Interference Characteristics of Broadband Power Line Communication Systems Using Aerial Medium Voltage Wires

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ABSTRACT

The promise of broadband power line (BPL) communications — broadband access to virtually every home in the United States — will remain unfulfilled if the radio emissions from these systems cause significant harmful interference to other users of the wireless spectrum. This article presents an elementary analysis of the physical mechanisms underlying these emissions, from which the interference characteristics of BPL systems can be derived. Numerical models are evaluated for idealized systems using overhead medium-voltage wires, a configuration that is of particular interest for U.S. deployments. The central conclusions of the analysis are:

- BPL interference is governed primarily by two parameters: signal power and electrical balance of system excitation.
- Interfering emissions are typically confined to the immediate vicinity of the BPL wire, but long-range effects cannot be neglected.
- Measurements on an installed BPL system suggest that it is operating within, but very close to, the limits set by rules recently adopted by the Federal Communications Commission.

INTRODUCTION

Broadband power line (BPL) communications has the potential to bring low-cost broadband access to virtually every home in the United States. Before this can become a reality, however, issues of compatibility with other users of the radio spectrum need to be resolved [1]. BPL systems typically operate in the so-called high-frequency (HF) band, a spectral region prized for long-distance communications. The possibility of large-scale deployment of potential interferers in this band has generated intense debate focused on the competition between the expected public benefit of BPL vs. possible harm to existing users. After extensive review of the issues, the U.S. Federal Communications Commission has issued a Report and Order permitting BPL to be operated on an unlicensed basis, subject to certain technical and administrative restrictions intended to protect licensed radio services [2]. The controversy has not subsided, however, because opinion remains divided as to whether or not the FCC restrictions provide adequate protection for these incumbent users.

This article, a tutorial introduction to the fundamental physical mechanisms in BPL systems responsible for generating radio interference, is intended to provide a foundation for informed discussion of interference issues. Focus will be primarily on configurations appropriate to deployments in the United States.

BROADBAND ACCESS OVER BPL[1]

The general notion of using electric power lines as a transmission medium for communications has been around for almost a century [3], but until the past decade or so only relatively narrow bandwidths (< 100 kHz) have been thought to be feasible. Advances in signal processing techniques, however, now enable tens, or perhaps even hundreds, of megabits per second to be carried over extremely hostile channels, such as residential power wiring. These same advances also make "last mile" (or "last kilometer") BPL delivery a realistic possibility. Approaches to BPL naturally depend on the architecture of the power distribution network. In Europe, for example, several dozen residences might be served from a single low-voltage (LV) cable operating at 230–400 V [4]. Key challenges at the physical layer include dealing with the high losses of the cable (several tens of decibels in a few hundred meters) and multiple, possibly time-varying, reflections associated with taps to individual residences [5]. Radiated interference, although significant, is a relatively minor issue because the conductors in the cable are closely spaced, so their radiation fields decay rapidly with distance from the cable. Extensive studies of cable properties and techniques for dealing with its limitations are available throughout the literature [6].

[1] *Although the term* BPL *generally includes systems deployed both outside and inside users' premises, in this article it will refer exclusively to outside systems. The term* access BPL, *used by the FCC to distinguish these systems from on-premises power line networking technologies, will not be used.*

The situation in the United States is markedly different. The bulk of neighborhood power distribution is over medium voltage (MV) lines, which operate in the 10–40 kV range. These, in turn, feed LV transformers, each of which serves only a few homes (e.g., a half dozen). Although newer MV deployments tend to be served by buried MV wires, most existing MV plant in the US is aerial, supported near the top of utility poles. In contrast to the typical European (LV) situation mentioned above, aerial MV plant in the US is an efficient transmission medium, with loss of just a few decibels per kilometer (discussed later). Radiation, on the other hand, is a much larger concern. Long elevated MV wires have far greater potential to cause interference than buried LV cable. This issue, which is of fundamental importance to BPL deployment in the United States, has been clearly articulated [7], but elementary analyses of the physical mechanisms governing such interference remain unavailable (at least in the open literature). The remainder of this article is intended to address that deficiency.

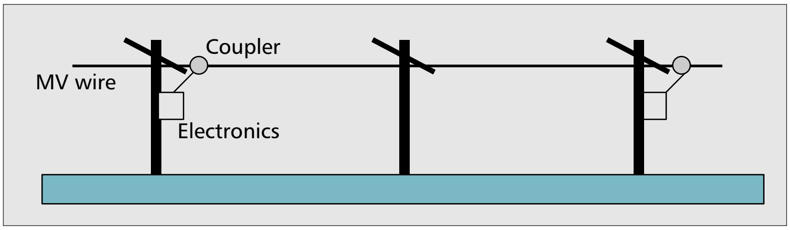

Figure 1. *BPL system using aerial MV wires.*

BPL System Model

Baseline System

The MV BPL system we study here is shown schematically in Fig. 1. A copper or aluminum MV wire is supported on the uppermost crosstrees or insulators of utility poles spaced roughly 50 m apart. BPL signals, typically in the frequency range 2–30 MHz, but occasionally up to 50 MHz, are injected into the wire (or tapped from it) by couplers located at intervals of approximately 100 m. BPL signals, once launched onto the MV wire, are typically not repeated at each coupler (as they are, e.g., in T1 carrier systems). Rather, they may pass through several couplers before regeneration. Thus, each coupler should be viewed as relatively transparent; most of the available signal power passes straight through, with only a modest fraction tapped off to the associated receiver. (This small *transmission loss* should not be confused with the much larger *coupling loss* or *tap loss*, which describes the loss associated with coupling a signal onto or off of the MV wire.)

The considerations outlined above lead to the simple BPL radiation model shown in Fig. 2. The MV wire is assumed to be long compared to the intercoupler spacing. For the source we choose an inductive coupler, which consists of a ferrite ring around the MV wire, energized by a winding on the ring driven by a signal source [8]. The electromagnetic force (EMF) generated by such a coupler is represented in our model by a simple voltage generator. Other couplers in the system, shown by dotted loops, are assumed to have no effect on the injected signal as it propagates. Despite its simplicity, this model exposes all the basic mechanisms associated with signal propagation and radiation in the BPL system. Additional considerations, such as reflection or attenuation by couplers and other MV line discontinuities, can have important consequences in practical deployments, but for an initial understanding of BPL interference the idealized model of Fig. 2 is all we need.

The source in Fig. 2 generates current waves that propagate to the left and right along the wire. The resulting electromagnetic fields fall into the following three categories [9].

Guided mode: Responsible for transporting signal energy along the MV wire. In the approximation of a perfectly conducting ground plane, the guided wave is just the TEM mode associated with the parallel wire transmission line made up of the MV wire and its image under the ground plane. (Effects of ground dissipation will be discussed later.) The key feature to note about this mode is that the associated interference decays rapidly in directions perpendicular to the wire (~inverse-square with distance), but slowly along its length.

Radiation mode: Carries power into space. This mode, which is also called the *far-field mode*, serves no purpose in a BPL system, but is the source of long-range interference effects because the fields decay relatively slowly (~1/distance). The characteristics of this radiation have been studied in the context of the Beverage antenna, whose radiation pattern is a narrow "pencil" beam directed away from the generator and nearly coaxial with the MV wire. [10] The radiative contributions of cur-

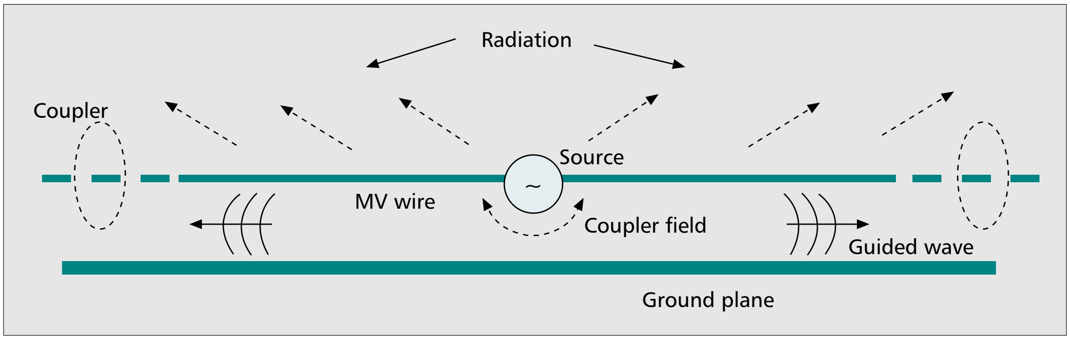

Figure 2. *Electromagnetic model of a BPL system.*

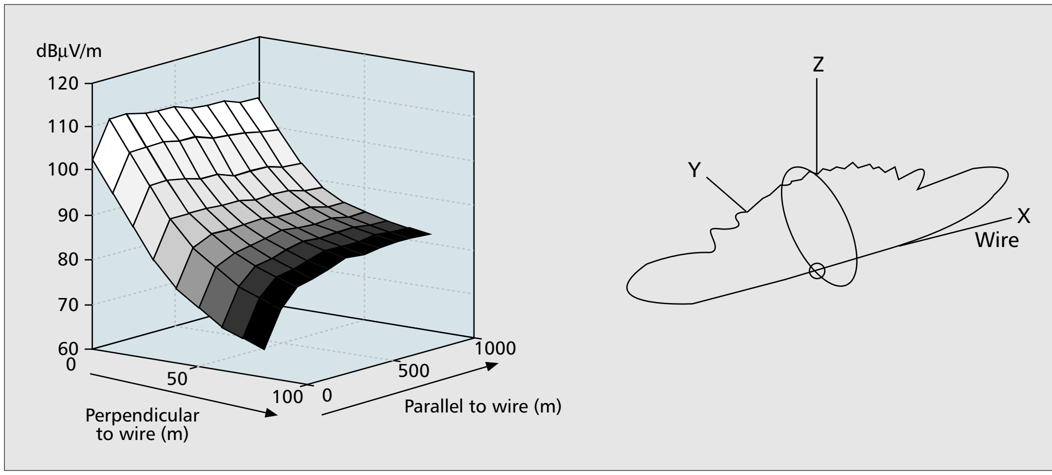

Figure 3. *2 MHz electric near-fields 2 m above street level (left) and far-field pattern (right). Indicated distances are measured at ground level from a point directly beneath the coupler. The maximum far-field gain perpendicular to the wire is 12 dB below the forward peak.*

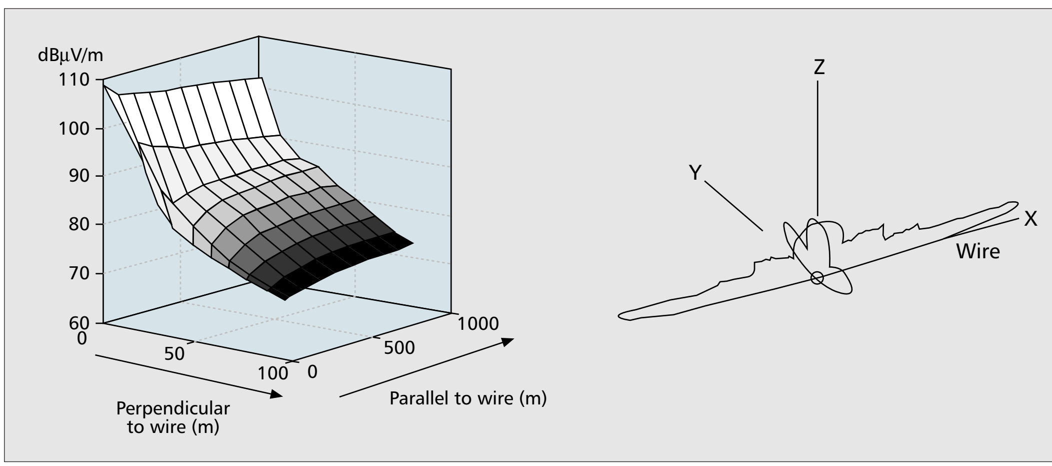

Figure 4. *20 MHz electric near-fields (left) and far-field pattern (right). The maximum far-field gain perpendicular to the wire is 22 dB below the forward peak.*

rents in the wire add coherently in this direction, whereas they tend to cancel at angles farther off axis.[2]

Coupler fields: Associated with the discontinuity caused by the source. These fields, which are associated with the coupler itself (rather than the MV wire), are localized near the coupler (~inverse-cube distance dependence) and are not major contributors to BPL interference. They are discussed briefly in the Appendix.

This qualitative discussion, while helpful in developing an intuitive picture of BPL interference, is too idealized to enable quantitative analysis. Additional effects, especially ground dissipation and higher-order transmission line modes, which cannot be handled in simple closed form, need to be included (see, e.g., [11, 12]).[3] Numerical integration of the Maxwell equations with appropriate boundary conditions (lossy wires and ground) is conveniently handled with EZNEC/4 v3.0, a widely used program based on the Numerical Electromagnetics Code-Method of Moments (NEC-4) calculating engine developed at Lawrence Livermore Laboratory [13]. The structure shown in Fig. 2 was modeled using 1 cm diameter copper wires (~6×10^7 mho/m) supported 10 m above ground level and extending 1 km to the left and right of the generator. Reflections from the ends were minimized with 200 m tapers that terminated in lossy transmission lines 3 cm above ground level. Ground was assumed to have "average" characteristics: dielectric constant of 13 and conductivity of 0.005 mho/m.[4]

The guided and radiated fields were calculated for 1 W signal power at 2 and 20 MHz to expose frequency-dependent behavior. The results, shown in Figs. 3 and 4, confirm the qualitative discussion presented earlier. The rapid decay of the guided mode in directions perpendicular to the MV wire is clearly visible, as is the narrow forward beam of the radiation mode, which sharpens with increasing frequency, going from 0.6 dB above isotropic (dBi) at 2 MHz to 16 dBi at 20 MHz. The slow decay of the guided mode (~4 dB/km) as one moves parallel to the MV wire is due primarily to ground dissipation. (Copper losses at 20 MHz are only a few tenths of a decibel per km.) Apart from the forward gain of the MV "antenna," behavior from 2 to 20 MHz is only weakly frequency-dependent. Finally, note that near-

[2] *In practical BPL systems, discontinuities in the MV lines, such as mismatched terminations, cause reflections, which can disrupt this cancellation and lead to additional far-field radiation [1].*

[3] *I thank my colleague Mohsen Kavehrad for directing me to this body of work.*

[4] *Unlike the detailed BPL calculations developed by ARRL and the National Telecommunications Information Agency (NTIA), the present discussion focuses on a simplified, idealized model in order to give insight about the fundamental processes at work, with a minimum of system-specific detail [1, 14].*

field effects persist along the length of the wire, not just in the immediate vicinity of the coupler.

It should be borne in mind that far-field effects can be especially troublesome, because HF emissions, unlike microwaves, can travel thousands of kilometers via ionospheric "bounce." Also, note that even though far-field radiation is contained primarily in the forward beam, long-range effects in directions perpendicular to the wire can also be significant.

Balanced Configurations

By adding a modest amount of complexity to a BPL system, it is possible to greatly suppress both the near and far fields. The idea is to use two MV wires instead of one and drive them differentially, as shown in Fig. 5. The opposed currents, traveling side by side down the wire, will generate fields that tend to cancel one another; the closer the wires, the better the cancellation [3]. The near fields at 20 MHz, using wires separated horizontally by 1 m, are shown as the horizontal balance data in Fig. 6 for locations 200 m downstream from the coupler, along with the fields for the single-wire system discussed earlier. The suppression effect of balanced operation is clear. It also should be noted that the far-field gain at 20 MHz for the balanced system is –14 dBi; a reduction of about 30 dB from that of the unbalanced line. (Negative gain means that most of the available RF power is carried by the guided transmission line mode; only a small fraction is radiated into space.)

Instead of driving a second MV wire, as discussed above, it is also possible to implement "vertical" differential excitation by driving an MV wire plus the neutral wire that typically runs below it at the lower boundary of the "power space" on utility poles. The near fields at 20 MHz associated with this configuration, with the neutral wire 3 m below the MV line (7 m above street level) are shown as vertical balance in Fig. 6. Field suppression compared to the unbalanced case is apparent, especially at larger distances, but is not as good as with the horizontally balanced configuration discussed above, probably because of greater wire separation and imperfect balance with respect to earth ground. The far-field pattern at 20 MHz is similar to that shown in Fig. 4, with a peak gain of 1.5 dBi.

It should be noted that the effectiveness of the vertically balanced approach may be seriously compromised by the grounding wires that are typically connected to the neutral wire at every other utility pole and run vertically into the earth. These grounds unbalance the system and degrade the cancellation associated with differential drive.

Comparison with Experiment

Near-field characteristics of a vertically balanced BPL system were measured by an AT&T Labs team in February 2004. The fields measured approximately 2 m above street level for a resolution bandwidth of 10 kHz are shown in Table 1. Definitive comparisons with predictions based on the numerical model of the previous sections are difficult because the power level used on the MV wires is vendor-proprietary information.[5] We can make a *plausible assumption*, however, that the BPL transmitter can generate +20 dBm (comparable to WiFi and cellular power levels) and that the coupling loss to the MV wire is about 10 dB. (Stronger coupling would mean significant attenuation of MV signals passing through the coupler, which in turn would make it difficult for a transmitter to reach beyond the immediately adjacent coupler.) Thus, in a system bandwidth of ~20 MHz the signal spectral density is ~ –63 dBm/Hz on the MV wire. The fields predicted for this power density are shown in Table 1. The close agreement with measurement is satisfying, but almost certainly fortuitous, given the large uncertainties in developing the comparison. Nonetheless, the results are encouraging evidence that our numerical model probably captures the fundamental interference mechanisms of BPL systems, at least in the vicinity of the power line near street level.

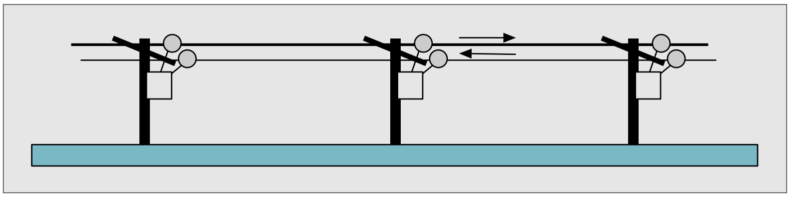

Figure 5. *A (horizontally) balanced system using differential drive.*

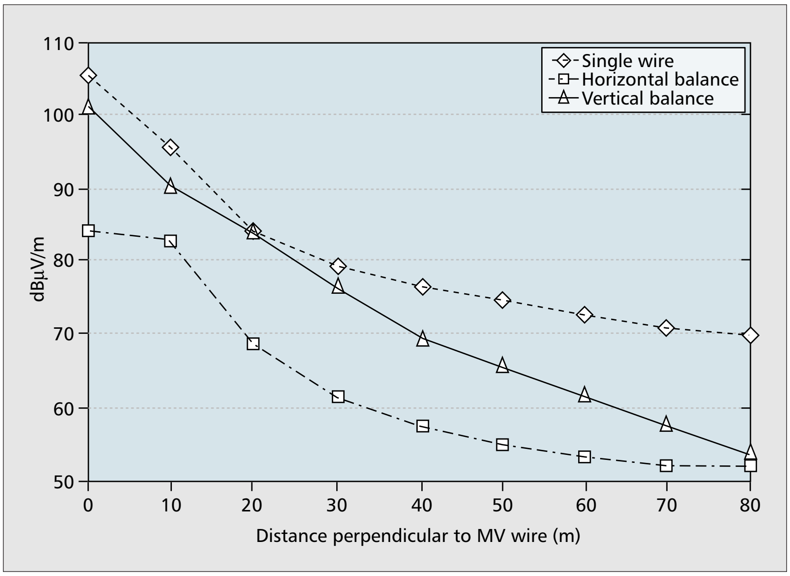

Figure 6. *Near fields at 20 MHz (2 m above street level) for 1 W signal power.*

Measurement location	Under wire
Frequency (MHz) (10 kHz resolution BW)	12.5
Measured field (dBµV/m)	~55
Modeled field (dBµV/m)	~50

Table 1. *Measured and modeled field strengths for a vertically balanced system.*

[5] *Despite repeated requests to the vendor, this author was unable to obtain such information.*

Although the most intense interference from a BPL system is confined to the immediate vicinity of the MV wire, serious long-range effects can also occur. The problem is especially acute for aeronautical services, where an aircraft flying above a BPL network can be simultaneously exposed to radiation from hundreds of transmitters.

FCC Regulations and System Implications

Field Strength Limits

The models developed above enable estimates of the radiation generated by BPL systems. The central question to be addressed now is: What are the implications of this radiation in terms of interference with other users of radio spectrum?

Since BPL is operated as an unlicensed service, it is governed by the so-called Part 15 rules. [15] Until recently, these rules were inadequate for BPL systems, because they did not give an unambiguous procedure for measuring their radiation and hence verifying compliance with the rules. The amended Part 15 rules, however, announced in the FCC Report and Order cited earlier, are expected to remedy this problem. They prescribe, among other requirements, measurements near street level at a horizontal separation of 10 m from the MV line. For systems operating between 1.7 and 30 MHz, the field-strength in a 9 kHz bandwidth must not exceed

$$E = 30 \times (30/d)^2 \ \mu\text{V/m}, \quad (1)$$

where d is the slant distance in meters between the measuring antenna and the nearest point of the BPL system (Part 15, S. 15.31 and 15.209) The Part 15 rules require measurements only in the vicinity of the MV wire (essentially near-field measurements). We see below that far-field effects, although not regulated explicitly by the rules, can also be significant.

Let us apply Eq. 1 to a vertically balanced system, such as the one discussed earlier. The Part 15 limit at the 10 m location (slant distance 14 m) is 43 dB μV/m (in a 9 kHz bandwidth). Scaling the field at 10 m shown in Fig. 6 to assure operation below the 43 dBuV/m limit, we find a maximum allowed signal power of –48 dBW. This in turn corresponds to a spectral density limit of –58 dBm/Hz, a level moderately higher than the (assumed) –63 dBm/Hz signal level used in the system. It should not be surprising that system designers use nearly the maximum signal power that still allows them to satisfy the field limit prescribed by the Part 15 rules.

Harmful Interference

Satisfying the limits of Eq. 1 is only part of the obligation for operation under Part 15. Harmful interference, even if caused by systems operating within those limits, could force shutdown of BPL equipment. Quantifying the likelihood of such harmful interference is extremely difficult, because a negligible level of interference for a shortwave listener tuned into a powerful broadcast (>500 μV/m) might be totally unacceptable to a radio amateur listening to a weak transmitter halfway around the world. It should be borne in mind, for example, that radio amateurs routinely work with signals weaker than 30 μV/m.

To gain insight into this problem without getting tangled in myriad details, let us compare the interference from BPL to the radio noise background (mostly manmade) that already exists around us. If the BPL interference is less than that background, we can reasonably assert that BPL is essentially invisible. (This may be an overly stringent demand on the BPL system, but at least it gives us a starting point for discussion.) Alas, even with this simple criterion, we are confronted with ambiguity, because different measurements of background noise yield widely differing results. A common model for HF radio noise in business areas gives typical field strengths of about 20 dBμV/m in 9 kHz bandwidth. [16] Unpublished measurements in an urban area by ATT Labs, on the other hand, suggest a far noisier environment, in the vicinity of 35 dBμV/m in the same bandwidth [17]. Rather than debate which, if either, is correct, we use both 20 and 35 dBμV/m to get some rough bounds on the problem. At these background levels, the field strengths shown in Fig. 6 for a vertically balanced system operating at –58 dBm/Hz (the Part 15 limit discussed earlier) yield an interference range of between 20–40 m. Outside this range the interference from the BPL system falls beneath the existing background.

Although the most intense interference from a BPL system is confined to the immediate vicinity of the MV wire, serious long-range effects can also occur. The problem is especially acute for aeronautical services, where an aircraft flying above a BPL network can be simultaneously exposed to radiation from hundreds of transmitters. [1] It is likely that the main far-field lobes from a few of these devices will be aimed directly at the aircraft. In addition, contributions from the remaining transmitters can also be significant because of small but non-negligible off-axis radiation, a problem made worse by inevitable discontinuities in the MV wires, as mentioned earlier. To protect services deemed especially vulnerable to BPL interference, the FCC Report and Order excludes BPL operation from specified frequencies and in some cases from specified geographic locations.

BPL Susceptibility to Incoming Interference

The preceding discussion has focused on interference that might be caused by a BPL system, which is naturally the main concern of the FCC. However, the system models analyzed above can also be used to study another important problem, susceptibility of the BPL system to an outside source of interference, such as a nearby shortwave transmitter. Calculating the effect of an interferer is simplified if we place a resistor equal to the MV antenna impedance (typically 600 Ω with very small imaginary part) in series with the generator in Fig. 2. It will act as an (approximately) matched load for the MV antenna without changing its gain. If we assume the interferer also has a matched antenna, by reciprocity the end-to-end loss is the same in either direction, so the interference power received by the BPL system is

$$P_b = P_i G_b G_i (\lambda/4\pi r)^2, \quad (2)$$

where P_i is the interfering transmitter power, G_b is the effective gain of the BPL antenna (the MV wire), G_i is the gain of the interferer's antenna, λ is the wavelength, and r is the distance between the interferer and the BPL system. Assuming $G_i = G_b = 1.5$ dBi, a 20 MHz 1 kW transmitter in the main beam of the MV antenna at a range of 1 km will deliver approximately 5 dBm to the BPL system. At shorter ranges the received power level will show approximately an inverse-square increase. The problem of incoming interference becomes especially serious if the interfering signal is strong enough to cause nonlinear saturation effects in the BPL system.

At shorter ranges the received power level will show approximately an inverse-square increase. The problem of incoming interference becomes especially serious if the interfering signal is strong enough to cause non-linear saturation effects in the BPL system.

UNFINISHED BUSINESS

The preceding tutorial discussion presents the fundamental ideas governing interference in BPL systems, and provides quantitative estimates of these effects for idealized configurations. A thorough evaluation of the effects of interference, however, requires a deeper look at several issues. A few of the most important are outlined below.

MV line discontinuities: This topic, which has been mentioned several times already, requires further study. Discontinuities such as MV branches, transformer taps, insulator jumpers, and unmatched BPL repeater terminations perturb the guided mode and therefore generate unwanted radiation. In addition, they cause standing waves along the MV line, which can lead to antenna lobes with complex spatial and frequency behavior. The unpredictable quasi-random nature of the discontinuities in a typical MV deployment makes the problem especially challenging.

Collective effects: This article has focused on the interference associated with a single BPL transmitter, with discussion of collective effects confined to a brief mention earlier. The integrated effect when many such transmitters are used to serve a given geographical area will be the subject of Phase 2 of the NTIA study of BPL.

Ionospheric reflections: The collective effects mentioned above are exacerbated by the high effective reflectivity of the ionosphere at frequencies below about 30 MHz. Far-field BPL radiation, although initially directed at an upward angle, might not simply continue into space. Rather, it could bounce off the ionosphere and return to earth at distances ranging from a few to thousands of kilometers from the source. (This is often referred to as skywave propagation.) Such long-range effects may require international regulatory cooperation. This topic will be dealt with in Phase 2 of the NTIA study of BPL.

Optimal design: Ideally, a BPL system should accomplish its communication objective while contributing minimum interference to its surroundings. Optimizing such a system would involve simultaneous consideration of many factors, including radiated interference, characteristics of background noise, how it is coupled into the BPL system, and the ability of coding and MAC strategies to deal with it. The goal of such an optimization would be to define the fundamental limits of BPL communication within two constraints: the existing radio noise background and the radiated interference limits imposed by governmental regulations.

ACKNOWLEDGMENTS

I am deeply grateful for the assistance of the AT&T Labs Electromagnetic Compatibility Group (especially Bob Bennett, Hank Bergmann, Bob Roman, Larrie Sutliffe, and Tom Willis), and helpful discussions with my colleagues throughout AT&T Labs, especially B-J. Kim and N. K. Shankaranarayanan.

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BIOGRAPHY

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APPENDIX: FIELDS ASSOCIATED WITH AN INDUCTIVE COUPLER [18]

The following approximate analysis shows that the interference generated by an inductive coupler *by itself* is negligible compared to the interference generated by the currents induced on an MV wire passing through the coupler.

The goal of such an optimization would be to define the fundamental limits of BPL communication within two constraints: The existing radio noise background and the radiated interference limits imposed by governmental regulations.

An inductive coupler can be thought of as a simple toroidal transformer, with the primary winding energized at frequency f by the BPL transmitter and the secondary being the MV wire — in effect, a single-turn secondary winding. We treat the toroid as a loop carrying a time-varying magnetic field dB/dt. Starting from the well-known analysis of a current-carrying loop, and using the symmetry of the Maxwell curl equations, we conclude that the toroidal transformer exhibits an electric dipole moment (in Gaussian units) of

$$p = (a^2/4c)dF/dt) \qquad (2)$$

where a is the radius of the toroid, c is the speed of light and F is the total magnetic flux within the toroid.

The electric fields generated by this magnetic flux have three major consequences:

- Induced EMF on the MV wire
- Local (dipole) fields in the vicinity of the coupler
- Far-field dipole radiation

The first of these is the voltage source shown in Fig. 2. The induced emf is given by Faraday's Law:

$$V = (1/c)dF/dt. \qquad (3)$$

Item 2 above is the dipole field generated by the coupler; its magnitude at street level is

$$E_{dip} \approx (p/h)((2\pi f/c)^2 + (j2\pi f/ch) - 1/h^2), \qquad (4)$$

where h is the height of the coupler above the street. Note that the dipole field is an increasing function of frequency.

The third item, far-field dipole radiation, is characterized by a total radiated power of

$$P_{dip} = (c/3)(2\pi f/c)^4 p^2. \qquad (5)$$

We wish to compare Eqs. 4 and 5 with the fields associated with the guided and radiation modes discussed earlier. For the near field, the guided mode shown in Fig. 2 is approximately the TEM field associated with a two-wire transmission line having wires spaced a distance $2h$ apart. The electric field at street level is given approximately by

$$E_{guide} \approx V/h \cdot \ln(4h/d), \qquad (6)$$

where d is the wire diameter.

For f *= 20 MHz,* h *= 10 m,* a *= 10 cm, and* d *= 1 cm, the dipole field (Eq. 4) is approximately 50 dB weaker than the guided-wave field (Eq. 6).*

In the far-field region, the Beverage antenna shown in Fig. 2 has a radiation efficiency of roughly 50 percent. (The non-radiated power is dissipated in the ground or delivered to a matched load at the end of the wire [10].) Thus, the power in the radiation field is

$$P_B \approx 50\% \cdot (1/2)V^2/Z, \qquad (7)$$

where Z, the impedance of the wire over the ground plane, is given by

$$Z = (2/c) \cdot \ln(4h/d). \qquad (8)$$

Combining Eqs. 6 and 7, we find

$$P_B \approx V^2c/8\ln(4h/d). \qquad (9)$$

The ratio of the radiated power of the dipole (Eq. 5) compared with that of the Beverage antenna (Eq. 9) is thus approximately $(1/6) \cdot (2\pi af/c)^4 \cdot \ln(4h/d)$. *For* a, f, h *and* d *as above, the dipole power is thus down by approximately 54 dB compared with the Beverage power*. (NB: This discussion has focused on total radiated power. There may, of course, be specific spatial directions where there are deep nulls in the Beverage far-field pattern, in which case the dipole radiation might be stronger than the Beverage contribution.)

The preceding discussion shows that the fields associated with the inductive coupler *per se* are orders of magnitude smaller than the fields associated with the MV wire, and may therefore be neglected in a discussion of first-order interference effects in BPL systems.