Technical Considerations for Broadband Powerline (BPL) Communication

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***Abstract* -- The use of the electric power transmission and distribution system as a transmission medium for broadband communications is considered. It is found that there are three significant technical hurdles to be overcome before successful implementation of such systems can be accomplished. The first is the relatively high attenuation rate due to discontinuities such as taps, transformers and other devices connected to the system. The second is the relatively high background noise on power lines. The third is government regulated limitation on transmitted power for the unlicensed systems that use the power system as a communications medium.**

I. INTRODUCTION

The possible use of the power transmission and distribution system as a waveguiding structure for high data rate or broadband communications (e.g., internet connection) will be examined in this paper. Generally, the higher the rate of information transfer (i.e., data rate measured in bits per second (B/sec)), the larger the signal bandwidth and the higher the range of frequencies used will be. Since internet connections may require bandwidths well in excess of 1 MHz, the use of frequencies up to 30 MHz will be considered.

The fundamental question to be asked is how the power system (designed to be operated at 50/60 Hertz) responds to signals in the 2 – 30 megahertz range. Clearly, the power system was not designed for this application.

The most significant advantage of broadband power line communication (BPL) systems over their wired competition (e. g., xDSL and cable modem) is that they do not require an entirely new infrastructure. The most serious technical challenges to BPL systems have been found to be first, attenuation due to junctions such as taps, connected elements such as transformers and the lack of matched transmitter/receiver impedances, second, relatively high (and very frequency dependent) background noise usually due to induced radio broadcast signals, and third, legal limits on electromagnetic emissions from these unlicensed systems. The first causes the attenuation rate for high frequency signals to be quite high and very frequency dependent and (together with background noise and input power limitations due to the latter two) results in possibly unacceptable limits on the range of the system. Reduction of the attenuation to more reasonable levels through system conditioning may require a financial investment that is incompatible with the requirement that the system be profitable.

II. SOURCES OF CHANNEL ATTENUATION

There are two major causes of high frequency attenuation in a power line communications channel. The first is attenuation due to ohmic absorption in the materials that make up the physical channel. This absorption varies with frequency and leads to attenuation rates of approximately 1 dB/km. The second (and by far most important) is attenuation due to reflections from abrupt discontinuities and mismatched impedances (e.g., underground to overhead risers, taps, transformers and capacitors) that occur along the power line. These reflections cause part of the signal to be diverted away from the receiver and absorbed in other parts of the system. This phenomenon can lead to attenuation rates of 40 dB/km or more.

A. Transformers

The effect of transformers on the propagation of high frequency signals is complex. The shunt capacitance of a transformer will present a short circuit to the high frequency signals. However, this capacitance is in parallel with inductances and thus may resonate and present high impedances at least for certain frequencies. One result of this is that the transmission of signals through a transformer is a very strong function of frequency. Measurements of the attenuation of high frequency signals across transformers range from 10 – 20 dB and are strongly dependent on frequency.

B. Junctions, Connected Devices and Mismatches

Consider the very simple 1 km long single phase power system with a wire radius and spacing of 1 cm and 1 m respectively as shown in Fig. 1. The characteristic impedance of this line is 636 Ω. In this system there is a shunt capacitance halfway along the line and neither the transmitter nor the receiver is "matched" to the transmission line's characteristic impedance. Note further that the impedance of a 100 pF capacitor at 1 MHz is approximately 1600 Ω and decreases with frequency beyond 1 MHz. The "attenuation" (i.e. the ratio V_{out}/V_{in}) is shown in Fig. 2. Between 0.1 and 1 MHz, the average attenuation is about 10 dB. Beyond that, the attenuation can exceed 40 dB. In addition, it is clear that the attenuation is strongly frequency dependent.

It can be concluded that even simple models with mismatches, junctions and connected devices result in attenuations far in excess of the 1 dB/km expected for matched uniform transmission lines with no connected devices or junctions.

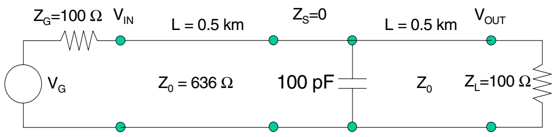

Fig. 1. Uniform transmission line with a shunt 100 pF capacitor at its center and mismatched at transmitter and receiver since each has a 100 Ω input impedance

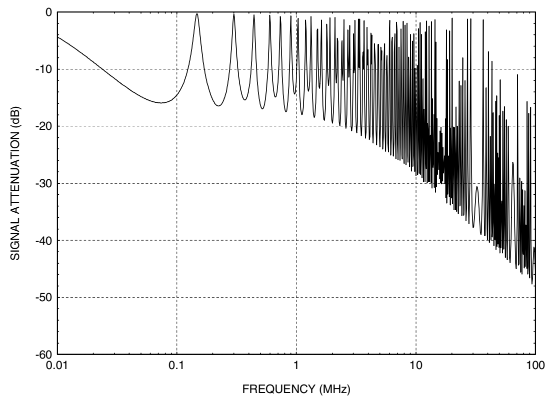

Fig. 2. The attenuation (i.e. V_{out}/V_{in}) for the system shown in Fig. 1

Recent experience with BPL systems installed on overhead distribution lines with relatively few (i.e., fewer than roughly one per 100 m) devices such as transformers, capacitors, taps, and underground risers suggests typical attenuation rates on the order of 30 dB/km. For the same lines, the maximum distance between repeaters is approximately 600 m for a communication rate of at least 10 Mbps. Note that the communication rate available to any one user may be smaller than this since the transmission system is shared by all of its users. Overhead distribution lines with a larger density of attached devices may exhibit similar attenuation rates and maximum distances between repeaters, but there can be no guarantee of this. Underground distribution lines typically exhibit attenuation rates that are three times as high as those for overhead lines. However, this is often compensated for by the substantially lower noise levels on most underground lines, since they do not tend to pick up radio broadcast signals.

Experiments on sub-transmission lines (i.e., 69 kV) have shown that repeaters may be spaced as far as 1200 m or more apart for a communication rate of 10 Mbps. It can be inferred from this result that attenuation rates on higher-voltage lines may be even lower. The reason for this is likely related to the smaller number of attachments, and more uniform dimensions. Reducing this attenuation would appear to be an important goal for BPL designers.

III. Electromagnetic Emissions from BPL Systems

A. Balanced Systems

Consider a two-wire transmission line as shown in Fig. 3. If the vertical wires are removed, the wires carry equal and opposite (i.e. balanced) continuous wave (CW) currents, then the "equivalent" electric field (i.e. the magnetic field multiplied by the impedance of free space = 120π) is 30 μV/m or 29.5 dBμV/m (i.e., the US Federal Communications Commission (FCC) limit) at 30 meters from the power line for a wire current of only 447 μA! Further, if the characteristic impedance of the parallel wire transmission line is Z_0 = 550Ω, then the maximum single frequency power flowing (without violating the US FCC limit) on the transmission line is 109 μW or –9.6 dBm!, European limits are even more stringent as will be illustrated later.

Although this power level is extremely small, it should be noted that it is for a CW signal. It will be shown later that the use of broadband modulation techniques partially offsets this limitation. Of more concern, however, is the fact that the currents may not be balanced as assumed here. Unbalance can lead to significantly higher radiated fields [1].

B. The Effect of System Unbalance

Consider next the possibility of creating unbalanced currents on power lines at high frequencies by reinserting the vertical wires (to simulate ungrounded vertical ground wires) into Fig. 3.

At low frequencies it can be shown that no currents pass through the vertical wires since they are open circuited. This is the expected result. At higher frequencies, however, the vertical wire current can be significant as shown in Figure 4. These unbalanced currents generate electromagnetic fields that can dominate the emissions from balanced systems [1].

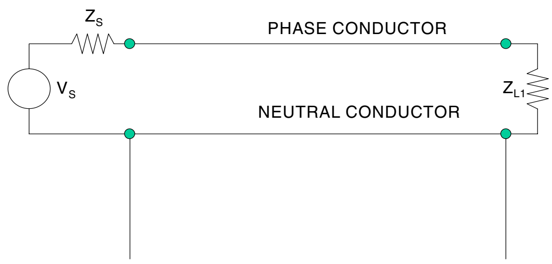

Fig. 3. Simplified circuit for studying power system radiation (vertical wires are removed for the balanced case)

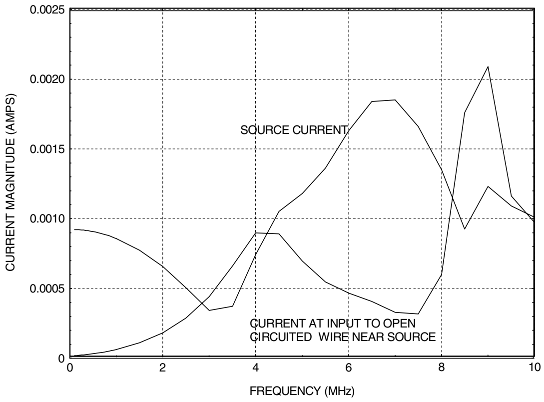

Fig. 4. High frequency source and left vertical wire input current

IV. Relevant Government Regulations on Electromagnetic Emissions

A. US Federal Communications Commission (FCC) Regulations

Here, portions of the Code of Federal Regulations, Volume 47, Part 15 (CFR47-15) relevant to BPL systems will be quoted. This type of system is a power line carrier systems and is defined as, "an unintentional radiator employed as a carrier current system used by an electric power utility entity on transmission lines for protective relaying, telemetry, etc. for general supervision of the power system."

CFR47-15 says that "carrier current systems" (A system, or part of a system, that transmits radio frequency energy by conduction over the electric power lines. A carrier current system can be designed such that the signals are received by conduction directly from connection to the electric power lines (unintentional radiator) or the signals are received over-the-air due to radiation of the radio frequency signals from the electric power lines (intentional radiator) used as unintentional radiators (A device that intentionally generates radio frequency energy for use within the device, or that sends radio frequency signals by conduction to associated equipment via connecting wiring, but which is not intended to emit RF energy by radiation or induction) or other unintentional radiators that are designed to conduct their radio frequency emissions via connecting wires or cables and that operate in the frequency range of 9 kHz to 30 MHz… shall comply with the radiated emission limits for intentional radiators provided… in Table 1.

	Measurement	
Frequency [MHz]	Field strength [µV/m]	Distance [m]
1.705-30.0	30	30

TABLE 1.
FCC Field Strength Limits for Carrier Current System

The emission limits shown in the above table are based on measurements employing a CISPR quasi-peak detector with a 9 kHz bandwidth. These systems are to be measured for compliance using the American National Standards Institute (ANSI) standard C63.4–1992, entitled "Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz,"

In addition to meeting these standards CFR47-15 requires that:

(a) persons operating intentional or unintentional radiators shall not be deemed to have any vested or recognizable right to continued use of any given frequency by…

(b) Operation of an intentional, unintentional, or incidental radiator is subject to the conditions that no harmful interference is caused….

(c) The operator of a radio frequency device shall be required to cease operating the device upon notification by a Commission representative that the device is causing harmful interference.

B. European Regulations

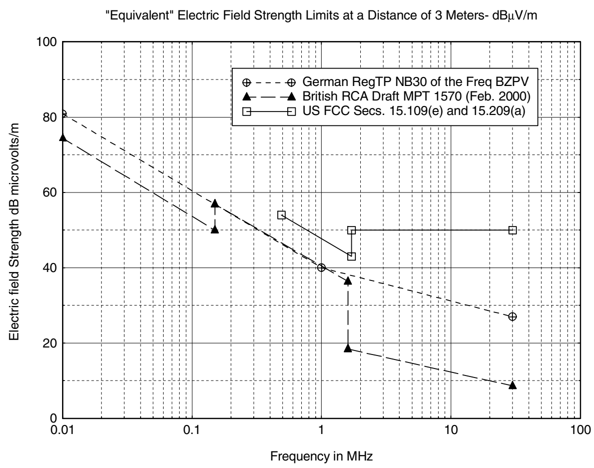

Fig. 5. German limits according to Requirements 30 (NB30) of the FreqBZPV from the RegTP, compared with the limits of Draft MPT 1570/Feb 2000 from the British Radio Communications Agency and the limits of the US Federal Communications Commission in Sections 15.109(e) and 15.209(a) of Title 47 of the Code of Federal Regulations

Although no homogenized European Standard for radiation from BPL systems exists at this time, national standards have been drafted by both the United Kingdom and Germany. A graph that shows these along with the FCC standards is given in Fig. 5. It is assumed that the signals are measured with a CISPR standard receiver with a 9 kHz bandwidth using a loop antenna at a distance d of 3 m from the power line. For limits not specified at a 3 meter distance (i.e. d= 1 meter for MPT 1570 from 9 k to 1,6 MHz and d = 30 meters for FCC section 15.209(a)), the requirements were scaled to d = 3 meters by adding the commonly used "1/d" or "far field" attenuation factor 20 $\log_{10}$(d(meters)/3). The logarithm of the free-space wave impedance $20\log Z_0$ is added to the magnetic field strength to convert it to an "equivalent" electric field. For the German and British regulations, the use of peak detectors is specified, while quasi-peak detectors are specified by US regulations. While the response of these two detectors is quite different for impulsive signals with low repetition rates, it is likely that the quasi-peak response will be 2 – 3 dB lower than the peak response for typical communications signals.

It is clear that since the European standards are at least 20 dB more conservative than the US standards, legal operation of BPL systems in Europe is even more problematic. Note that had the more appropriate "near field" attenuation factor $40\log_{10}$(d(meters)/3) from FCC Section 15.31(f) been used, the difference between US and European regulations would have been even greater.

V. ENGINEERING RESPONSES TO DESIGN CHALLLENGES

A. Reducing Emissions to Acceptable Levels

A number of methods have been proposed for designing systems that will both be compatible with existing field emission limits and not cause unacceptable interference to licensed users of the high frequency spectrum.

The most important fact to note is that the CISPR receiver required by the United States and European countries is a narrowband receiver with a bandwidth of 9 kHz. If the power of a modulated signal is spread out over a wide bandwidth (as is usually the case), the signal power within the CISPR receiver bandwidth will be reduced. Thus, the wider the bandwidth of the signal, the smaller the "equivalent" fields measured by the CISPR receiver. This is illustrated in Fig. 6.

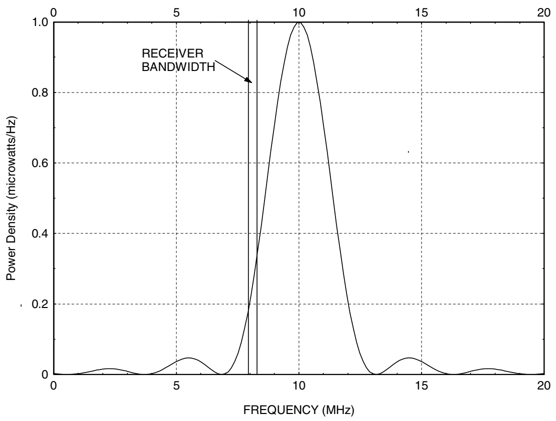

Fig. 6. Power spectral density for a random binary digital signal centered at 10 MHz with a bit rate of 3.14 MHz. Also shown is the bandwidth of a narrowband receiver

Here, the power spectral density of a random binary digital signal centered at 10 MHz is shown. In this case the bit rate is 3.14 MHz. The total transmitted power for this signal is 3.14 Watts. The power received in a 9 kHz bandwidth (as specified by the FCC standards) is only 2.24 milliwatts; 31.5 dB less than the total signal power. Clearly, this is a considerable improvement.The reduction of attenuation can effectively reduce emissions since reduced attenuation means that smaller transmitter powers are required. One approach to reducing attenuation is to improve the system matching. This process, however, is difficult since the match must be achieved over a very wide bandwidth. Another approach is too use ferrite chokes on ground wires. These devices can isolate signals junctions that can cause additional attenuation. They also reduce unbalanced currents in the system and hence reduce emissions.

B. Modulation schemes for very complex channels

As mentioned above, the power line channel presents some very difficult design challenges. Specific problems include attenuation, input impedance and background noise that vary with both time and frequency, delay spread due to multipath propagation, modulation of the input impedance by the power frequency voltage, various types of noise and interference from narrow band signals. The challenge to the designer is to select a modulation scheme that works well in this environment.

One scheme that has been successfully used in this environment is Orthogonal Frequency Division Multiplexing (OFDM). With OFDM the signal is transmitted on a large number of operating frequencies (i.e., carriers) within the usable spectrum. The data rate for the signal on each carrier is equal to the overall data rate divided by the number of carriers. Given this, the symbol length can be made longer and the effects of delay spread due to multiple reflections minimized. Another advantage of such a system is that carriers on sensitive portions of the spectrum (e.g., amateur radio bands) can simply be turned off to avoid interference.

VI. RECENT CHANGES IN FCC REGULATIONS

In October of 2004, the FCC issued a Report and Order that related to what they define as Access Broadband over Power Line (Access BPL) [2]. In this report and order, Part 15 of Title 47 Code of Federal Regulations was modified in several ways. First, BPL was defined as "A carrier current system installed and operated on an electric utility service as an unintentional radiator that sends radio frequency energy on frequencies between 1.705 MHz and 80 MHz over medium voltage lines or over low voltage lines to provide broadband communications and is located on supply side of the utility service's points of interconnection with customer premises. Access BPL does not include power line carrier systems as defined in Section 15.3(t) of this part or In-House BPL as defined in Section 15.3(gg) of this part."

The emission limits as given in Table I and Fig. 5 remain unchanged. The methods by which adherence to these limits is to be established, however, have been changed and will be discussed later in this section.

With respect to interference, the new FCC rules state, "Access BPL systems shall incorporate adaptive interference mitigation techniques to remotely reduce power and adjust operating frequencies, in order to avoid site-specific, local use of the spectrum by licensed services. These techniques may include adaptive or "notch" filtering, or complete avoidance of frequencies, locally used by licensed radio operations." The regulations go on to specify that these filters attenuate emissions by 20 and 10 dB below the Part 15 regulations below and above 30 MHz respectively.

Further, the regulations state that, "Access BPL systems shall comply with applicable radiated emission limits upon power-up following a fault condition, or during a start-up operation after a shut-off procedure, by the use of a non-volatile memory, or some other method, to immediately restore previous settings with programmed notches and excluded bands…"

In addition, "Access BPL systems shall incorporate a remote controllable shut-down feature to deactivate, from a central location, any unit found to cause harmful interference, if other interference mitigation techniques do not resolve the interference problem."

Finally, the FCC has stated that Access BPL systems may not 1) use certain "excluded" bands of frequencies, 2) be located in certain "exclusion zones and 3) be used without coordinating with appropriate agencies in certain "consultation areas."

The last major change to the regulations is a methodology for verifying that BPL systems meet FCC emissions standards. Here, just the regulations for overhead lines will be given. Additional regulations for underground installations can be found in [2].

The measurements made to certify a particular system are to be made "*in situ*" on three typical installations at which the ambient signal level is 6 dB below the applicable limit. The equipment under test (EUT) includes, "all BPL electronic devices e.g., couplers, injectors, extractors, repeaters, boosters and electric utility overhead or underground medium voltage lines." Testing is to be performed with power settings at the maximum power level and using the maximum RF injection duty factor (burst rate). With respect to the latter, the detector to be used is quasi peak if the burst rate is at least 20 bursts per second and a peak detector otherwise.

The regulations specify that, below 30 MHz, a magnetic loop antenna at 1 meter above ground should be used. Its plane should be oriented vertically and the emission maximized by rotating the antenna 180 degrees about its vertical axis. Above 30 MHz, an electric field sensing antenna shall be used and the signal maximized for antenna heights between 1 and 4 meters above ground, for both horizontal and vertical polarizations.

The details about where the measurements are to be made and at what frequencies follow.

1) "Measurements should normally be performed at a horizontal separation distance of 10 meters from the overhead line. If necessary, due to ambient emissions, measurements may be performed at a distance of 3 meters. Distance corrections are to be made in accordance with Section 15.31(f) of the Rules."

2) "Testing shall be performed at distances of 0, ¼, ½, ¾, and 1 wavelength down the line from the BPL injection point on the power line. Wavelength spacing is based is based on the mid-band frequency used by the EUT. In addition, if the mid-band frequency exceeds the lowest frequency injected onto the power line by more than a factor of two, testing shall be extended in steps of ½ wavelength of the <u>mid-band</u> frequency until the distance equals or exceeds ½ wavelength of the <u>lowest</u> frequency injected. (For example, if the device injects frequencies from 3 – 27 MHz, the wavelength corresponding to the mid-band frequency of 15 MHz is 20 meters, and the wavelength corresponding to the lowest injected frequency is 100 meters. Measurements are to be performed at 0, 5, 10, 15, and 20 meters down line – corresponding to zero to one wavelength at the mid-band frequency. Because the mid-band frequency exceeds the minimum frequency by more than a factor of two, additional measurements are required at 10 meter intervals until the distance down-line from the injection point equals or exceeds ½ of 100 meters. Thus, additional measurement points are required at 30, 40, and 50 meters down line from the injection point.

3) "Testing shall be repeated for each Access BPL component (injector, extractor, repeater, booster, concentrator, etc.)"

4) "The distance correction for the overhead-line measurements shall be based on the slant range distance, which is the line-of-sight distance from the measurement antenna to the overhead line. Slant range distance corrections are to be made in accordance with Section 15.31(f) of the Rules. (For example, if the measurement is made at a horizontal distance of 10 meters with an antenna height of 1 meter and the height of the BPL-driven power line is 11 meters, the slant range distance is 14.1 meters [10 meters vertical distance and 10 meters horizontal distance]. At frequencies below 30 MHz, the measurements are extrapolated to the required 30-meter reference distance by subtracting 40 log(30/14.1), or 13.1 dB

from the measured values. For frequencies above 30 MHz, the correction uses a 20 log factor and the reference distance is specified in 15.109 of the Rules.)"

VII. RESPONSE TO CHANGES IN THE FCC REGULATIONS

It is no understatement to say that the response to the changes in the FCC regulations has been swift. First to respond is the association of amateur radio operators in the US, the American Radio Relay League. In a letter dated Nov 1, 2004, The ARRL has expressed its disappointment with the current administration's failure "to prevent radio spectrum pollution by BPL systems." In this letter, they outline a number of reasons why the Report and Order will not prevent harmful interference. One specific concern was their belief that the filtering required in excluded bands was not sufficiently large. More information about the ARRL's response can be found at the ARRL web site, www.arrl.org.

ARRL officials continue to mull possible formal responses to the Report and Order. The ARRL Executive Committee already has authorized the filing of a *Petition for Reconsideration*. It further authorized the ARRL General Counsel to "prepare to pursue other available remedies as to procedural and substantive defects" in the BPL proceeding.

VIII. REFERENCES

[1] Paul, C.R., *Introduction to Electromagnetic Compatibility*, Wiley Interscience, New York, 1992, 765 pp.

[2] FCC, "Amendment of Part 15 regarding new requirements and measurements guidelines for Access Broadband over Power Line Systems and Carrier Current Systems including Broadband over Power Line Systems, Report and Order 04-245 issued October 28, 2004