51.6 dBμV/m. The effect of the fixed notch of the HomePlug device has been included by subtracting 35 dB from the field strength levels for those frequency points within the amateur radio bands.

B. Single House

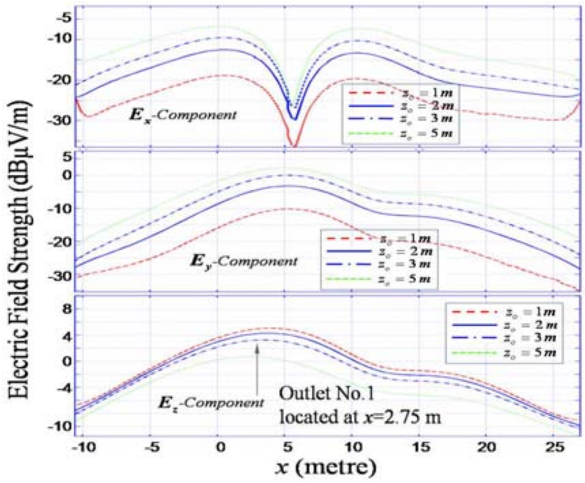
For the single house case, fields are generated for two situations: the device transmitting data via the No.1, No.3 and No.5 outlets in turn, and three devices transmitting simultaneously via these outlets.

Four observation planes (back, front, left and right) were set up 10 metres from each side of the house, as illustrated in Fig. 5. On each plane, field strengths were calculated at heights z_o= 1, 2, 3 and 5 metres above the house floor.

The values on the back observation plane have been shown to be significantly larger than those on the other three planes, because all outlets were located on the back wall. Two examples of the field strengths, obtained along the back side, are presented in Figures 10 and 11. These results show that: (1) field strengths in the signal-injected polarization (E_z -fields in this study) are in general at least 5 to 10 dB higher than other polarization components. Significant fields appear at around 0.5 metre above the ground for z-directed fields, and at 5 metres for the other components; (2) variation of the E_z -field levels with height is quite small, with at most 5 dB change. In contrast, the variation with height for the E_x- and E_y -fields is considerable.

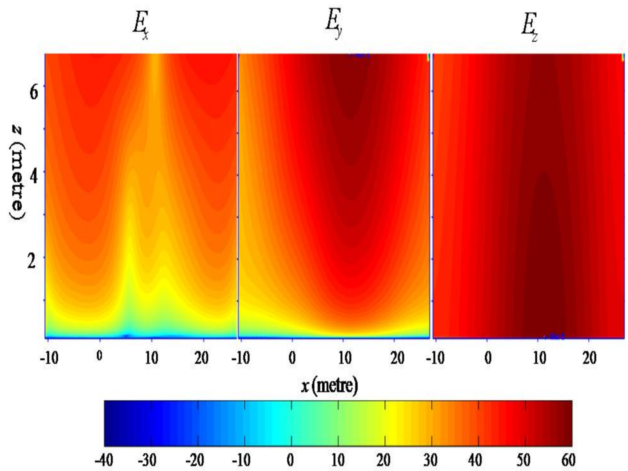


(a): Electric field strength maps

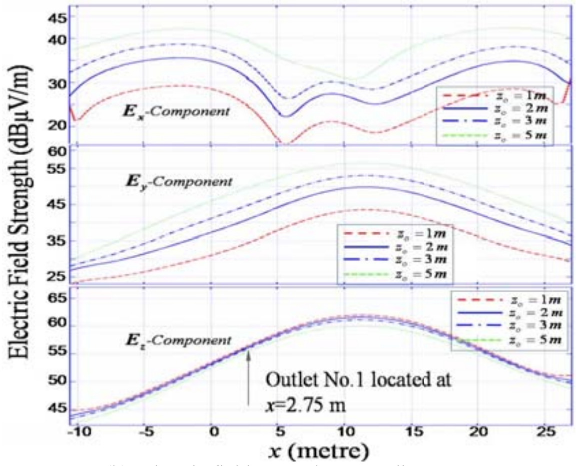


(b): Electric field strength versus distance

Fig. 10: Electric field strengths for outlet No.1 injection and at 11.225 MHz, calculated 10 metres away from the back side of the house. (a): Electric field strength maps. (b): Electric field strengths versus the distance along the line 10 metres away from the user's house and at the heights of 1, 2, 3 and 5 metres.



(a): Electric field strength maps



(b): Electric field strength versus distance

Fig. 11: Electric field strengths for outlet No.1 injection and at 10.175 MHz, calculated 10 metres away from the back side of the house. (a): Electric field strength maps. (b): Electric field strengths versus the distance along the line 10 metres away from the user's house and at the heights of 1, 2, 3 and 5 metres.

As observed earlier, the radiated emissions of the E_z – fields, along the back side, represent the worst interference levels. The maximum (worst case) values of E_z- fields over the frequency range of 4.49 - 20.9 MHz are presented in Fig.12.

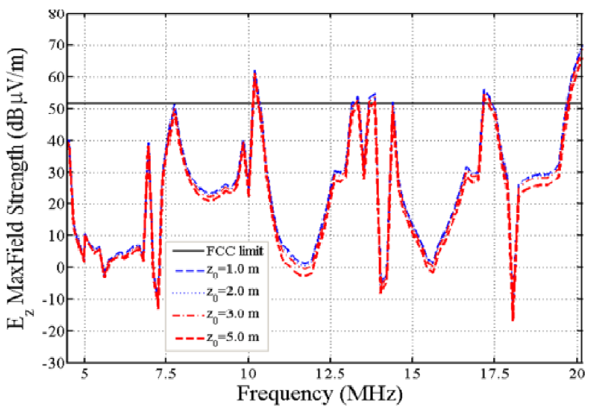


Fig. 12: Maximum E_z-field strength (dBμV/m) for outlet No.1 injection and frequency range 4.49 - 20.9 MHz, calculated at 10 metres from the back side of the house, at heights of z_o= 1, 2, 3 and 5 metres, and compared with the FCC limit.

Fig.12 indicates that the power level should be reduced to less than -65 dBmW/Hz, to satisfy Part 15 rules. In addition, strong radiated emissions are generally associated with frequencies with small reflection coefficients, especially below 20 MHz. This can be seen from the comparison of the field values in Fig. 12 with the reflection coefficients at outlet No.1, shown in Fig. 13. However, field strengths and reflection coefficients at those frequencies are not directly proportional. Smaller reflection coefficients at certain frequencies indicate that more signal power is injected into the in-home wiring via an outlet. However, the distributions of near fields are dependent not only the injected power but also on details of the wiring configurations and loading patterns.

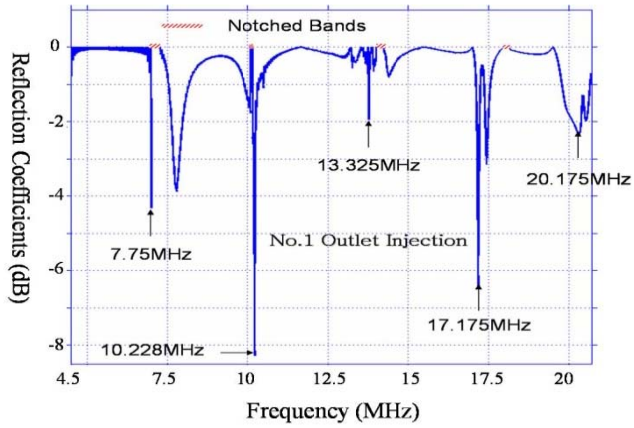


Fig. 13: Reflection Coefficient (dB) versus frequency for the No.1 outlet injection. Four Amateur Bands are excluded, 1): 7 - 7.3 MHz, 2): 10.1 - 10.15 MHz 3): 14.0 - 14.25 MHz and 4): 18.068 - 18.168 MHz.

Cumulative interference from multiple HomePlug devices, has been investigated by considering three devices operating simultaneously at the same frequencies. The maximum E_z-fields along the back side are presented in Fig. 14. RF signals, propagating in the complex wiring structures, experience multiple reflections and scattering due to impedance discontinuities, resulting in changes to the signal polarizations and varying time delays from the devices to the observation points, thus affecting the amplitudes and phases of the field components. This reverberant phenomenon has been discussed by Perini [11]. Constructive and destructive interference occur among the multiple versions of these signals. Thus the cumulative emissions exhibit a different behaviour from that of a single device, Fig. 12. In particular, the strongest values and their frequencies are quite different from those for single injection. Fig.14 also shows that the 10.1-10.15 MHz notch wholly fails to protect this amateur radio band, even with a -35 dB notch depth.

C. A Community of Four Houses

The cumulative effect from four houses has also been examined in this study. In Fig.15, these houses are configured in two rows, separated by 8.5 metre backyards. Two houses in each row are aligned along their front sides, with a 7 metre separation. For simplicity, in each house, three users have access to their in-home networks simultaneously via the No.1, 3 and 5 outlets of Fig. 4. Two situations are considered. In the first, all four houses contain these PLC users. In the second, only one house out of the four has PLC users, with the interference to its non-user neighbours examined.

Thus cumulative radiation from the four-house community has been calculated for a total of 12 devices transmitting data simultaneously. Fig. 16 shows the maximum E_z-field along the back side at heights of 1 and 3 metres above the floor.

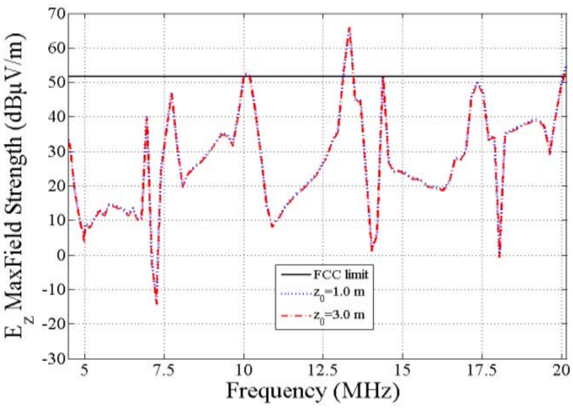


Fig. 14: Maximum E_z -field strength (dBμV/m) for three outlet simultaneous injection and frequency range 4.49 - 20.9 MHz, calculated 10 metres away from the back side of the house and at heights of z_o= 1 and 3 metres, and compared with the FCC limit.

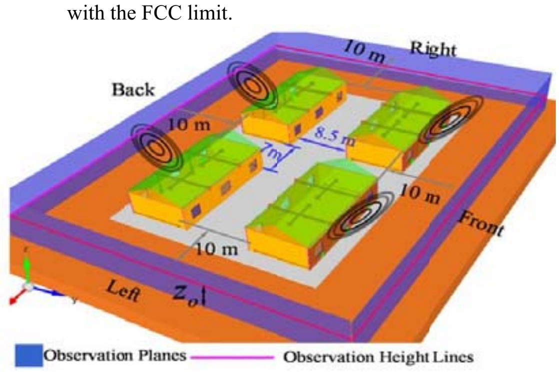


Fig. 15: Numerical simulation setup, showing a neighbourhood of four houses fully equipped with in-home PLC networks. Four observation planes are placed 10 metres from each side of the neighbourhood with measurement lines on each plane.

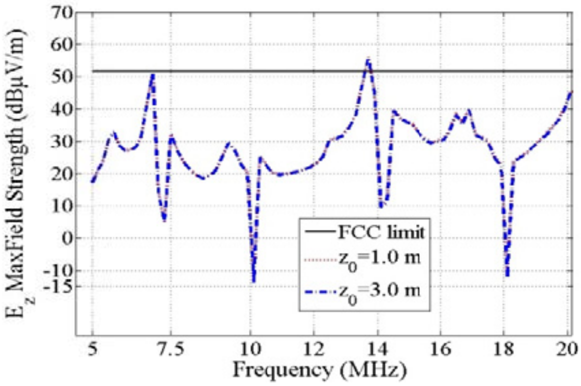


Fig. 16: Maximum E_z -field strength (dBμV/m) for the three outlet simultaneous injections and frequency range 4.49 - 20.9 MHz, calculated 10 metres away from the back side of the house and at heights of z_o= 1 and 3 metres, and compared with the FCC limit.

As shown in Fig. 16, the highest strengths appear at around 13.7 MHz, exceeding the FCC limit by 5 dB. Comparison of cumulative fields from the community can be made with the single house fields shown in Fig. 14. No increase in emission is seen from the four house community. This suggests that emissions are generally localized to those houses where they are installed and to some extent within an area of about 10 x 10 metre^2. This gives HomePlug devices a much more localized interference potential than access PLC, placed on the long medium-voltage lines [7].

In dense urban residential areas, or in rooms of an apartment building, or in one unit of a row of town houses or condominiums, separations between PLC users and non PLC users are less than 10 metres. In such circumstances, interference to neighbours (non PLC users) is unavoidable even with a moderate transmitting level [12, 13]. To examine this potential for interference, the same neighbourhood of four single houses has been considered, with only the far left house operating as a PLC user. The separation from this user's house to its nearby back yard neighbour is 8.5 metres, and to its right neighbour 7 metres, as shown in Fig. 17.

Electric field distributions at back-yard neighbours have been calculated, with an example shown in Fig. 18. Very strong RF fields are induced in the vicinity of its direct backyard neighbouring house. The highest induced field levels could exceed the FCC limit by up to 30 dB. Thus the potential for interference in adjacent houses appears very large. Unfortunately at this time, no HomePlug manufacturer has any solutions should such interference be reported [12, 13].

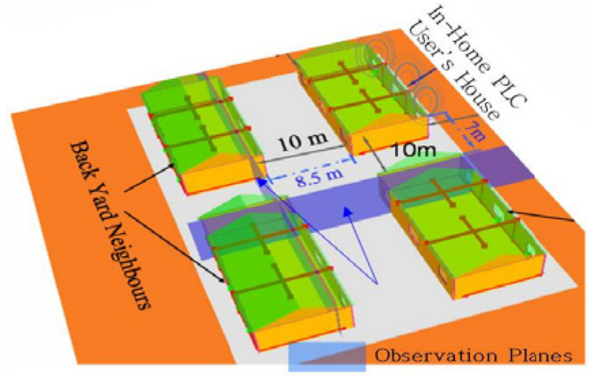
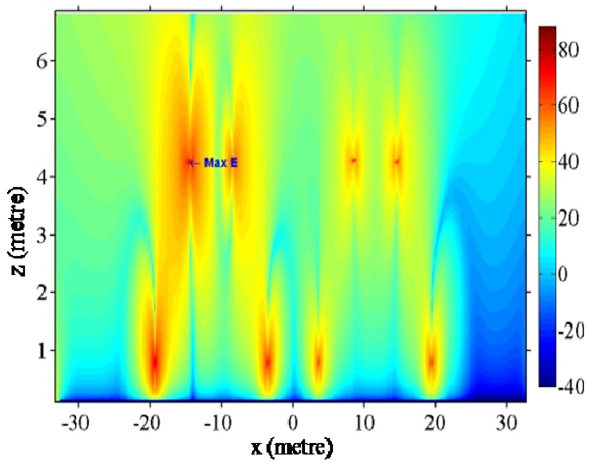
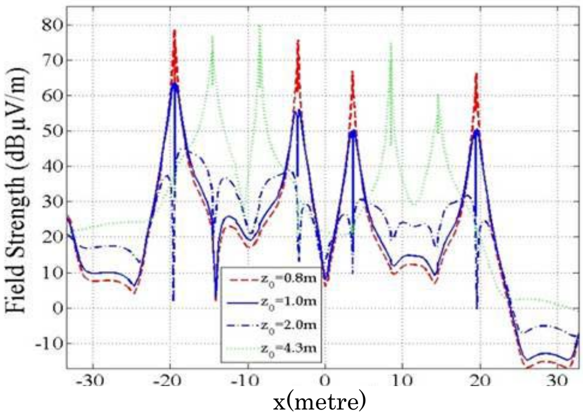


Fig. 17: A neighbourhood of four houses, with only the far left house as an in-home PLC system user. Two observation planes were placed 10 metres away from the user's house, within neighbouring houses.



(a): Electric field E_x strength map



(b): Electric field E_x strength versus distance

Fig. 18: Vertical electric field E_x strengths (dBµV/m) at 5.525 MHz calculated in the backyard neighbour house at a horizontal distance of 10 metres from the PLC user's house. (a): Electric field E_x strength map. (b): Electric field E_x strength versus the distance along the line 10 metres away from the user's house. These are displayed as sharp peaks. Widths of some peaks with a level higher than the FCC limit extend as far as 3 metres.

V. Summary and Conclusions

This study has examined in-home PLC systems within a representative wiring configuration of a bungalow. A total of five duplex receptacles, two types of loads and four light bulbs terminate this wiring. One of the HomePlug products 30 dB pre-notched to amateur radio bands, was used in the calculations. Extensive numerical simulations, using FDTD software, give the interference characteristics of in-home PLC systems with broadband signals injected into three outlets. Key conclusions of the analysis are

- House wiring, as seen at each injection point and at certain frequencies, can act as a resonant antenna. Characteristics have been examined in the context of "wire antennas". Excluding those resonant bands deeply notched for the amateur bands, the probability of the in-home wiring acting as an efficient radiator has been shown to be very small. However, the radiation characteristic is highly dependent on the wiring configurations and the location of the RF device. For a region or city with full-scale deployment of in-home PLC service, it is expected that numerous branches, wiring configurations, and appliances and loads will be joined and compounded almost at random. Cumulatively, it is highly possible for those resonant frequencies to appear at any location of the PLC device spectral range. Such in-home wiring would then become very efficient, and the total radiated power available would be sufficient to increase the radio noise floor.

- The emissions from in-home PLC systems in the near-field are generally localized in nature. However, this does not mean that interference to neighbours in dense urban residential areas is avoidable even at a transmitting level in compliance with FCC rules.

- Signal power and impedance discontinuities in the in-home network are two basic parameters governing PLC emission. The nature of impedance discontinuities is very complex and essentially unpredictable. Possible techniques to reduce the emission such as a "programmable notching" have been suggested, whereby the PLC system might itself determine automatically which parts of the spectrum are occupied by radio signals and how deep the notches should be, and not be fixed. This determination could be partially based on the reflection coefficients at the signal injection ports. With this technique, utilities/providers can instruct their systems to radiate less in certain parts of the RF band, or avoid them.

References

[1] HomePlug standard available from the website http://www.homeplug.com.

[2] FCC, Report and Order, "In the Matter of Amendment of Part 15 Regarding New Requirements and Measurement Guidelines for Access Broadband over Power Line Systems" Adopted October 14, 2004, Released October 28, 2004.

[3] Industry Canada, "Consultation Paper on Broadband over Power Line (BPL) Communication Systems", July, 2005.

[4] G.Vos and J. Verpoorte, "Electromagnetic modeling of power line communication", National Aerospace Laboratory (NLR) Report NLR-CR-2003-125, Feb. 2003.

[5] A. Vukicevik, M. Rubinstein, F. Rachidi, J. L. Bermudez, M. Schneider and P. Favre, "Review of the Electromagnetic Compatibility PLC Work at the Swiss Federal Institute of Technogy and the University of Western Switzerland", 10th IEEE International Symposium on Power Line Communications and its Applications, Orlando, FL., USA, March 26-29, 2006, pp. 304-308.

[6] M. Ishihara, D. Umehara and Y. Morihiro, "The Connection between Radiated Emissions and Power Line Network Components on Indoor Power Line Communications,", ibid., pp. 309-312.

[7] M. Zhang and W. Lauber, "Evaluation of Interference Potential of PLC System", 10th IEEE International Symposium on Power Line Communications and its Applications, ibid., pp. 291-296.

[8] M. Zhang and W. Lauber, "Evaluation of Interference Potential of In-Home PLC System", CRC Technical Report Phase II, VPTWS-TM-07-08-01, Ottawa, Canada, May, 2007.

[9] M. Zhang and W. Lauber, "Evaluation of Interference Potential of In-Home Power Line Communication System", 12th IEEE International Symposium on Power Line Communications and its Applications, Jeju Island, Korea, April 2-4, 2008, pp. 263-268.

[10] User's Manual for EMPIRE, version 4.13, Oct 2005, at: http://www.empire.de/.

[11] J. Perini and P. Perini, “Properties of Fields in Reverberant Environments and its Implication”, 2007 IEEE International Symposium on EMC, Honolulu, Hawaii, July 8-13, 2007, Paper Session: TH-AM-5.
[12] J.H. Stott, “Potential Threats to Radio Services from PLT System,” EBU Technical Review, July, 2006.
[13] ARRL, “Broadband over Power Line (BPL) and Amateur Radio”, available from website: http://www.arrl.org/tis/info/HTML/plc/.

Ming Zhang was born in Beijing, China. He received the B.Sc and M.Sc degrees in physics from Yunnan University, China, in 1982 and 1987, respectively, and the M.Sc and Ph.D degrees both in electrical engineering from University of Manitoba, Canada, in 1995 and 2002.

From 1987 to 1992, he was a lecturer and Researcher at the Department of Physics, Yunnan University. In 1999, he was with Integrated Engineering Software Inc., Winnipeg, Canada, as a research and development engineer, working on the development related to numerical solution of three-dimensional time-harmonic eddy-current problem. In 2000 and 2001, he was with Nortel Networks, Ottawa, Canada as a research and development /testing engineer. He is currently with Electromagnetic Compatibility Research Group at theCommunication Research Centre, Ottawa, Canada, as a research scientist.

Dr. Zhang is a member of the IEEE, and an editor of Progress In Electromagnetics Research (PIER).

Wilfred R. Lauber (S'66-M'70) was born in Windsor Ontario. He graduated from the University of Waterloo, Waterloo Ontario Canada, in 1968 with a BaSc in electrical engineering, and in 1970 with a MaSc in electrical engineering majoring in Statistical Communication.

In 1970 he joined the Communications Research Centre (CRC) in Ottawa as a research engineer in the Radio Research Laboratory. He has published several papers on measurements and modeling of the electromagnetic environment from HF to UHF and contributed to CCIR (now ITU-R) reports for both atmospheric and man-made noise. He is presently the research program manager of the Electromagnetics and Compatibility Research Group of the Terrestrial Wireless Research Branch at CRC.

Mr. Lauber is an active member of the IEEE EMC Society. He is an associate editor of the IEEE EMC Transactions on Undesired Sources (noise). He has received several awards from the EMC Society, Certificates of Acknowledgement in 1986, 1997 and Certificates of Appreciation in 1989, 1993, and 1995.